The Impact of Advanced Driver Assistance Systems on Vehicle Dynamic Performance and on the Driver

by

Robin Allen Auckland

Submitted in accordance with the requirements
for the degree of Doctor of Philosophy.

UNIVERSITY OF LEEDS
The University of Leeds
School of Mechanical Engineering

June 2008

The candidate confirms that the work submitted is his own and that the appropriate credit has been given where reference has been made to the work of others.

Acknowledgements

I would like to thank my supervisors, Dr Warren Manning and Professor Oliver Carsten for their continual support and guidance throughout the duration of this project. Their understanding of the subject area was of great assistance, and their insightful discussions at Friday morning meetings were a great source of inspiration for the work ahead.

I would not have been able to complete this PhD without the assistance of Hamish Jamson, and Tony Horrobin. Their knowledge of the driving simulator and willingness to help, proved invaluable when developing and conducting the final experiments.

While not directly connected with the work, credit should be given to my parents, who provided support and assistance in times of need, as well as the occasional financial top up.

I would also like to thank the various occupants of G54b, who have provided me with many distractions from this PhD, when required (and sometimes when not). As well as many useful hints and tips, about the whole post graduate experience. A special mention should go to my girlfriend Sara, for putting up with me while writing up, and assisting in proof reading the final document.

Abstract

This research concerns issues arising in the design and implementation of advanced driver assistance systems, specifically longitudinal and lateral controllers; their effects on the dynamic performance of the vehicle, and their impact on the driver.

The current state of the art is discussed as part of an extensive literature review, which highlights prominent gaps in the published research. There is a lack of understanding as to the effects of adverse environmental factors on the vehicle dynamics, and the effects of the systems' on the comfort of the driver. A novel twin track approach was taken to investigate these issues: the effects of the systems' on the vehicle dynamics were monitored using a range of off-line simulation tools, while the systems' impact on the driver was considered using an on-line driving simulator experiment.

An adaptive cruise control system was developed, tuned to provide a comfortable response and implemented on a sophisticated off-line 9 degree of freedom vehicle model, with a non-linear tyre model. The system was tested in a range of environmental conditions. These simulations highlighted the good performance of the system in wet conditions, and revealed some possible driver conflicts.

Two lateral control systems were developed, one based on a look down methodology, and the second on a more driver emulating look ahead approach. The systems were tested using the same high fidelity vehicle model, and an extensive range of suitable motorway manoeuvres. The systems were compared, proving the comfort and stability benefits of the look ahead system.

The longitudinal and lateral control systems were integrated with the University of Leeds driving simulator. Ten subject drivers drove with and without the systems through a range of scenarios, some of which required evasive action. The impact of the systems on the driver, and the driver's response to safety critical scenarios was assessed. Results displayed little safety benefit of the systems in evasive scenarios, but drivers perceived improved awareness and comfort when under their control.

The potential of advanced driver assistance systems to make driving a more comfortable and safe experience has been demonstrated, although the system engineer must consider the impact of the systems on the driver throughout their design and implementation.

Publications

Some parts of the work presented in this thesis have been published in the following articles:

Auckland, R. A., Manning, W. J., Carsten, O. M. J., Levesley, M. C., and Crolla, D. A. (2005). Dynamic Performance of Adaptive Cruise Control Vehicles. *SAE 2005 World Congress*

Auckland, R. A., Manning, W. J., and Carsten, O. M. J. (2006). Dynamic Analysis of Lateral Control Systems. In *Proceedings of AVEC '06: The 8th International Symposium on Advanced Vehicle Control*, pages 747 – 752

Auckland, R. A., Manning, W. J., Carsten, O. M. J., and Jamson, A. H. (2008). Advanced driver assistance systems: Objective and subjective performance evaluation. *Vehicle System Dynamics*, 46(1 supp 1):883 – 897

Contents

1 Introduction to Research 1

1.1 Advanced Driver Assistance Systems 1
  1.1.1 Longitudinal Control 2
  1.1.2 Lateral Control 3
1.2 Vehicle Dynamic Modelling 4
1.3 Human Impact Assessment 4
1.4 Literature Review 5
  1.4.1 Longitudinal Control 5
    Current State of the Art 6
    Control Strategies 8
    Performance Requirements of ACC 11
    Human Factors Research 12
    Collision Warning Systems 14
  1.4.2 Lateral Control 15
    Current State of the Art 16
    Lane Keeping 17
    Driver's Lateral Control Behaviour 20
    Lane Changing 21
  1.4.3 Combined Longitudinal and Lateral 24
  1.4.4 Driving Simulators 25
  1.4.5 Critical Review of Literature 27
  1.4.6 Conclusions from the Literature 29
1.5 Aims and Objectives 30
  1.5.1 Aim 30
  1.5.2 Objectives 31
    Longitudinal Control 31
    Lateral Control 31

1.6 Thesis Outline 31

2 **Vehicle Modelling and Simulation** **34**
2.1 Two Degree of Freedom Lateral Model 35
2.2 Three Degree of Freedom Model 37
2.3 9 Degree of Freedom Full Vehicle Model 39
2.3.1 Side Winds 42
2.3.2 Superelevation 43
2.4 Tyre Modelling 43
2.5 Validation 45
2.5.1 Validation Results 46
Lateral Behaviour 46
Longitudinal Behaviour 50
Combined Lateral and Longitudinal Behaviour 52
Validation Conclusions 53

3 **Longitudinal Control** **55**
3.1 Detailed Controller Design and Analysis 56
3.1.1 Controller Design 56
3.1.2 Control Tuning 59
3.1.3 Test Scenarios 62
Environmental Conditions 63
Comfort Impacts 64
Operation While Cornering 64
3.1.4 Analysis 65
Environmental Conditions 65
Comfort Impacts 68
Operation while Cornering 69
3.1.5 Conclusions 70
3.2 Hierarchal Control Scheme Design and Analysis 71
3.2.1 Integration of Speed Control to ACC 72
3.2.2 Powertrain Integration and Controller Design 75
Acceleration Limits / Short Headway Gains 76
3.2.3 Test Scenarios and Analysis 79
Lead Vehicle Acceleration Tests 79
Sinusoidal Lead Vehicle Acceleration 82
Lead Vehicle Cut In 85

3.3 Summary of Results 87

4 Lateral Control **88**

4.1 Test Scenarios 89
  4.1.1 Lane Keeping Scenarios 89
  4.1.2 Lane Changing Scenarios 90
  4.1.3 Disturbance Scenarios 92
  4.1.4 Summary 95
4.2 Look Down Controller Development 95
  4.2.1 PID Control Overview 95
    PID Tuning Methodology 98
    PID Control on the Full Vehicle Model 100
  4.2.2 Combined Internal Model and PID Control 102
4.3 Look Down Analysis 108
  4.3.1 Lane Keeping Results 108
    Straight Roads 108
    Curved Roads 108
  4.3.2 Lane Changing Results 111
    Standard Lane Changes 111
    Evasive Lane Changes 112
  4.3.3 Summary 117
4.4 Look Ahead Controller Development 118
  4.4.1 Control Methodology 119
  4.4.2 Processing Road Data 120
  4.4.3 Error Estimation Techniques 121
  4.4.4 Controller Tuning 122
    Look Ahead Distance 123
    Number of Look Ahead Points 127
    Gain Tuning 130
4.5 Look Ahead Analysis 134
  4.5.1 Lane Keeping Results 135
    Straight Roads 135
    Curved Roads 135
  4.5.2 Lane Changing Results 136
    Standard Lane Changes 136
    Evasive Lane Changes 137

4.5.3 Disturbance Results 139
Low Friction 139
Superelevation 141
Side Winds 143
Split-μ 144
4.5.4 Comparison with Look Down Scheme 146
4.5.5 Summary of Results 151

5 Driving Simulator Development **152**
5.1 The University of Leeds Driving Simulator 153
5.1.1 Motion System 154
Motion System Tuning 157
5.1.2 Vehicle Cab 157
5.2 Vehicle Model Integration 158
5.2.1 Steering Model 159
5.2.2 Slip Calculations 160
5.2.3 Powertrain 160
5.3 Longitudinal Control Integration 161
Incremental Set Speed 161
Incremental Headway 162
Out of Range Behaviour 162
Testing Procedure 162
5.3.1 High Level State Logic 163
5.3.2 Human Machine Interface 164
5.4 Lateral Control Integration 168
5.4.1 Input Integration 169
5.4.2 Output Integration 170
5.4.3 Fade-In of Control Action 170
5.4.4 High Level State Logic 171
5.4.5 Human Machine Interface 171
5.5 Scenario Development 173
5.5.1 Adaptive Cruise Control Scenarios 173
Acceleration in Bend 173
Lead Vehicle Deceleration 174
Car Cutting In 175
5.5.2 Lane Keeping System Scenarios 176

Lane Drop 176
Narrow Lanes 176

6 Driving Simulator Experimentation **178**
6.1 Experimental Design 178
6.1.1 Subjects 178
6.1.2 Protocol 179
6.1.3 Road Layout 180
Sample ACC Road Layout 181
Sample LKS Road Layout 181
Subject Road Allocation 181
6.1.4 Subjective Measures 182
Acceptability 182
Concentration 183
Experience 183
Trust 183
6.2 Results and Analysis 184
6.2.1 ACC Scenarios 185
Lead Vehicle Deceleration (LVD) 185
Car Cutting In (CCI) 187
Acceleration in Bend (AIB) 189
6.2.2 LKS Scenarios 190
Narrow Lanes 190
Lane Drop 193
6.2.3 Subjective Evaluation 194
Acceptability 194
Concentration 195
Experience 195
6.2.4 Summary of Results 197

7 Discussion and Conclusions **198**
7.1 Work Covered 198
7.1.1 Longitudinal Control 198
7.1.2 Lateral Control 200
7.1.3 Driving Simulator Development and Experimentation 200
Objective Evaluation 201
Subjective Evaluation 202

7.2 Conclusions 203
7.3 Future Work 203

References **205**

A Modelling Parameters **214**
A.1 Vehicle Parameters 214
A.2 Look Ahead Control Parameters 215
A.3 Tyre Parameters 215

B Simulator Experiment Documentation **217**

List of Figures

1.1 University of Leeds Driving Simulator (UoLDS) 5
1.2 Adaptive cruise control modes 6
1.3 Block diagram of Nissan ACC system (Iijima et al. 2000) 10
1.4 Distribution of average brake response times (Cheng et al. 2002) 15
1.5 Video based look ahead sensor (Iteris Inc. AutoVue^{TM}Lane Departure Warning (LDW) system) 16
1.6 Honda lane keeping assistance system - geometric model (Takahashi and Asanuma 2000) 18
1.7 Eye movement during lane change manoeuvre. (Salvucci and Liu 2002) . 22
1.8 Generic controller architecture system. (Michon 1993) 25
1.9 Methods of motion generation in driving simulators 26

2.1 The 2dof 'bicycle' model 36
2.2 Definition of longitudinal slip 38
2.3 9dof vehicle model, longitudinal, lateral and yaw dof's 40
2.4 9dof vehicle model, pitch, longitudinal and wheel dof's 40
2.5 9dof vehicle model, roll and lateral dof's 41
2.6 Side wind modelling 42
2.7 Additional lateral forces generated when the vehicle is banked 43
2.8 Example Pacejka 'carpet' plot 44
2.9 10m/s 0.1g step steer - validation results 47
2.10 10m/s 0.3g step steer - validation results 48
2.11 30m/s 0.1g step steer - validation results 48
2.12 30m/s 0.5g step steer - validation results 49
2.13 30m/s 0.3g sine steer - validation results 50
2.14 10m/s 0.1g straight line acceleration - validation results 51
2.15 30m/s 0.3g straight line braking - validation results 51
2.16 Cornering lift off - lateral validation results 52

2.17 Cornering lift off - longitudinal validation results 53

3.1 Longitudinal control description 57
3.2 Influence of speed control on control objectives 60
3.3 Surface plots of the influence of $K_{P_{sp}}$ and K_{P_h} on control objectives . . . 61
3.4 Headway response of the ACC system to low accelerations 65
3.5 Longitudinal acceleration response of the ACC system to low accelerations 66
3.6 Headway response of the ACC system to 0.2g accelerations 66
3.7 Longitudinal acceleration response of the ACC system to 0.2g accelerations 67
3.8 Headway response of the ACC system to out of range accelerations 68
3.9 Longitudinal acceleration response of the ACC system to out of range accelerations 69
3.10 Pitch acceleration response of the ACC system to out of range accelerations 69
3.11 Trajectory taken when ACC system caused vehicle to accelerate 70
3.12 ACC effects on roll acceleration 71
3.13 The effects of the control bound on the headway of the vehicle 73
3.14 The effects of the control bound on the longitudinal acceleration of the vehicle 74
3.15 ACC control flow diagram 76
3.16 Revisions to ACC controller design 77
3.17 Effect of control limits on acceleration when maintaining headway 78
3.18 Headway of vehicles with control limits and TTC dependent gains 79
3.19 Headway response of vehicle to 3m/s^2 lead vehicle acceleration 80
3.20 Acceleration response of vehicle to 3m/s^2 lead vehicle acceleration 80
3.21 Headway response of vehicle to -5m/s^2 lead vehicle acceleration 81
3.22 Acceleration response of vehicle to -5m/s^2 lead vehicle acceleration . . . 82
3.23 Velocity response of vehicle to low frequency sinusoidal lead vehicle velocity 83
3.24 Headway response of vehicle to low frequency sinusoidal lead vehicle velocity 83
3.25 Velocity response of vehicle to high frequency sinusoidal lead vehicle velocity 84
3.26 Headway response of vehicle to high frequency sinusoidal lead vehicle velocity 84
3.27 Acceleration response of vehicle to high frequency sinusoidal lead vehicle velocity 85

3.28 Headway response of vehicle to CCI event 86
3.29 Acceleration response of vehicle to CCI event 86

4.1 Reference lateral acceleration for a SLC 91
4.2 Reference lateral acceleration for an ELC 93
4.3 Overview of the Ackermann approach to lateral error calculation 96
4.4 Block diagram of PID lateral control strategy 98
4.5 Tuning output of 9dof PID lateral control system for a SLC at 60mph . . 101
4.6 Tuning output of 9dof PID lateral control system of a 0.5g ELC at 60mph 102
4.7 Simple Internal Model Control (IMC) 103
4.8 Block diagram of yaw rate IMC of the 2dof vehicle model 105
4.9 Yaw rate and lateral error plots from yaw rate IMC 106
4.10 Comparison of IMC and PID control schemes for ELC 0.1g manoeuvre at 70mph 107
4.11 Block diagram of 9dof IMC model 107
4.12 Block diagram of 9dof IMC & PID model 108
4.13 Response of look down systems during a flat corner at 30mph 109
4.14 Response of look down systems during a flat corner at 50mph 110
4.15 Response of look down systems during a flat corner at 70mph 111
4.16 Response of look down systems during a SLC at 30mph 112
4.17 Response of look down systems during a SLC at 70mph 113
4.18 Response of look down systems during a 0.1g ELC at 30mph 113
4.19 Response of look down systems during a 0.1g ELC at 70mph 114
4.20 Response of look down systems during a 0.5g ELC at 30mph 115
4.21 Response of look down systems during a 0.5g ELC at 50mph 116
4.22 Response of look down systems during a 0.5g ELC at 70mph 117
4.23 Overview of look ahead lateral control scheme 119
4.24 Method of calculating path radius of curvature and heading angle 121
4.25 Method of calculating look ahead lateral errors 123
4.26 Trajectory of vehicle for ELC with varying preview distance 125
4.27 Lateral position error of vehicle for ELC with varying preview distance . 125
4.28 Lateral acceleration of vehicle for ELC with varying preview distance . . 127
4.29 Trajectory of vehicle for ELC with varying preview points 128
4.30 Lateral position error of vehicle for ELC with varying preview points . . . 128
4.31 Lateral acceleration of vehicle for ELC with varying preview points . . . 130
4.32 Trajectory of vehicle for ELC with varying gain magnitude 131

4.33 Lateral error of vehicle for ELC with varying gain magnitude 132
4.34 Lateral acceleration of vehicle for ELC with varying gain magnitude . . . 133
4.35 Trajectory of vehicle for ELC with varying yaw and displacement gains . 134
4.36 Trajectory of vehicle for flat corners 135
4.37 Trajectory of vehicle for SLC 137
4.38 Trajectory of vehicle for 0.1g ELC 138
4.39 Trajectory of vehicle for 0.5g ELC 139
4.40 Trajectory of vehicle for 0.1g ELC at various μ 140
4.41 Trajectory of vehicle for 0.5g ELC at various μ 141
4.42 Trajectory of vehicle during an elevation disturbance on a straight road . . 142
4.43 Trajectory of vehicle during an elevation disturbance on a curved road . . 143
4.44 Trajectory of vehicle during a 45°side wind disturbance on a straight road 143
4.45 Trajectory of vehicle during a 90°side wind disturbance on a straight road 144
4.46 Trajectory of individual wheels during 70mph 0.5g ELC with split μ 0.85:0.4 145
4.47 Trajectory of vehicle during 70mph 0.5g ELC with split μ conditions . . 145
4.48 Trajectory of vehicles with look down and look ahead controllers for a SLC at 50mph 146
4.49 Lateral acceleration of vehicles with look down and look ahead controllers for a SLC at 50mph 147
4.50 Trajectory of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC 147
4.51 Lateral acceleration of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC 148
4.52 Roll acceleration of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC 148
4.53 Steering angle of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC 149
4.54 Trajectory of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC 149
4.55 Lateral acceleration of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC 150
4.56 Roll acceleration of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC 150

5.1 University of Leeds Driving Simulator 153

5.2 Response of a hexapod to a step change in acceleration 156
5.3 UoLDS motion system design 156
5.4 Sample output from *PREVIEW* development tool 163
5.5 State logic of the ACC 164
5.6 ACC steering wheel controls 165
5.7 Examples of ACC displays in production vehicles, from left to right *Audi, BMW, VW* 166
5.8 Location of the LCD screen for ACC display 167
5.9 ACC GUI in its four states, *Disabled, Enabled - No Leader, Enabled - Leader, Danger* 167
5.10 Integration of ACC, including driver 168
5.11 State logic of the LKS 171
5.12 Steering wheel button to enable/disable the LKS 172
5.13 The three states of the LKS GUI, from left to right: *Disabled, Engaged, Unavailable* 172
5.14 Overview of the acceleration in bend (AIB) event 173
5.15 Overview of the lead vehicle deceleration (LVD) event 174
5.16 Overview of the car cutting in (CCI) event 175
5.17 Overview of the lane drop event 176
5.18 Overview of the narrow lanes event 177

6.1 Schematic of an ACC road layout 181
6.2 Schematic of an LKS road layout 182
6.3 Time to collision data for LVD scenario 185
6.4 Minimum headway data for LVD scenario 186
6.5 Brake reaction time data for LVD scenario 186
6.6 Time to collision data for CCI scenario 187
6.7 Minimum headway data for CCI scenario 188
6.8 Brake reaction time data for CCI scenario 188
6.9 Time to lane crossing data for AIB scenario 189
6.10 Cumulative lateral error data for AIB scenario 190
6.11 Maximum lateral error data for AIB scenario 190
6.12 Heading recovery time data for narrow lanes scenario 191
6.13 Cumulative lateral error data for narrow lanes scenario 192
6.14 Cumulative steering effort data for narrow lanes scenario 192
6.15 Heading recovery time data for lane drop scenario 193

6.16 Brake response time data for lane drop scenario 194
6.17 Acceptability of ADAS 195
6.18 Perceived attention and anticipation levels with ADAS 196
6.19 Perceived comfort and enjoyment levels with ADAS 196

List of Tables

1.1 Typical performance specifications of ACC radar sensors (Abou-Jaoude 2003) 8
1.2 AHS steering actuator requirements (Sebastian et al. 1997) 17

3.1 Surface coefficients of friction (Khatun et al. 2002, Sakai and Hori 2000) 63
3.2 The effects of headway control bound on control response 75

4.1 Design parameters for flat corners (Highways-Agency 1993) 90
4.2 Trajectory parameters for a SLC 92
4.3 Trajectory parameters for an ELC 93
4.4 Road design parameters for superelevation 94
4.5 Ziegler-Nichols PID tuning method 99
4.6 Summary of PID tuning scenarios 99
4.7 Cumulative lateral position error (ms) for lane change manoeuvres with varying preview distance 126
4.8 Maximum lateral acceleration (m/s^2) for lane change manoeuvres with varying preview distance 127
4.9 Cumulative lateral error (ms) with varying preview points 129
4.10 Maximum lateral acceleration (m/s^2) with varying preview points 130
4.11 Cumulative lateral error (ms) with varying gain magnitude 132
4.12 Maximum lateral acceleration (m/s^2) with varying gain magnitude 134
4.13 Flat corner results for look down system 136
4.14 Standard lane change results for look down system 137
4.15 0.1g evasive lane change results for look down system 138
4.16 0.5g evasive lane change results for look down system 139
4.17 Super elevation disturbance results 142
4.18 Straight line side wind disturbance results 144

5.1 Dynamic characteristics of the UoLDS motion system 157

5.2 ACC controls 165
5.3 Sample road data from the LADS 169

6.1 Experimental design including counterbalancing of events 182

Nomenclature

α	tyre slip angle
β	vehicle sideslip angle
δ_f	front axle steering angle (at the wheels)
ε	angle of side wind
γ	superelevation inclination angle
μ	tyre/road friction coefficient
ω	angular wheel speed
ϕ	roll angle
ψ	yaw angle
ρ	density of air
ρ_{ref}	normalised reference yaw rate
σ	tyre longitudinal slip ratio
τ	time delay period
θ	pitch angle
a	distance from the centre of gravity to the front axle
A_s	projected side area of vehicle
a_x	longitudinal acceleration
a_y	lateral acceleration

b	distance from the centre of gravity to the front axle
B_ϕ	total roll stiffness
B_θ	pitch stiffness
$B_{f\phi}$	front roll stiffness
$B_{r\phi}$	rear roll stiffness
C	cornering stiffness of axle
C_ϕ	roll damping
C_θ	pitch damping
d_{lw}	lane width
d_p	look ahead preview distance
e_i	projected lateral error at look ahead point $\mathrm{p_i}$
F_x	longitudinal force
F_y	lateral force
G	plant process
h_{cg}	height of centre of gravity above ground
h_p	height of centre of mass above the pitch axis
h_r	height of centre of mass above the roll axis
h_w	time headway
I	pitch angle
I_{xx}	roll moment of inertia
I_{yy}	pitch moment of inertia
I_{zz}	yaw moment of inertia
J_{max}	maximum lateral jerk level
K	control gain

K_ψ	look ahead heading control gain
K_i	look ahead lateral gain
l_s	longitudinal distance from centre of gravity to look down sensor
l_{wb}	wheelbase length
LMU_x	pacejka longitudinal force scaling coefficient
LMU_y	pacejka lateral force scaling coefficient
m_b	sprung vehicle mass
m_f	total mass on front axle
m_r	total mass on rear axle
m_t	total vehicle mass
M_z	yaw moment
r	yaw rate
R_{ref}	radius of curvature
r_{ref}	specific reference yaw rate
R_r	tyre rolling radius
s	distance along specified trajectory path
S_d	inter vehicle spacing - distance headway
T	torque
t	time
t_w	track width
u	longitudinal velocity
v	lateral velocity
V_{sw}	side wind speed
x	longitudinal displacement

y	lateral displacement

Subscripts

f	front
l	lead vehicle
r	rear
s	subject vehicle
x	longitudinal
y	lateral
ψ	yaw
h	headway
sp	speed
sw	side wind

Abbreviations

ABS	Anti-Lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AHS	Automated Highway System
AIB	Acceleration In Bend
BRT	Brake Reaction Time
CAN	Control Area Network
CAS	Collision Avoidance System
CCI	Car Cutting In
CG	Centre of Gravity
CLE	Cumulative Lateral Error
CSE	Cumulative Steering Effort
dof	Degree(s) of Freedom
ELC	Evasive Lane Change
FCW	Forward Collision Warning System
GPS	Global Positioning Systems
GUI	Graphical User Interface
HMI	Human Machine Interface
HRT	Heading Recovery Time
IMC	Internal Model Control
IVI	Intelligent Vehicle Initiative

LADS	Leeds Advanced Driving Simulator
LDW	Lane Departure Warning Systems
LKAS	Lane Keeping Assistance System
LKS	Lane Keeping System
LVD	Lead Vehicle Deceleration
MLE	Maximum Lateral Error
NADS	National Advanced Driving Simulator
PID	Proportional Integral Derivative
SLC	Standard Lane Change
TTC	Time To Collision
TTLC	Time To Lane Crossing
TTS	Time To Speed
UoLDS	University of Leeds Driving Simulator

Chapter 1

Introduction to Research

Chapter 1 presents the introduction to this research and a critical review of the literature. Advanced Driver Assistance Systems are introduced along with the concept of off-line vehicle modelling, and driving simulators. A review of the literature is presented detailing the current state of the art, before current control methodologies are assessed. Human factors studies are also reviewed; including driving simulator experiments, and field testing. A critical summary of the literature is given, before the aims and objectives of the research are stated. The chapter ends with a description of the contents of this thesis.

1.1 Advanced Driver Assistance Systems

An Advanced Driver Assistance System (ADAS) is a term given to a tool which is designed to support or simplify the driving task. Many types of systems have been developed and released onto the market over recent years. Generally these systems fall into one of two categories, passive and active, depending on their level of influence over the vehicle. Passive systems include collision warning systems, lane departure warning systems, and blind spot detection. Active systems use similar sensing technology to the passive systems, but take the assistance one step further by impacting directly on the control of the vehicle. These active systems include: Adaptive Cruise Control (ACC), lateral control systems, and automatic parking systems. The systems can also be split up into those that improve the comfort and convenience of driving, with the long term aim of semi-autonomous driving, and those designed to improve the safety of the driving experience.

These new technologies bring with them a range of both engineering and human factor challenges and implications. Much of the current published research tends to concentrate on one side of these problems, with little consideration as to the impact on the other area. This is especially relevant in the active systems which must provide both a high degree of precision to accurately control the vehicle, and also a human centred approach which is appreciated by a wide range of drivers. This body of work aims to tackle both the technological and human impacts of two types of active ADAS. The two functions in question are longitudinal control and lateral control. Longitudinal control is used to refer to systems such as ACC, which impact on the acceleration and braking of the vehicle. Lateral control refers to systems which impact on the steering behaviour of the vehicle such as a Lane Keeping System (LKS).

Much work has been carried out into the development of sensing technology which is robust enough to provide accurate data for the control system in a range of conditions and scenarios. While the sensors to be used in these systems are considered and their limitations taken into account, they do not form the main area of this research.

1.1.1 Longitudinal Control

Longitudinal control concerns the driving and braking motion of the vehicle. For the purpose of this research, this heading is used to encompass all longitudinal based systems. The main system in question is adaptive cruise control. ACC is an extension of a basic cruise control system, which as well as maintaining a desired vehicle speed, can also adapt the vehicle's speed to changing traffic conditions by an automatic acceleration. The system consists of two main parts:

Sensing A radar sensor is generally used which is mounted at the front of the vehicle. This can accurately monitor the distance to, and velocity of, the vehicle in front, up to a distance of 120m ahead.

Controlling Given the desired vehicle speed, inter-vehicle spacing and actual distance to the vehicle in front. The control system must either maintain the desired speed or reduce the vehicle speed to maintain a desired gap.

The aim of an ACC system is to improve the comfort and experience of driving by removing the car following task from the driver, reducing workload. The systems that have already been released on the market are marketed as a comfort aid, but it is also thought that they could have safety benefits for the driver.

With these systems already on the market, one may assume that sufficient research had been completed in the area. The literature review conducted in Section 1.4 suggests this is not the case. Initial uptake of the ACC systems has been slower than manufacturers had hoped. This research has been undertaken to assess both the vehicle dynamic and human factor issues with the system, that may be in some part responsible for their apparent lack of popularity with customers.

1.1.2 Lateral Control

While longitudinal control ADAS have been available on the market for a number of years, lateral control systems have only recently been released. More passive systems such as lane departure warning systems have been available on commercial vehicles for some time, but recently they have filtered down on to passenger vehicles. In some cases these have been developed into simple lane keeping systems, which provide additional steering torque if the vehicle unnecessarily crosses the lane boundary, to correct the trajectory. The future of such systems lies in full lateral control of the vehicle. For such a system to function the following attributes must be developed:

Sensing A system must be capable of recognising the vehicle's current position within a lane, and also the projected position depending on the lane boundary and vehicle heading. Although this difficult task is further complicated by other vehicles and a variety of lane markings, capable sensing systems are currently available and are in use in lane departure warning systems.

Controlling Given the vehicle's position, a control system is required to induce the required lateral motion of the vehicle to maintain a desired trajectory.

The initial aim of the system is to reduce the driver workload required in tracking the current lane position of the vehicle, but it is also hoped to use the system to perform safe and efficient lane changes in standard and evasive scenarios. With suitable sensing systems available on the market, this research concentrates on the impact of the control system on the vehicle dynamic response of the system. Throughout the study, attention is also paid to the impact on the driver of such a system, as their confidence and support of the technology are vital for its long term success.

1.2 Vehicle Dynamic Modelling

In order to improve the understanding of vehicle dynamics and handling performance, vehicle simulation models have been developed for many years. The aim of these models is to sufficiently capture the vehicle's handling performance with a set of equations. The effects of a range of simple and complex manoeuvres can then be investigated repeatedly, without the need for expensive vehicle prototype testing. The same techniques can also be used to develop and test vehicle control systems.

Much of the research that has been carried out into the effects of ADAS has used simplistic 2 or 3 degree of freedom (dof) vehicle models. While these models provide a good starting point for control design, they fail to fully capture the necessary vehicle motions, and are not suitable for the high-speed evasive manoeuvres that these systems may be capable of.

1.3 Human Impact Assessment

In order for ADAS to be accepted by the customer / driver, they must be both useful and satisfying. While there is much human factors research into the impact of ACC on the driver, these publications generally consider only the effects on the driver, and not how the driver's experience and vehicle dynamic performance are linked. Vehicle modelling tools provide an excellent platform to assess the impact of the systems on the vehicle dynamics, and allow suggestions as to the effect on the driver to be made. But, to fully investigate the driver's reactions to the systems their participation is required. Field testing of vehicle control systems is expensive; it can be difficult and dangerous to conduct experiments with large volumes of traffic, which need to be repeated to obtain significant results. In this kind of scenario a driving simulator is an ideal tool to allow traffic behaviour and emergency manoeuvres to be recreated.

The University of Leeds recently installed a high fidelity driving simulator (Figure 1.1), that was used in this research to assess the impact of the ADAS on the driver. The simulator benefits from a 8dof motion base which can recreate realistic vehicle accelerations to mimic the comfort impact of the systems on the driver. The simulator is also equipped with an immersive full vehicle cab to ensure that the driving experience is as close to real driving as possible.

Figure 1.1: University of Leeds Driving Simulator (UoLDS)

1.4 Literature Review

The aim of this review is to investigate the current standing of the research into Advanced Driver Assistance Systems. For the purpose of this project we are concerned with three main areas, firstly longitudinal control and warning systems, this covers all ACC systems and collision warning systems, and looks into the current state of the art and proposed future applications; secondly lateral control systems, here lane keeping and lane changing systems are investigated and assessed. Finally the combination of both longitudinal and lateral controllers are discussed. In each section the engineering problems and possible solutions are examined, as well the human factor issues.

1.4.1 Longitudinal Control

The term Advanced Driver Assistance System (ADAS) covers a wide range of vehicle based tools, that are installed to in some way aid the driver, be it for safety purposes, or for comfort. These systems include: intelligent headlights, obstacle warning, and stability control systems. In this section we shall look at ADAS that work to control the longitudinal position, velocity and acceleration of the vehicle.

Longitudinal control systems have been in development for over twenty years, but have only recently (last 5 years) been released onto the public market. Control and implementation methods have changed over the years; previously the tendency in the early 1990s was more toward Automated Highway Systems (AHS), which required measurements at both infrastructure and vehicle level (Vahidi and Eskandarian 2003). The principle behind AHS was to form platoons of vehicles that followed each other closely at motorway speeds, without the possibility of collision. With shorter inter-vehicle spacing, motorway capacity can be greatly increased (Darbha and Rajagopal 1999). This system required vehicles with compatible communication devices and also the redevelopment of motorway infrastructure.

Whilst AHS development is still ongoing, current short term trends have moved towards ADAS (Known as the Intelligent Vehicle Initiative (IVI) in USA). By dealing solely with a single vehicle, new driver assistance systems can be easily implemented without expensive road infrastructure changes. For this reason cooperative systems, i.e. those requiring information from the local road network or another vehicle, are not the main focus of this review.

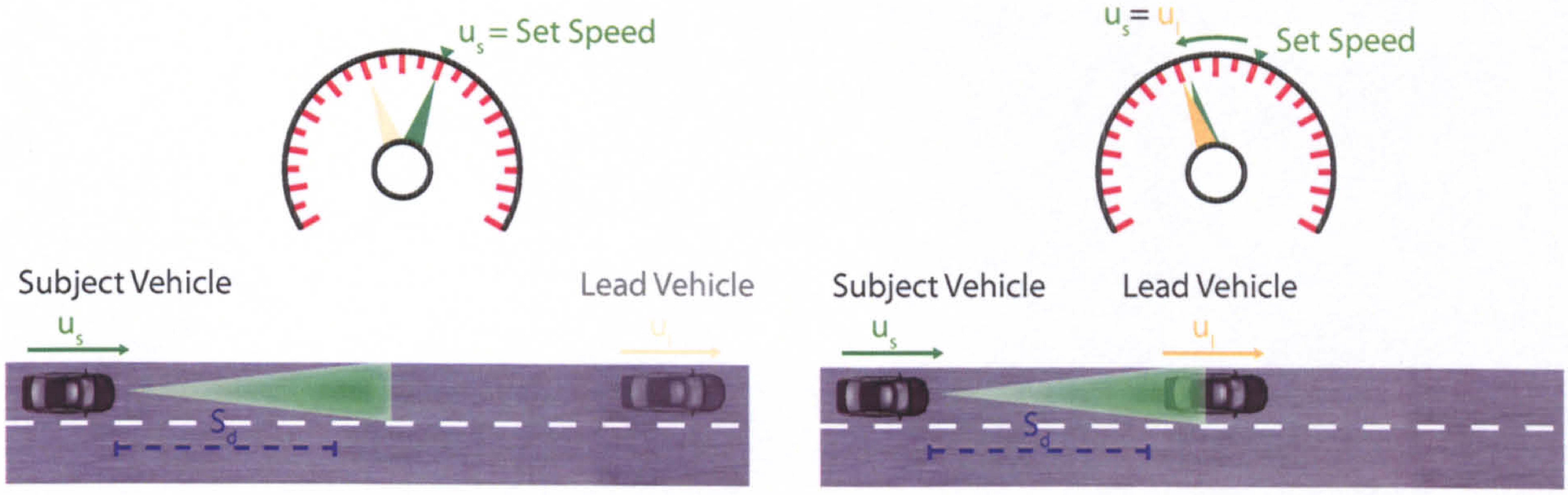


Figure 1.2: Adaptive cruise control modes

A vehicle equipped with an ACC system can detect a leading vehicle and maintain a specified spacing between itself and this lead vehicle, termed 'headway'. When no lead vehicle is within range, the subject vehicle travels at a constant set speed defined by the driver (Figure 1.2). Modern radar technology is used to monitor the distance to the leading vehicle; control algorithms can then be applied to maintain the 'headway', or maintain the set speed.

There is a vast amount of published literature from the past twenty years concerning ACC. The majority of the literature is split between technical engineering papers, and subjective human factors research; some of the best work is that which covers both areas, although this is less available.

Current State of the Art

Before discussing recent research and possible future applications of longitudinal control systems, it is useful to investigate the current standing of the technology in the automotive industry. ACC systems have been available on high specification vehicles (BMW, Mercedes) for a few years now, and more recently have been offered on more mid range vehicles such as the Nissan Primera. Some manufacturers have published overviews of their respective systems, Prestl et al. (2000) detail the BMW 'Active Cruise Control' and although there is little information on the control algorithms, the paper does demonstrate a working marketable product that is designed for customer comfort. Richardson et al. (2000) looked at the Jaguar ACC. Again this is concerned mostly with the driver interface and system components, but this time performance characteristics were also included, showing good system response.

To obtain a full understanding of how these control systems work, it is necessary to investigate the hardware used in the systems, particularly the sensors and actuators. The sensor in a longitudinal control system is a key component of the system, it must be able to:

- Reliably detect preceding targets in the vehicle path. (Richardson et al. 2000)
- Give robust performance for the lifetime of the vehicle, regardless of inclement weather. (Russell et al. 1997)
- Track targets in the lanes ahead in order to anticipate vehicles cutting in front of the driver, and in order to distinguish between targets that pose a threat and those that do not. (Abou-Jaoude 2003)
- Decipher between lanes on curved roads with minimum bend radius down to 125m, depending on the performance class of the system. (ISO/FDIS 2002)

With these main criteria in mind, radar technology was decided upon as the most viable means of monitoring. One of the major advantages it has over other types of sensors, such as optical or infrared sensors, is the ability to perform equally well during the day, the night, and in most weather conditions (Abou-Jaoude 2003). Similar radar technology has been used in the truck and bus industry since the early 1980's to provide simple collision warnings. These systems worked in the microwave frequency range of 10-24 GHz, but were too large and expensive to introduce into standard production cars. To reduce the physical size of the radar sensors, the frequency of operation was increased to the millimetre wave range. Most current millimetre wave radar systems operate in the 76-77 GHz frequency range (Rohling et al. 2001, Wegner 1998).

The most comprehensive discussion of these automotive radars was given by Abou-Jaoude (2003), the development of the systems was discussed as well as the testing methods used. A proposed set of performance specifications of ACC radar sensors is also given in Table 1.1.

With the surrounding conditions monitored by the sensor, some control theory is required to calculate the desired output (this control will be discussed in the following sec-

Table 1.1: Typical performance specifications of ACC radar sensors (Abou-Jaoude 2003)

Transmit Frequency		76-77 GHz
Transmit Power		>10 dBm
Target Detection Distance	Range	2-150m
	Accuracy	< ± 1m or ± 5%
Relative Velocity	Range	± 250km
	Accuracy	< ± 1km/h
Angular Coverage	Azimuth	± 8°wide coverage with 3°minimum resolution
	Elevation	3°to 4°single beam
Antenna Gain		26 to 34 dBi
Antenna Sidelobe Level		> 20 dbc
Update Rate		> 10Hz

tions). The desired response of the vehicle will inevitably be to remain at the constant speed, slow down, or to increase speed to the initial set speed. Actuators are required to perform these operations. Increasing speed can be achieved only by increasing throttle. This works in a similar way to conventional cruise control systems, and can be linked in with the engine management system. To slow down, engine braking can be used where low deceleration levels are required (again throttle control can be used). Where larger levels of deceleration are required, braking control must be utilised. This is performed by an actuator behind the brake pedal usually in the form of an electronically controlled vacuum booster. These actuators must be able to perform effectively together, and must have an excellent response time.

Control Strategies

Many different control techniques have been employed to tackle ACC. While the methods of these controllers differ, the overall control objectives of the systems remain the same. These objectives can be split into two sections, primary and secondary. The primary objectives are key to the function of the controller; for ACC these are speed control and headway control (either time headway or distance headway). Without efficient control of these two variables, the system will not function. Secondary objectives are those which add to the functionality of the system, but are not core to the main aim of the system. For ACC these are driver comfort, predictability and vehicle stability. Other important issues concerning the performance of a control system include its robustness, and complexity. A robust system is unaffected by modelling approximations, such as neglecting fast dynamic phenomena, or inaccuracies in estimating model parameters. Complex control schemes such as sliding mode control may provide improved responses when compared to that of simple Proportional Integral Derivative (PID) controllers but they are sometimes unnecessary and can cause problems if integrated with other systems.

Lu et al. (2002) discussed the possibility of a sliding mode controller, which results in a globally stable system, that is robust to errors in the measurement of the lead vehicle's velocity. This robustness is achieved by a series of noise filters. The paper also demonstrates a good design methodology, which can easily be modified to allow a similar controller to be used in other automotive areas (lateral control, etc.). Simulation evidence exists to prove the functionality of the controller. The controller is not validated using either a driving simulator or experimental vehicle; and so problems may arise in the integration of the system with the vehicle and driver. Although the vehicle is subjected to high braking forces, no reference has been made to the effect that these forces have on the dynamic performance of the system.

Another more simple control method was proposed by Ioannou et al. (1993). This was based on two PID controllers and an adaptive controller. The controller was tested in simulations and on actual vehicles. While the stability of the systems was not tested as rigorously as by Lu et al. (2002), the percentage tracking error was still within acceptable limits. The simplicity of the PID controller made it a suitable testing tool, before complex controllers were introduced. The paper also made some estimation as to acceptable levels of longitudinal acceleration and jerk or 'driving comfort constraints'. In this instance the controller's response was filtered to ensure that the vehicle remained within acceleration limits. These acceleration limits become even more important when one considers that ACC systems are currently being marketed as comfort aids, and not safety devices.

Nissan have discussed the details of their ACC system in Iijima et al. (2000). Some human factor issues were considered, and it was decided that the system should provide a similar braking response to that of the driver. Simulator tests were undertaken to monitor braking behaviour, and then the controller was developed to match the braking response of 'experienced, well-mannered' drivers. This may seem to be an ideal solution although confusion could arise when used by inexperienced drivers, as they may expect the response to mirror their habits. The response was achieved using a combination of feed-forward and feedback control (Figure 1.3).

Feed-forward is a simple control method that responds only to the inputs of the system. Because open-loop or feed-forward control responds in a predefined way, it is rather inflexible and only works for a limited set of conditions. Feed-forward control does have the advantage of fast responses, as it only has to carry out the predefined scheme. Feed-forward strategies are based around inverse plant models. These models are low in order,

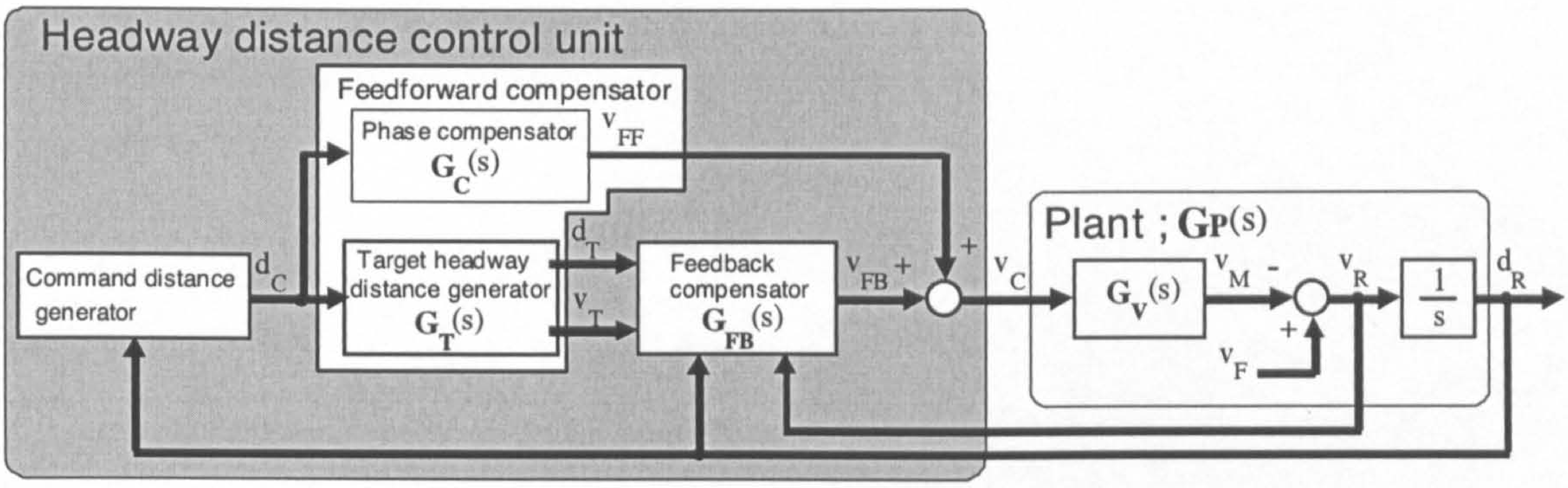


Figure 1.3: Block diagram of Nissan ACC system (Iijima et al. 2000)

complexity and often linear. As the inverse model becomes less representative of the actual vehicle, e.g. in non-linear handling, there is model mismatch and error between the desired response and actual response.

Closed-loop or feedback control on the other hand does not rely on predefined components to improve responses. Rather it 'feeds back' the real value of the property to be controlled, compares it to the desired value and adjusts the signal accordingly. It is therefore a lot more flexible, able to respond to a wider range of situations that do not have to be independently pre-considered during design, and can compensate for modelling inaccuracy. On the negative side, it introduces additional dynamics into the system and is therefore slower to respond than a feed-forward control.

The combination of these two control schemes can lead to very positive results, as errors can be overcome quickly by the feed-forward control and accurately by the feedback control. This is the case with the Nissan ACC system, where the frequency characteristics of longitudinal accelerations of the system are matched directly to that of an experienced driver.

An ACC system which is designed to automatically adapt its acceleration characteristics to different driving situations is proposed by Kesting et al. (2007). While the system shows promise, the researchers only consider the impact of the system on the congestion and traffic flow and fail to notice the possible gains that the system may provide in terms of driver comfort.

Other recent literature has focussed on the impact of these control systems on traffic flow and stability (Zhou and Peng 2005), complex assessment criteria(Gietelink et al. 2006), and Stop and Go technology (Maurel et al. 1999, Martinez and Canudas-de-Wit 2007), which is capable of control over the full range of vehicle velocity. While these systems provide an interesting extension to the existing ACC, for the purpose of this work we are more concerned with the high speed behaviour of the systems.

Performance Requirements of ACC

The international standard governing ACC systems (ISO/FDIS 2002), gives values for acceptable levels of acceleration, deceleration and negative jerk (rate of change of acceleration) as follows:

- The average automatic deceleration of ACC systems shall not exceed 3.0m/s^2 (average over 2s).
- The average rate of change of automatic deceleration (negative jerk) shall not exceed 2.5m/s^3(average over 1s).

While these values may provide adequate driver comfort levels longitudinally, they do not take into account the full dynamic performance of the vehicle. No reference is made to how the vehicle should pitch on a straight road, or pitch and roll on a curved road. The negative jerk value is interesting as it relates to the comfort experienced by the driver, but it is inherently instantaneous in nature. Averaging this data over time reduces the relevance of the result. Peak jerk levels would better reflect the performance of the system; although they may be difficult to measure accurately. Other system characteristics such as velocity operating range and minimum headway have been well researched and are provided in this standard.

If we also consider the manufacturers stated performance of their individual systems, it can be seen that there is much variance between what some believe is required, and what is achievable. Delphi's ACC system, currently available on some Cadillac and Jaguar cars, can, 'operate under a wide range of environmental conditions (dirt, ice, day, night, rain, or fog)' (Delphi 2003). Although this statement probably refers to the radar technology, drivers may also assume that the control part of the system will also perform in the differing levels of grip, caused by these 'environmental conditions'. No published literature is available to demonstrate the vehicle and system performance in these conditions.

Visteon's ACC system is marketed with the following features:

- Maintains safe distance between vehicles.
- Performs well in poor visibility conditions.
- Performs well during road turns and elevation. (Visteon 2004)

Again no published research is available to validate these claims. Other European manufacturers including Audi give subtle warnings about the limitations of their ACC systems:

> "Adaptive cruise control does not react to stationary objects or approaching vehicles. It should not be used on winding roads or in adverse weather conditions such as fog, ice or heavy rain." (Audi 2008)

The responsibility of use of the system is left entirely with the driver. This brings many more safety issues into the use of ACC: how does the driver know when to disable the system (At the first sight of rain? At the start of a shallow curve?). The usefulness of an ACC system could be greatly reduced. Constant monitoring and disabling/enabling of the system would introduce more driver operations, when the main point of an ACC system is to reduce the driver's workload. The subtleness of these manufacturer warnings could also lead to the driver ignoring them completely and using the system regardless of environmental conditions. The safety impact here is obvious - over-reliance on the system may cause severe accidents, due to a loss of control around bends or an under-estimation of the required stopping distance.

Bareket et al. (2003) proposed a methodology to assess the behaviour of an ACC system. This approach could be used to standardise ACC performance criteria. Eight tests were described to thoroughly monitor the actions of the system. These include constant speed following, deceleration of lead vehicle, 'wobbly' (low-amplitude, low frequency speed oscillations of the lead vehicle), and 'cut in' of a lead vehicle. Three generic controllers were then put through these tests and their performances were monitored. While the testing methodology ensured good vehicle tracking performance, it failed to look at the dynamics of the vehicle and therefore neglected the passenger comfort aspects of the system. Few other unified testing regimes are published.

Human Factors Research

In all forms of engineering research, the human side of the problem is beginning to be considered along with the technical side. This is the case with regards to longitudinal control. It would be pointless to produce a control algorithm and radar system without considering the driver and their impact on the problem. We are fortunate that plenty of psychological research concerning driver behaviour and attitudes has already been completed. Some of this work is now being applied to the engineering problem at hand. Some of the best research in this area combines both engineering theory and human factors psychology.

Some of the first engineering research to consider both of these areas was carried out by Fancher et al. (1998). This National Highway Traffic Safety Administration (NHTSA) Report gives details of an in-depth field operational test of ACC vehicles; both vehicle and driver performance were measured. Overall the drivers found the system 'remarkably attractive', although some felt that the acceleration and deceleration levels were too restrictive. The report also talked about the 'shared-control nature of ACC' and how a 'fine match to the perceptual and cognitive behaviour of drivers' was required to make a system successful.

Fancher et al. (2000) state that, 'to be human centred, driver assistance systems need to match the physical and mental capabilities of drivers'. To achieve this, Fancher et al. (2000) take into account the perceptual vision capabilities of the human when judging the distance of moving objects. A control scheme is then formed that takes this into account. The result was an adequate control system, although more work is required with regard to the driver's braking behaviour.

Weinberger et al. (2000) show the results of a long-term field operational test of the Bosch ACC implemented on the BMW 7 series car. There was no measure of driver or vehicle performance. Instead the 15 test subjects were questioned on their thoughts about the system throughout the four week trial period. The main interest of the study was the length of time required to learn how to use the ACC system, and while this value was claimed to be approximately 2 weeks, there were few other results from the research. This is disappointing as more could be found out about the driver's perception of system performance, with similar simple questionnaires and interviews.

Hoedemaeker (2000) conducted purely psychological work looking at the acceptance of ACC systems using driving simulator testing. Again the results were promising; approval came from both low and high speed drivers. The paper also gives some recommendations as to the possible limits of ACC systems, pointing out that adequate performance on rural roads is, at the moment unachievable. Drivers also seemed to accept very short headways (0.6 - 1sec) leading to increased motorway capacity, and drivers also preferred ACC systems with variable headway settings.

Other research which has considered the impact of the systems on the driver has also produced interesting results and issues which should be taken into account in system design. ACC is likely to be of most use to the driver in high-demand situations as a potential means of alleviating driver stress and workload (Stanton and Young 2005). Future ACC systems may require a new kind of display to help drivers identify cues to which they should attend (Stanton and Young 2005). Both the performance of ACC in terms of tracking error, and the compatibility of the system with the driver's expectation, should be taken into account in the design and parameter optimisation. That is, including comfort and safety terms in the control law may help to make ACC behaviour more acceptable (Zheng and McDonald 2005). ACC systems induce behavioural adaptation in drivers, in terms of changes in workload, hazard detection, and driving performance. In a simple simulator based study drivers reacted more slowly to a safety-relevant brake light detection task, and responded within a safe time margin 33% less often, when using ACC (Rudin-Brown and Parker 2004).

Comfort impacts on the driver have also been taken into account, but usually form the secondary concern of certain publications. Martinez and Canudas-de-Wit (2007) claimed that studies on comfort criteria of ACC systems are scarce. While Fancher et al. (2000) touched on the possibility of using human perception theory in order to obtain an acceptable inter-distance reference, no desired acceleration limits were given. Persson et al. (1999) presented an ACC system for low speed motion, where the desired acceleration was obtained from a model of real driver's behaviour data. Griffin (2007) considered the impact of vehicle vibration as a whole, and suggested methods for assessing the comfort levels of the driver/occupants, given the magnitude and duration of accelerations.

Collision Warning Systems

A forward looking radar/sensor required for ACC allows the vehicle to determine the existence of obstacles within its path. As the sensor also determines the rate of change of this distance, potential collisions can be predicted. A driver assistance system that provides only a warning, such as an audio tone, is referred to as a Forward Collision Warning System (FCW). This is purely a safety aid to provide feedback to the driver. The driver can then respond by decelerating, avoiding the collision, or taking no action. These passive systems differ from active system such as ACC and Collision Avoidance Systems (CAS) as vehicle control must still be performed by the driver.

With the improvements in radar technology and other 'vision' techniques, systems such as FCW and ACC are becoming more commonplace especially in smaller markets, such as public transport and heavy goods vehicles. However the actual technology behind the object detection of the system is beyond the scope of this project. It is assumed that there is radar or similar, capable of deciphering obstacles and providing the control system with a distance to the object.

As there is no control involved with FCW, only feedback to the driver, the interesting research concerns the way in which the driver is alerted. For instance, when is the best time to inform the driver? A system that informs the driver of any obstacle in a large field of view is going to signal very often. This may annoy the driver and cause them to stop using the system. On the other hand a system that only signals immediate danger may not provide enough warning to the driver. This problem is intensified when we consider the wide range of driver styles among those who may utilise the system. Some drivers prefer to accelerate and decelerate slowly and smoothly, whereas others prefer to brake late and sharp. Some human factors work has been undertaken to discover how drivers react with FCW systems.

Cheng et al. (2002) looked at types of auditory signal that can be used to alert the driver, as well as the different braking response of drivers. Driving simulator tests were taken by 36 subjects (experienced drivers aged 21-34). The test involved closing on a preceding vehicle, sudden cut-in of a vehicle from an adjacent lane, and lane departure of own vehicle. Figure 1.4 shows the braking responses of all subjects. Results to the right of the collision line mean that the collision was avoided either by a high deceleration (red - sharp braking), small response time (blue - early braking), or a combination of the two. The first thing that is noticeable from the graph is the wide range of responses, average decelerations varied from 3.5-6 m/s^2. This highlights the problem of driver styles; drivers who fell in the red circle (late, sharp braking) would need a less sensitive warning system to drivers in the blue circle (early, smooth braking).

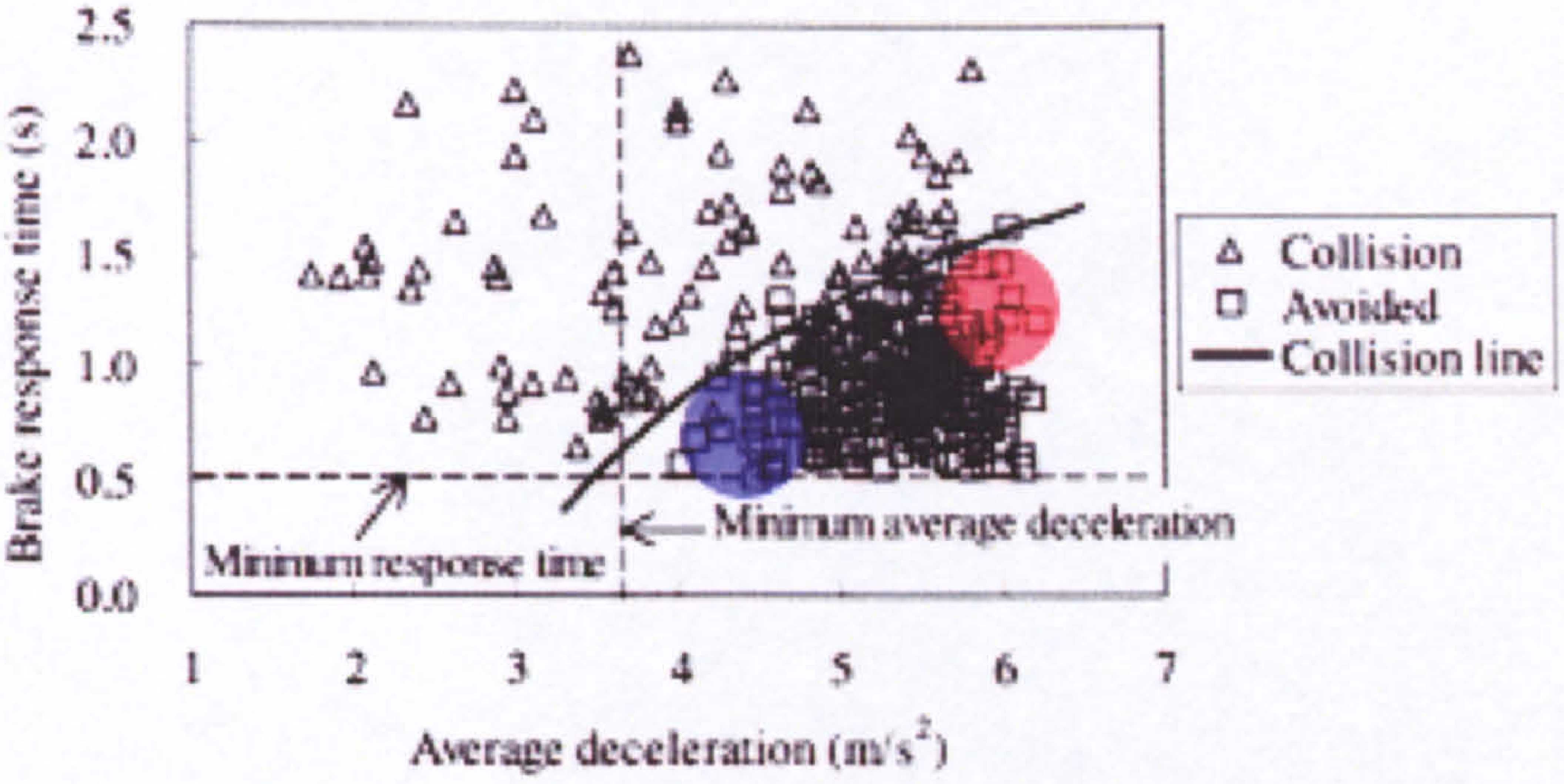


Figure 1.4: Distribution of average brake response times (Cheng et al. 2002)

1.4.2 Lateral Control

The TNO Report entitled ‘Development Scenarios For Advanced Driver Assistance Systems’ (Zwaneweld et al. 1999) presents suggestions for the way in which to develop ADAS. This ‘road map’ can be broken down into two distinct control areas: firstly longitudinal control, and secondly lateral control.

Lateral control of vehicles is an essential prerequisite for autonomous driving. Lateral control requires a detailed view of the road trajectory; this can come from look ahead or look down systems, depending on the point of measurement of lateral displacement. Look ahead systems replicate human driving by measuring lateral displacement ahead of the vehicle (Guldner et al. 1997); whereas look down systems use only the road information immediately available. The steering response of the vehicle can then be controlled to keep the vehicle on track. Proposed future developments also include the ability to change lanes and avoid collisions.

Current State of the Art

The TNO report suggests that lateral control is developed as a secondary idea after longitudinal control. While it is the case that there has been more research into longitudinal systems, there are some applications of lateral systems that are available today. The most common of these systems is the Lane Departure Warning System. These systems monitor the vehicle's position in the lane, and can inform the driver if they start to veer away, usually by means of a visual or audible alert. They have been employed in heavy goods vehicles, and public transport; and more recently in passenger vehicles (Citroën 2008). These systems do not incorporate any control of the vehicle. More recently active systems which assist the driver have been developed (Ishida and Gayko 2004, Polychronopoulos et al. 2005), which provide additional steering torque to correct the vehicle position, should the vehicle approach the lane boundary. Honda and Nissan have released such systems in the the commercial market as options on high end vehicles. The control logic behind these, and other academic based systems is reviewed in detail in the following section. These systems have only recently become possible through developments in hardware technology.

Similarly to longitudinal systems, the hardware in a lateral controller can be split up into two main sections: sensors and actuators. Much research is being undertaken into the best method of sensing the lane position of the vehicle. Many systems use a video based look ahead system that is able to decipher lane markings (Figure 1.5).

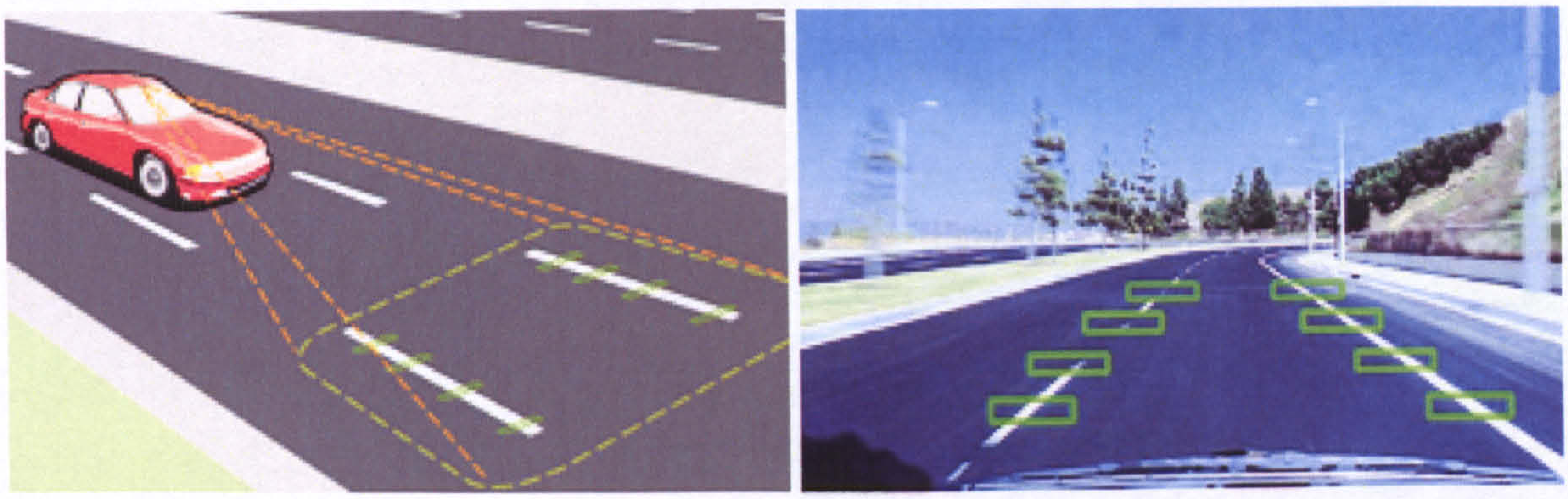


Figure 1.5: Video based look ahead sensor (Iteris Inc. AutoVue^{TM}Lane Departure Warning (LDW) system)

According to Bosch (2004) these vision based systems have a range of up to 80m. Other ways of sensing lateral position include magnetic markers (Chan et al. 2000), Global Positioning Systems (GPS) (Hernandez and Kuo 2004), ultrasonic, or microwave radar (Abou-Jaoude 2003). Citroën (2008) use an infrared system mounted underneath the vehicle, which monitors the lateral proximity to lane markings. While this is ideal for a lane departure warning system, more detailed road information is required to interpret the centreline of the lane.

Actuators for lateral control are used to operate the steering system of the vehicle: they must provide a smooth stable response to make sure the vehicle gets back on track safely and quickly. Sebastian et al. (1997) undertook the design and manufacture of a steering actuator for the California PATH Institute's Automated Highway System (AHS) The design requirements of the actuator are shown below (Table 1.2), although it is not clear how these are developed. While there is only little steering travel (5°) the accuracy level is very high (0.05°). This paper proposed a brushless motor to actuate the steering response. Others including Prohaska and Devlin (1998), proposed hydraulic actuators.

Table 1.2: AHS steering actuator requirements (Sebastian et al. 1997)

1	**Range**	at least ± 5°road wheel is required	
2	**Accuracy**	0.05°at road wheel or 2% road wheel angle which ever is greater	
3	**System Response (Time Domain)**		
		1°Amplitude	90% rise time = 0.1sec
		Max Overshoot	5%
		2% s.s Settling Time	0.35 sec
4	**System Response (Frequency Domain)**		
		45°phase lag at 5Hz for 0.5°amplitude sinusoid	
5	**Slew Rate**	at least 25°/sec	

Lane Keeping

There has been a large amount of engineering research into methods of lane keeping. Much of the work discussed here is concerned with the control algorithm that the vehicle will use. There has also been a considerable amount of research into the methods of estimating the path of the lane, given the data acquired by the sensing system (Bertozzi et al. 2000, Gern et al. 2000, Redmill et al. 2001). This estimation technique is not covered in this research, it is assumed that a recognition system is available to be used in conjunction with any control system.

Given the path, it is the job of the lateral control system to A) make sure the vehicle stays within a set distance of that path, and B) to ensure the vehicle has good handling and ride properties. The control algorithms investigated for these lateral controllers were, on the whole, not as complex as for longitudinal control, as it was assumed that the vehicle would remain in the linear range of handling. Non linear handling and stability of the vehicle have in the past been covered by Electronic Stability Controllers (ESC/ESP), as seen in Bosch (2004). It is important to consider the effects of the lateral control system on the stability of the vehicle. For general motorway lane keeping the vehicle should remain stable, but with adverse weather conditions and more severe manoeuvres stability may be compromised.

Most of the commercially available systems have not published details on their control logic. Although a test vehicle used in the development of the Honda Lane Keeping Assistance System (LKAS) is explained in Takahashi and Asanuma (2000). The lane keeping algorithm is proposed to ensure stability through steady state cornering, and maintains the target path by reducing lateral position and heading errors to zero (Figure 1.6 and Equations 1.1 - 1.3). The control output *Ta* is a steering torque which is used as an assistance to the torque generated by the driver.

$$
\begin{aligned}
Tf &= Cf \cdot \frac{V^2}{R} && (1.1)\\
Tb &= Yd \cdot Ka + \theta h \cdot Kb + \frac{d}{dt} \cdot \theta h \cdot Kc && (1.2)\\
Ta &= (Tf + Tb) \cdot Kd && (1.3)
\end{aligned}
$$

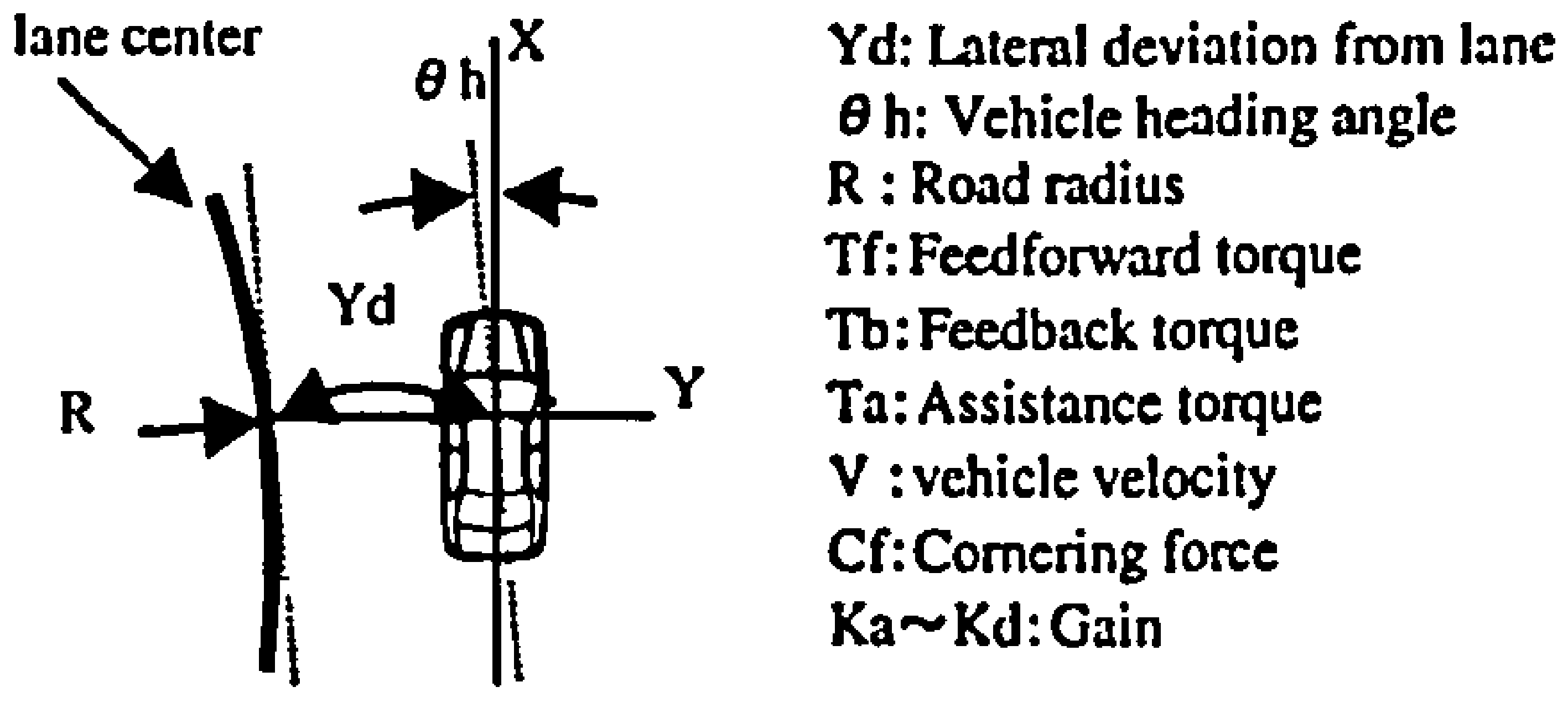


Figure 1.6: Honda lane keeping assistance system - geometric model (Takahashi and Asanuma 2000)

While it is useful to see the control logic used in a commercial system, especially the need for a damping term in the control of heading error, the actual gains used were not given. There were some brief results shown, which suggest that the steering effort required by the driver was reduced, but little detail was given as to the impact on the driver, or the test conditions used.

Many academic publications have investigated different methods of lateral control: PID algorithms are commonplace (Chen and Tan 1998, Hong et al. 2001), although other more complex methods such as sliding mode control (Guldner et al. 1994), and LQ theory (Leelavansuk et al. 2002) are becoming more common. All types of controller can be shown to provide a good lane tracking response provided they are tuned correctly.

Guldner et al. (1994) proposed a robust sliding mode control scheme to account for system uncertainties, and a wide range of operating conditions. Good lane tracking was achieved without any preview of the road curvature. Yaw rate feedback was also employed to assure good handling properties. The paper showed good simulation results, although as with much of the research, there was little about the dynamic handling of the vehicle which becomes important at high vehicle speeds, as the limits of linear handling are reached.

Hong et al. (2001) implemented a PI lateral control scheme, on a single track model (2dof), and a full multi-body vehicle model incorporating all suspension members (79dof). While there was nothing new to be seen from the controller, the research did show that complex high dof systems with lateral control can be simulated with positive results. Given that a full vehicle model was constructed, it was disappointing that nothing was said about the vehicle's dynamic performance. One of the suggestions for future work was 'integrating the lateral control and the longitudinal control to satisfy the limit of lateral acceleration against small curvature'. The integration of longitudinal and lateral controllers will be discussed in a later section of this chapter.

Another simple system that has been referenced throughout the literature was proposed by Ackermann (1993). The control strategy involved some extensions to a basic vehicle handling model, to include the lateral position and heading of a vehicle relative to a given path. While no simulated or field test results were included in this book, the system forms the basis of the control structure in many other publications (including Chen and Tan (1998), Guvenc and Guvenc (2002), Hernandez and Kuo (2003)); thanks to a simple approach to fully controlled lateral motion of the vehicle, which can be simply adapted or extended to give improved performance.

There are many issues concerning the driver involvement with lateral control systems; problems may arise when control is taken away from the driver. As the controller becomes more and more sophisticated, more and more control priority will be passed from driver to controller, but until autonomous driving is achieved some driver input will be necessary. Leelavansuk et al. (2002) looked at this problem in more detail. A cooperative controller was developed, and then a weighting coefficient was applied to vary the assistance level of the system. Computer simulation and driving simulator experiments showed good performance in lane keeping tests, under side winds and cornering. This performance was increased with a higher level of assistance, while driver workload was also reduced. At the highest assistance level, driver workload fluctuated because of interference between the driver and assistance system. It was therefore proposed that 'any new assistance system should be tested not only by computer simulation but also by driving simulator or experimental vehicle to confirm effectiveness'. The lateral control behaviour of drivers is considered in more detail in the following section.

Many other control strategies have been analysed. Kosecka et al. (1998) look at three possible alternatives: lead lag, full-state linear and input-output linearising. Of these the lead lag performs best, providing excellent lane tracking over a wide range of longitudinal velocities. A single track model was used in simulations and there was no driving simulator testing. Although little was said about the dynamic problems, an acceptable frequency range was suggested: 'for a comfortable ride no frequency above 0.1-0.5 Hz should be amplified in the path to lateral acceleration.' The human steering response was not considered, and the lack of driving simulation meant that it was difficult to see how these systems interacted with the driver.

Commercially available systems tend to be marketed as lane keeping 'assistance' systems, as they provide additional steering torque to aid the driver. Manufacturers insist that the driver is still in full control of the vehicle at all times. In fact the Honda system will disable itself if the driver removes their hands from the wheel for over 20s. Much of the research has proved that full lateral control of the vehicle is attainable without driver input, but for commercial and legal reasons, these types of system are some way from market.

Driver's Lateral Control Behaviour

In order for any lateral control system to be successful, it must be accepted by the driver. One way to improve this acceptance, is by replicating the lateral control behaviour of the driver, ensuring that they don't feel the system is as far removed from manual driving as possible. With this in mind, it was necessary to consider some of the driving modelling research that has been carried out, to assess the suitability of the models for use as part of a lateral control system. Due to different kinds of demands from driver model for a range of applications, a variety of driver models are available (Plöchl and Edelmann 2007). To limit this field we shall concentrate on advances in preview tracking lateral control. Macadam (2003) provides an excellent review of techniques used in the field. One of the limitations of the human driver that is discussed is the human time delay which can vary from 40ms - 400ms, depending on the type of stimulus. It was noted that drivers can reduce the effects of this delay by looking ahead and previewing upcoming features of the road (Reid and Drewell 1972). In a lateral control system this human delay time will be removed from the system, only delays due to the sensors and control logic will by present, this should improve response of the system in events where preview is not possible, such as side winds, etc.

Throughout driver modelling, one of the most changeable parameters is the preview distance used in the model. Some models used a preview time, so that the preview distance varies as the speed of the vehicle was changed (MacAdam 1981). Others used a fixed preview distance with a number of preview points along the preview vector (Sharp et al. 2000). This had the benefit of reducing the chance of a lateral control system failing due to poor preview data. Other models suggested that drivers made control decisions based on their own internal model of the vehicle (Ungoren and Peng 2005). Some models also included longitudinal control, as another function and are used in commercial vehicle modelling software applications.

Lane Changing

Another element of lateral control is lane changing. Using the same principles as lane keeping, the vehicle changes its path into a neighbouring lane. This can be used to overtake, exit junctions, or avoid possible collisions. Many challenges face the control engineer especially when linking the control system to the intentions of the driver. Other issues include the abruptness and aggressiveness of lane departure.

> "Lane changing is not simply a control problem, however; it involves both monitoring to maintain situation awareness and higher-level decision making to determine when to execute." (Salvucci and Liu 2002)

One of the most complex issues concerned with lane changing is monitoring the intentions of the driver. How does the controller decide when the driver wants to change lanes? At first, use of the indicators may seem like the most obvious choice, but research shows that drivers only use the indicators between 80%-90% of the time. When avoiding collisions the indicators are rarely applied, so more subtle means of observing these intentions are required. Yuhara and Tajima (2000) discussed the possibility of an Auto-Regressive Moving Average (ARMA) model to monitor small changes in steering wheel angle, and predict whether the driver was in lane following, or lane changing mode. This resulted in high prediction capability, and was shown to work with an advanced steering system at motorway speeds of up to 120km/h, in lane following and changing modes, on both straight and curved roads. Driving simulator tests were used to obtain driver data, although the sample size was too small (four subjects carried out five tests) to produce any realistic conclusions. More work is required to validate these findings and prove that the systems will work for a range of driving styles

Liu and Pentland (1997) proposed a scheme that used Hidden Markov Dynamic Models (HMDM). Here the control actions of the driver were used to infer what action they would execute. Control actions such as posture and steering wheel position, were modelled as a sequence of mental states, each with a characteristic pattern of driver control behaviour. The initial results of the simulator tests were unsatisfactory with correction recognition figures between 50% - 70%. This poor performance may have been due to inadequate monitoring of driver actions to use with the HMDM. Only a small sample of subjects (9) was used, and drivers were instructed when to manoeuvre. Future research was suggested allowing the driver to maintain a more natural style, with the hope of providing more accurate measures of their intentions.

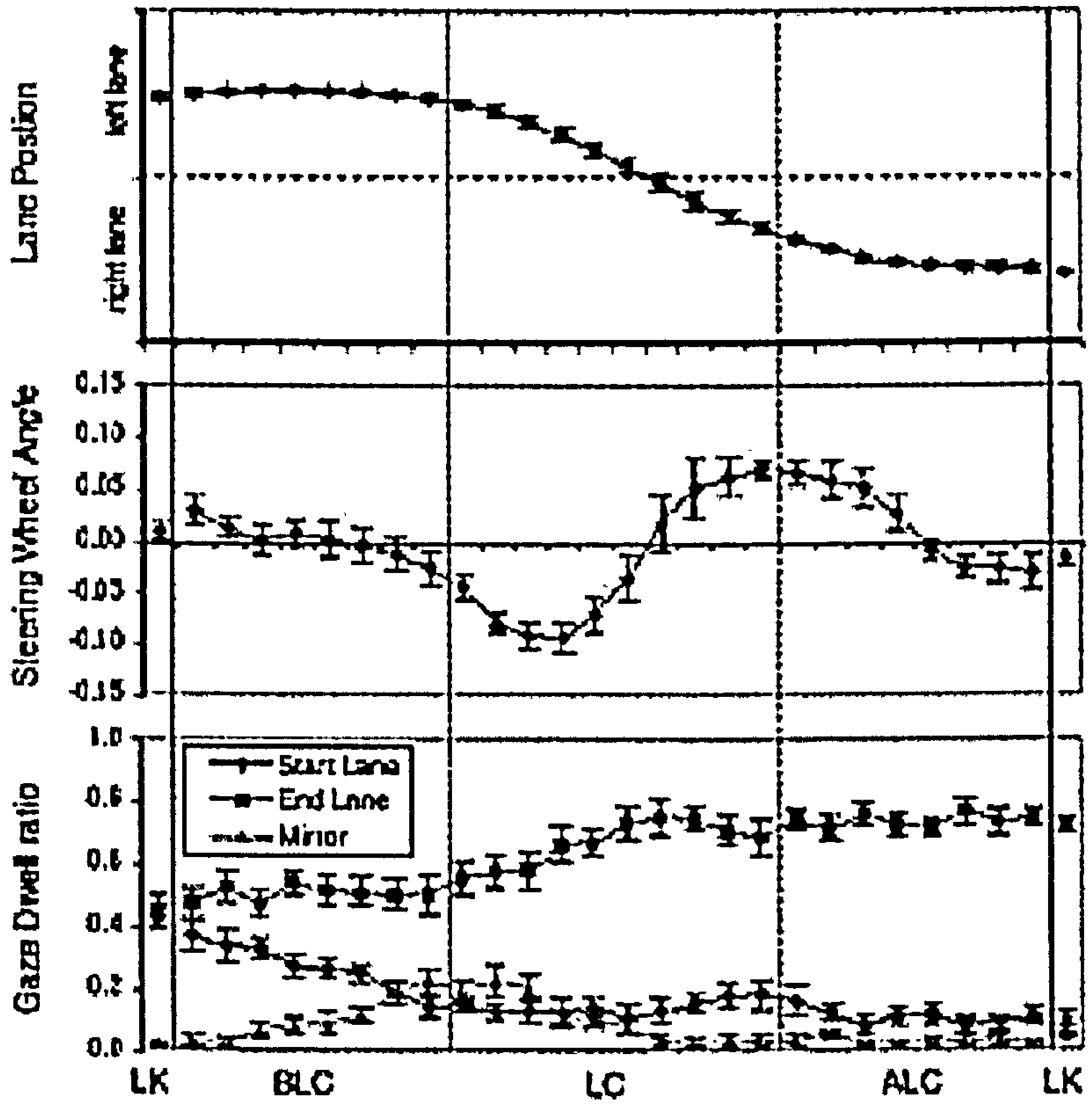


Figure 1.7: Eye movement during lane change manoeuvre. (Salvucci and Liu 2002)

Salvucci and Liu (2002) considered the eye movement of the driver as a measure of intention. Figure 1.7 shows the results of driving simulator tests, where the eye movement of the driver was monitored. The 'Gaze Dwell Ratio' showed the focus of the driver.

Before changing lane the driver shifted the majority of their attention into the destination lane, and immediately before the manoeuvre the driver looked in their mirror. This provided a good measure of driver intention, although again the sample size was small (11 subjects); more testing is required to validate the findings here. The eye movement data was not used to construct a lane change controller, but this was proposed for future research. The main problem with the research was the lack of real time analysis; all measurements were recorded and then processed after the simulation was over, which made real-time inputs to a controller impossible.

If it had been decided that the driver wished to change lanes, the lateral control system must find a safe and comfortable path upon which to travel. Kanaris et al. (2001) proposed methods for safe lane changing, and explored the impact of emergency braking at different points through the manoeuvre. As a result of this work a Minimum Safety Space for Lane Changing (MSSLC) was calculated. This was found to depend mainly on the relative speed of the two lanes of traffic, and the lane changing strategy of the controller (aggressiveness of manoeuvre). Theoretical simulations were carried out, although none of the work was backed up with driving simulator testing.

The control principles associated with lane changing are very similar to those of lane keeping. Instead of following the lane path, the vehicle must follow a prescribed trajectory into another lane. Given a motorway lane width of 3m, it can be seen that lane changing is a much sharper manoeuvre than lane keeping. With this 'sharpness' of turn the vehicle dynamics become even more important, especially while passenger comfort is still an issue. If the system is being used for collision avoidance, comfort is not a major concern, but here the vehicle must be able to change lanes quickly without becoming unstable.

Furukawa et al. (2002) investigated a system that assumes the driver instigates an evasive lane change; the aim of the controller was to provide the vehicle with stability throughout the manoeuvre. Yaw moment control was used as in many of the lane keeping systems. Computer simulation results showed that vehicle stability was much improved over manual driving, and also the time it took for the following vehicle to avoid the obstacle was reduced.

A fully operative autonomous vehicle was demonstrated in Hatipoglu et al. (2003), yaw rate control and smooth switching were employed to ensure a steady, accurate response. The vehicle performed well in lane change manoeuvres on straight roads, and although not tested, the system should be capable of similar results on curved roads. There was no mention of how the vehicle performed dynamically in terms of pitch and roll rates.

1.4.3 Combined Longitudinal and Lateral

Previously lateral and longitudinal control systems have been considered individually; here the integration of both systems is discussed. Where both systems exist and perform correctly, vehicle following, lane keeping, and lane changing manoeuvres are possible. This can provide a safer driving experience with vastly reduced workload for the driver, but with this added complexity comes more engineering and human factor issues:

- Are driver comfort levels still attained?
- How are the controllers supervised (overall control)?
- Is the driver 'in the loop'? If so how are they kept alert?
- How does the vehicle perform dynamically?

Some of these problems have been looked at in previous research, but many areas are only discussed briefly, if at all.

Rajamani et al. (2000) considered the two controllers separately, and then proposed a supervisor system that switched between the controllers when necessary. Simulator results were backed up with physical vehicle testing, with up to eight vehicles travelling in a platoon. The system performed well in all manoeuvres including lane changing and entry-exit of the platoon. No driver intention modelling was present; instead the system followed a pre-specified scheme of manoeuvres. The tests were performed at speeds of 60mph, but no information was given as to the dynamic performance of the vehicles. No collision avoidance manoeuvres were undertaken.

Beji and Bestaoui (2001) looked purely at the integration of the two controllers. Although the authors talked about the need for extended dynamic modelling given the high speeds of operation, they surprisingly chose to neglect both pitch and roll. Computer simulations of three manoeuvres were conducted: straight road lane following, curved road lane following, and a lane change. The paper gave brief results, but does not seem to utilise the longitudinal element of the control apart from to reduce speed before lane change. The sliding mode control scheme performed adequately although more testing (computer and driver simulation) is required.

One of the most interesting areas of combined control is the interaction between the two (or more) systems, and how the operation of one system takes priority over others. Michon (1993) discussed this in more detail and proposed a high level architecture to assign operations to specific controllers (Figure 1.8).

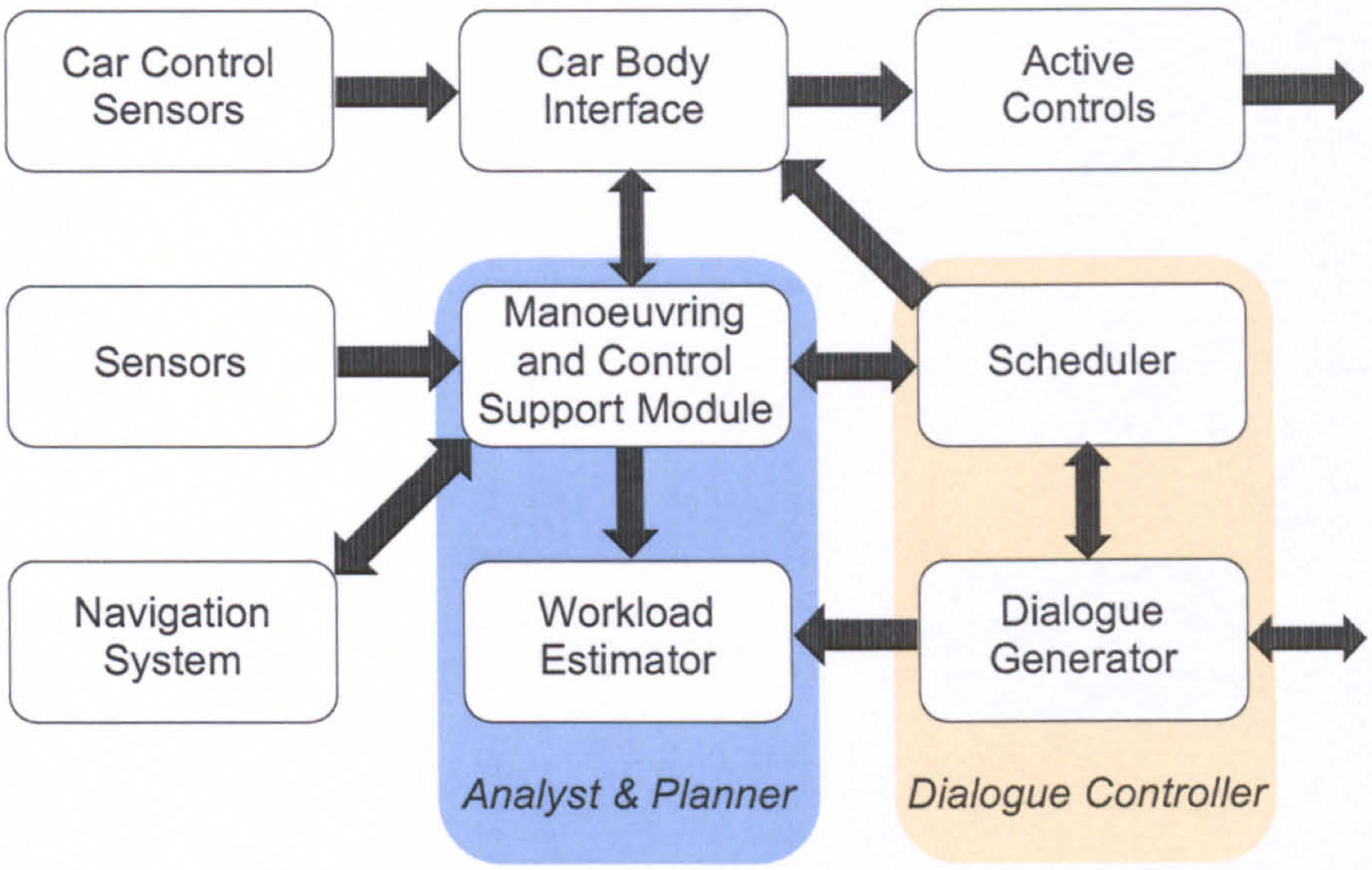


Figure 1.8: Generic controller architecture system. (Michon 1993)

When this research was performed, many of the technological advances required to implement combined longitudinal and lateral control were not available, but the principles were still valid. In this scheme individual modular controllers were given a 'unique and limited intelligence'. This architecture then provided an overall intelligence to allow all features of the vehicle to function correctly.

1.4.4 Driving Simulators

Driving simulation is used throughout the automotive industry to aid in the devolvement of new technologies and further the understanding of driver behaviour. Simulators can generally be split up by their ability to generate motion. As shown in Figure 1.9, there are static simulators (Leeds Advanced Driving Simulator (LADS)), motion bases (Renault SCANeR II), longitudinal tracks (DaimlerChrysler) and recently lateral and longitudinal tracks (National Advanced Driving Simulator (NADS), University of Leeds Driving Simulator (UoLDS)). A considerable increase in computing power has meant that these systems can function efficiently, with highly realistic graphics and sound. New driver related technologies can now be tested rigorously in real life scenarios without the cost of implementation and testing on road vehicles.

An increased level of validity can be achieved with these new simulators. Fixed base simulators rely solely on visual display and force feedback steering, whereas motion bases provide the driver with perceivable rolling and pitching behaviour, and can also replicate longitudinal and lateral accelerations. Newton and Best (2006) claimed that motion was

(a) LADS - Fixed Base (b) Renault - Hexapod

(c) MARS - Lateral Track (d) NADS - 9dof System

Figure 1.9: Methods of motion generation in driving simulators

second only to visual cues in the human perception of the simulator. Longitudinal and lateral track simulators take these motions even further - The NADS is regarded as one of the most advanced high fidelity driving simulators in the world (Heydinger et al. 2002). A 330°yaw ring combined with a 6dof hexapod provides realistic rolling pitch and yaw behaviour, but, as well as replicating longitudinal and lateral accelerations through rotation of the hexapod, a 20m x 20m X-Y motion system is integrated to provide physical lateral motion. This gives an increased degree of realism and allows emergency and/or high speed manoeuvres to be performed.

Some ACC systems have been investigated using driving simulators to test not only the functionality of the system, but more importantly the way the driver interacts with the system. Reymond et al. (2000) discussed the implementation of an ACC system on the Renault SCANeR II Motion base simulator; professional expert drivers were employed to validate the realism and vehicle behaviour. The results were promising with the test drivers confirming good 'driving sensations'. Simple tuning of the ACC system was also possible without presenting risks to the test drivers of prototype vehicles.

Nagiri et al. (2004) discussed the implementation of a personally adaptive driving support system on a single track driving simulator. This simulator provided accelerations up to 0.5g, but the travel for lateral motion was only 0.35m. Longitudinal travel was 4m allowing sustained acceleration and braking to be simulated. This worked well for straight line research, but would be less successful for high speed cornering, which was not covered.

1.4.5 Critical Review of Literature

After reviewing the literature regarding longitudinal control, it may seem that all areas of the topic have been covered. But looking more closely, it is clear that some areas concerning the implementation of controllers on advanced vehicles and the interaction with the driver have not been fully investigated.

Many of the technical papers relating to ACC considered the use of complex control schemes to perform a task that had already been controlled successfully using much simpler systems. The reason for these complex controllers was not always visible in the research; maybe the systems were developed to be robust to changeable conditions and driver adaptability.

Although ACC systems have been implemented on production vehicles, only a small amount of published literature concerned the acceptable levels of driver comfort, especially when cornering at high speeds. Neither physical testing nor computer simulation of these issues have been reported in the literature. Much of the longitudinal research focused on the controller and the vehicle, in many cases a more driver centred view should be taken, not only with regards to comfort levels, but also the way the controller interacts with the driver.

While ACC systems are regarded as a comfort device (to reduce driver workload), there are also many safety issues raised by their implementation and everyday use. The main factor is the systems' applicability in changing environmental conditions. Manufacturers have differing views on this; some believe they can be used in a wide range of conditions (and frictional characteristics) including ice, dirt, rain, or fog, while others provide drivers with warnings of when not to use the system, reducing the applicability of the system. No published literature considered the performance of the controller and vehicle in this wide range of conditions, in either simulation or physical testing.

The human factors issues also have a considerable effect on FCW systems. It has been shown that drivers respond to braking situations in markedly different ways. This variability was evident not only between drivers, but also with the same driver in different situations. For this reason, it is very difficult to effectively classify different driving styles. The value of the FCW system will greatly depend on these driving styles (early/late braking) and the ability to work alongside the driver; a driver who brakes late may become annoyed with a system that constantly alerts them and a driver who brakes early may not react in time to a late alert. This could lead to the driver disabling the system or even a serious accident.

Lateral warning and control systems are at an earlier stage of development than that of longitudinal. Although many simulations and some physical tests have been carried out, there are many areas in which improvements need to be made. Again many of these problems were concerned with the way the system would perform in conjunction with the driver and other sophisticated control systems readily available on today's cars.

Control research was focused on ensuring that the vehicle follows a given path in both lane keeping and lane changing manoeuvres; only the yaw rate and lateral acceleration of the vehicle were taken into account. While these are important to a successful controller, other factors have so far been neglected. The full dynamic performance of the vehicle must be monitored to ensure that instabilities in the handling are not created. This is especially important at high speeds when undertaking sharp manoeuvres (small radius of curve, or collision avoiding lane change).

One of the main concerns in human factors research is driver intentions during lane changes and other driver-dependent manoeuvres. In a basic road vehicle with no assistance, the vehicle relies solely on driver input, and with a fully automated vehicle the manoeuvre will be managed completely by the controller. In-between these two extremes lateral assistance systems will need to be gradually introduced on the market; this is where problems arise: who has control - driver or assistance system? Different techniques have been developed to monitor driver behaviour in an attempt to predict the intention of the driver, so that the controller can be employed without a specific driver input (such as indicator use). Approaches including driver's eye movement, steering wheel position, and vehicle position have been developed; but none of these techniques have provided a reliable scheme that could be used for a range of drivers. They relied on post processing techniques, and were not currently suitable for real-time use on vehicles.

There is very little research into the combined use of longitudinal and lateral control in a single vehicle context. Some of the work on automated highway systems considered this idea and it was hoped that this work can be adapted to produce a more viable ADAS. Road tests have shown that the systems can work in conjunction with each other, although these tests consider only basic road manoeuvres and not any form of collision avoidance. 'Supervisors' have been proposed to dispel conflicts between systems although this work is purely theoretical and is yet to be fully tested.

Driving simulators provide an excellent platform to test new vehicle technologies, without the need for field testing, cutting down the risks involved as well as the costs associated with prototype manufacture. Fixed base simulators can provide good results although some realism is lost, as the accelerations which would be generated in a real vehicle cannot be reproduced. Motion bases or hexapods can replicate these accelerations in 6dof resulting in a more realistic driving experience. The small displacements in the actuators (approximately 0.3m-1m) mean that the accelerations can only be maintained for a short period of time. This can lead to problems in high speed or emergency manoeuvres. A lateral/longitudinal track simulator provides the system with more sustainable accelerations, and can therefore be used effectively for high speed cornering and emergency manoeuvres.

1.4.6 Conclusions from the Literature

- There has been in-depth research into longitudinal control, especially in complex methods of control.
- Fully developed ACC systems have been released on to the market and implemented in a wide range of vehicles.
- There is a good understanding of ACC desired system performance values, levels of longitudinal acceleration, useable headway range, etc.
- Little is known about the roll and pitching behaviour of vehicles with longitudinal control systems, this is especially important for driver comfort.
- Human factors work on both ACC and longitudinal collision warning systems has shown the need for systems to be adaptive to differing driving styles (late/early braking)
- There has been little research on the use of ACC in conjunction with other ADAS and chassis control systems such as ABS, traction control or lateral control.
- Lane departure warning systems have been released on to the market - competent vision systems are available.
- Theoretical controllers have been developed to provide effective lateral control for both lane keeping and lane changing modes, these are yet to be implemented on marketable vehicles.

- Although research into predicting driver manoeuvre intentions has been performed, the findings were not very positive. All analysis was carried out by post processing, when real time analysis is required, if the monitoring systems are ever to be used effectively.
- Most lateral research was concerned with the tracking performance of the vehicle, and not the roll and pitching behaviour - which could lead to instabilities in the vehicle handling.
- There is a lack of research into combining longitudinal and lateral controllers, especially the impact on the driver and vehicle at high speeds.
- Driving simulators provide a good means for testing ADAS; increased simulator fidelity provides a more accurate response for high speed manoeuvres.

1.5 Aims and Objectives

1.5.1 Aim

The above literature review has shown that there has been a lot of worthwhile research into longitudinal and lateral ADAS. Although, there are still areas which require further investigation. The main areas of under-developed research concern the system's full dynamic performance in normal and adverse weather conditions. This is especially important given the impact on driver comfort and safety. For this reason it was proposed that the current research be developed to incorporate pitching and roll behaviours (full vehicle model). Dynamic behaviour can then be monitored and the controllers tuned to ensure driver comfort levels are maintained, while the vehicle stability can be proved for a wide range of environmental/frictional conditions. It is also hoped to improve the understanding of ADAS by developing a range of test scenarios that can be used in this, and future research.

While driving simulator testing of ADAS has been carried out, it has generally focused on one part of the control problem. This research hopes to investigate the drivers reactions to the system as well as monitoring the impact of the system on the performance of both the vehicle and the driver. This should improve the understanding of the drivers interactions with the system and highlight potential conflicts.

1.5.2 Objectives

Longitudinal Control

1. Develop a simple longitudinal controller and examine its dynamic performance using a full vehicle model simulation.
2. Improve the understanding of longitudinal control at high vehicle speeds in a wide range of favourable and adverse conditions.
3. Investigate the driver's interaction with the system, during standard and evasive driving manoeuvres.

Lateral Control

1. Link both human factors and engineering research to develop a 'human centred' lateral controller.
2. Improve the understanding of lateral control at high vehicle speeds in favourable and adverse conditions.
3. Assess the safety and comfort impacts of lateral control on the driver.

1.6 Thesis Outline

This body of work took a twin track approach to attain the objectives set. Initially offline simulations were carried out to assess the impact of both longitudinal and lateral control systems on the vehicle dynamics. While the driver was considered at all stages of this analysis, this platform did not allow the direct assessment of the effects of the systems on the comfort and experience of the driver. These were investigated using a driving simulator experiment, which considered the use of the systems in normal and evasive scenarios. This novel approach, where the impacts on the vehicle and driver were assessed in tandem, was used to uncover solutions to make systems more appea2ling to drivers, whilst ensuring the dynamic performance of the vehicle was not compromised. This thesis is set out to in two parts to cover this two pronged approach, details of the content of each chapter are set out below:

Chapter 2 proposes a range of vehicle models which are used throughout this research to develop and test ADAS. The vehicle models range from a simple 2dof model to a sophisticated 9dof full vehicle model, that fully captures the desired vehicle motions. Tyre model choice is discussed, before the full vehicle model is validated using the industry standard CarSim®simulation package. These high fidelity vehicle models, with non linear handling properties provide a new means of assessing the high speed and comfort impacts of ADAS.

Chapter 3 discusses the development of a longitudinal control system using a range of off-line simulation tools. This is initially done at a detailed level allowing the fundamental adaptive part of the control system to be monitored, without the influence of other components. For the first time in the field, the performance of the system and its effects on the vehicle dynamics are considered in adverse weather conditions. Then secondly the system is integrated with other control elements and powertrain models to explore how the performance of the full system would translate through the vehicle dynamics and back to the driver. The system is tested using a wide range of manoeuvres, to fully capture possible scenarios that the systems may be subject to during road usage. The longitudinal and pitch accelerations are monitored throughout to ensure the comfort levels of the driver are maintained.

Chapter 4 investigates two types of lateral control systems that aim to fully control the lateral motion of the vehicle. An extensive range of scenarios are developed to assess the systems' performances examining typical motorway manoeuvres including straight, and curved roads, as well as lane changes. These tests are described in detail as a suggested evaluation platform for lateral control systems that are developed in the future. A look down system is initially considered, which monitors only the current vehicle position. Its performance and impact on the driver are assessed and discussed, before a more driver emulating approach is taken. This time a look ahead system is used, so that the system has an idea of the future path of the road (much like the human driver). This system is tested using the same events as the look down systems and the results of the two are compared. Again, for the first time the impact of environmental factors on the vehicle dynamics of the systems are investigated. The high fidelity vehicle model allows the effects of the system on the comfort levels to be monitored over the full range of vehicle handling.

Chapter 5 discusses the benefits of the University of Leeds Driving Simulator (UoLDS), and details the steps that were taken to effectively integrate the ACC and Lane Keeping System (LKS) developed in previous chapters. A novel Human Machine Interface (HMI) through which the driver will interact with the system, is implemented for the LKS, and current technologies are refined to create an ideal solution for the ACC HMI. The chapter also details the development of five new simulator scenarios designed to investigate the impact of the systems on the driver.

Chapter 6 details the experiments that were conducted in the driving simulator, from design to analysis. The road layout and traffic scenarios are developed to allow drivers to experience both standard and evasive operation of the systems. A structured questionnaire is developed to assess the systems acceptability, and the drivers trust, experience and general opinions of the systems. Objective results from the simulator study are presented and discussed comparing assisted to unassisted driving, and attempts are made to validate these results with findings from the subjective questionnaires.

Chapter 7 summarises the findings of this research with reference to the new and novel ideas discovered. Recommendations for future work in the field are discussed.

Chapter 2

Vehicle Modelling and Simulation

Chapter 2 proposes a range of vehicle models which are used throughout this research to develop and test ADAS. The vehicle models range from a simple 2dof model, to a sophisticated 9dof full vehicle model. Tyre model choice is discussed, before the full vehicle model is validated using the industry standard CarSim® simulation package.

Vehicle simulations are used extensively in both vehicle dynamics and control system development. They provide a cost efficient test bed on which new concepts can be developed prior to, or as an alternative to real vehicle testing.

Vehicle models can be constructed to isolate aspects of the real vehicle's behaviour, creating the benefit of allowing the influence of certain aspects of the vehicle (e.g. lateral behaviour at constant speed) to be investigated in isolation. Many such vehicle models have been created for this research, all designed to examine certain aspects of the vehicle and/or controller in more detail. This chapter discusses the development of these models, initially with simplified models which were used in the development of control systems in later chapters; and secondly considering the more sophisticated models used to test these control systems. Other elements of the vehicle model were later taken into account in more detail including the tyre model, and additions that were required to install the vehicle model on the Leeds Driving Simulator.

2.1 Two Degree of Freedom Lateral Model

When designing a lateral control system, the lateral motion of the vehicle is of most importance, longitudinal behaviour will have a secondary impact on the system and can be put to one side for now. The most simple way of capturing this lateral motion is through a single rigid body, with the freedom to move over the ground plane, due to external moments and forces. The forward speed of the body is assumed to be constant and the body is allowed to move laterally and rotate about the global z-axis, yawing. Certain assumptions and conditions are required to idealise the vehicle motion:

- The road surface is flat and level
- The vehicle structure is rigid
- The forward speed of the vehicle is constant, and therefore negligible change in aerodynamic forces
- Any aerodynamic resistance is overcome by the cruise control system maintaining vehicle speed

As the vehicle body is constrained to move in only 2dofs, there is no rolling or pitching motion of the sprung mass on the suspension and no lateral or longitudinal load transfer, this is a major deficiency of the 2dof vehicle model. The lack of lateral load transfer, means that forces can be summed across axles, and so the model has become commonly known as the ‘bicycle’ model. This model forms the basis for all future vehicle models used in this research. A reference frame is defined in Figure 2.1, and is used throughout this research, with lateral motion (v) positive to the right of the vehicle, steering angle (δ_f) positive when the wheel is steered to the right, and yaw motion (r) positive clockwise from the top of the vehicle (SAE 1976). These variables were defined local to the vehicle, other parameters may in future be defined globally. Assuming conservation of both linear and angular momentum, it was possible to formulate the following equations of motion for the system:

$$m_t(\dot{v}+ur) = F_{yf}+F_{yr} \tag{2.1}$$

$$I_{zz}\dot{r} = aF_{yf}-bF_{yr} \tag{2.2}$$

The tyre forces (F_{yf},F_{yr}) and their calculation are vitally important to the accuracy of the vehicle model. Section 2.4 discusses sophisticated tyre modelling techniques in detail;

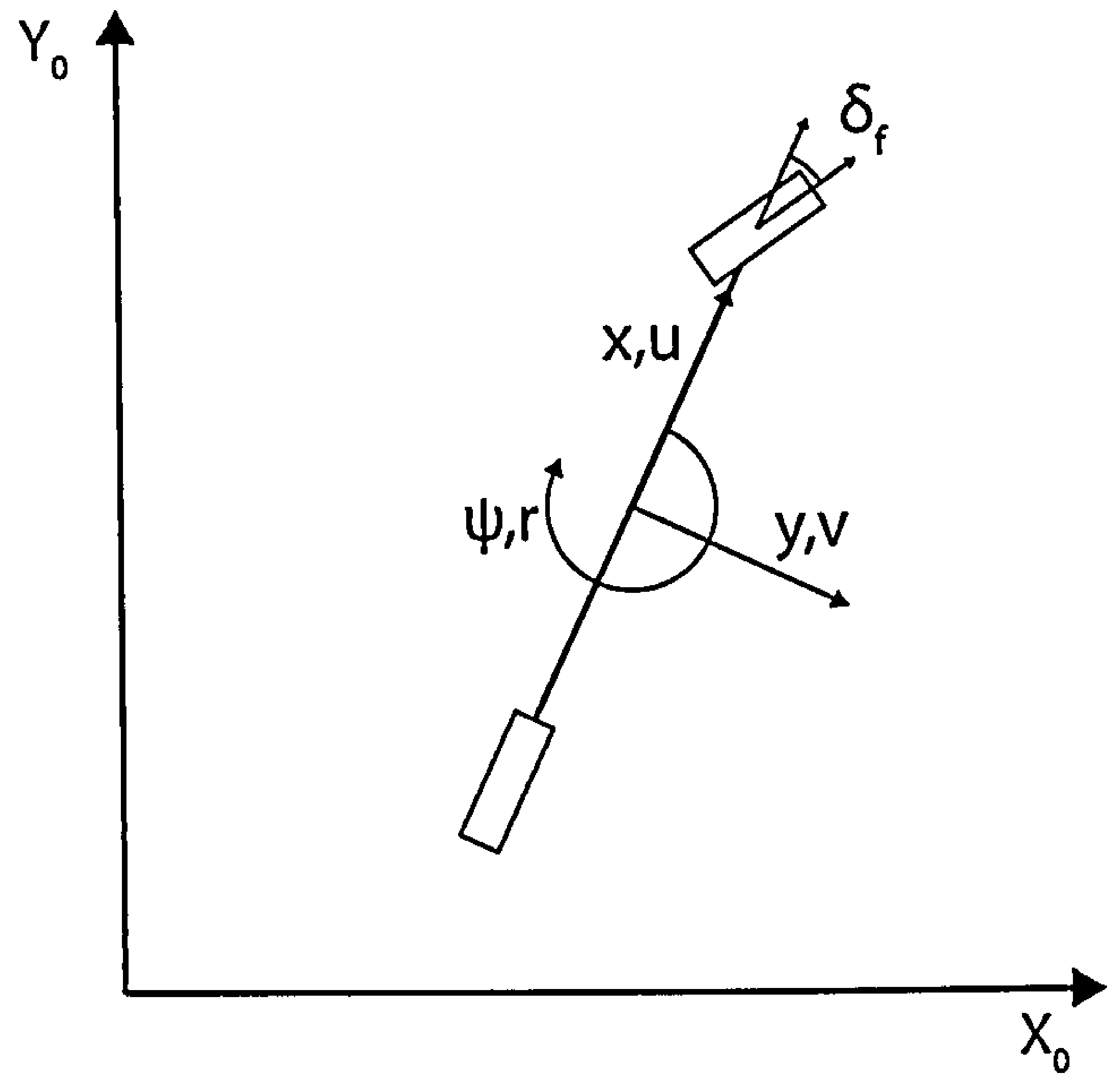


Figure 2.1: The 2dof 'bicycle' model

but for this simple model, available lateral tyre force was calculated as a linear function of slip angle (α) and vertical tyre load.

$$F_y = -C\alpha \tag{2.3}$$

Where C is the cornering stiffness at a given vertical load F_z. As there was no load transfer in this model, F_z can be assumed constant. Front and rear slip angles were defined as follows.

$$\alpha_f = \frac{v+ar}{u} - \delta_f \tag{2.4}$$

$$\alpha_r = \frac{v-br}{u} \tag{2.5}$$

Combining Equations 2.1,2.2, 2.3, 2.4 and 2.5 yields the following:

$$m_t(\dot{v}+ur) = -\frac{C_f+C_r}{u}v - \frac{aC_f-bC_r}{u}r + C_f\delta_f \tag{2.6}$$

$$I_{zz}\dot{r} = -\frac{aC_f-bC_r}{u}v - \frac{a^2C_f+b^2C_r}{u}r + aC_f\delta_f \tag{2.7}$$

and when rearranged into matrix form:

$$\begin{bmatrix} m_t & 0 \\ 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} \frac{C_f+C_r}{u} & m_t u + \frac{aC_f-bC_r}{u} \\ \frac{aC_f-bC_r}{u} & \frac{a^2C_f+b^2C_r}{u} \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} = \begin{bmatrix} C_f \\ aC_f \end{bmatrix} [\delta_f] \quad (2.8)$$

There are then two inputs to the system: the constant forward velocity u, and the front steer angle δ_f. The steer angle can be input as a time history, allowing a range of manoeuvres to be investigated. Eventually this steer angle will be provided by the lateral control system. These equations can be solved using a state space approach.

The key benefits of this model are:

- The model can be used as a set of state space equations, which allow simple control integration.
- Quick to solve - due to the small number of equations.
- Only a small amount of vehicle data is required.
- Simple to see underlying influence of certain factors, without other motions confusing the engineer.

The main limitations of this type of model are:

- Constant speed means that the model is unsuitable for longitudinal control systems.
- Pitch and roll accelerations are also not modelled.
- The cornering stiffness approximations are only valid for the linear handling regime, and are therefore not suitable for high speed manoeuvres.

2.2 Three Degree of Freedom Model

For development of the longitudinal controllers, it was necessary to develop a vehicle model that would be simple enough to interrogate, but with the required dofs. Longitudinal motion was the most important additional dof, as it was this that would eventually be controlled by the ACC system. It was also important to consider the lateral and yawing motions of the vehicle, as this would allow the controller to be tested in a range of combined acceleration manoeuvres. With these new constraints, it was again possible to use the equations of motion described in Equations 2.1 and 2.2, combined with a further equation to describe the longitudinal motion of the vehicle.

$$m_t(\dot{u} - vr) = F_{xf} + F_{xr} \tag{2.9}$$

Similarly to the lateral tyre forces, longitudinal forces can be calculated as a function of vertical load and longitudinal slip angle σ, where the longitudinal slip angle is defined in Figure 2.2 and Equation 2.10.

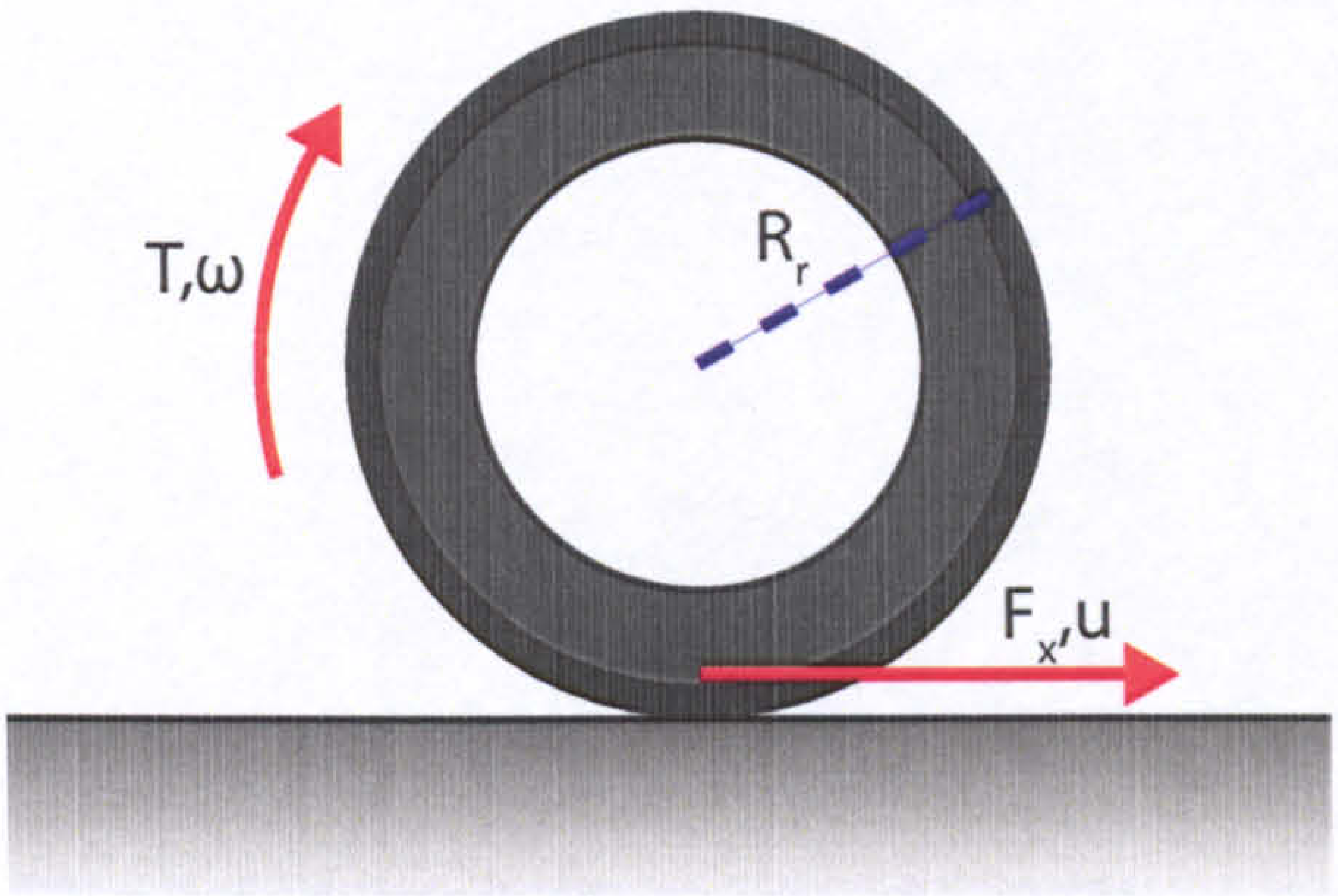


Figure 2.2: Definition of longitudinal slip

$$\sigma = \frac{-(u - R_r\omega)}{u} \tag{2.10}$$

In later models a full powertrain was modelled to represent the drive and brake forces at each wheel, but for this simple model it was assumed that a torque, T, could be generated directly at each axle. This torque could be input to the model as a time history or control variable. It was then used to calculate the angular velocity of the wheel as follows:

$$\omega = \int (T - F_x R_r)dt \tag{2.11}$$

As forward velocity, u, is now not constant, the equation can no longer be solved using the linear state space method. Instead the necessary terms were computed to calculate the three accelerations. These values were then integrated to find the respective velocities which could then be used in the next time step to again calculate acceleration. This caused 1 time step of 'lag' in the model. The time step used in the simulation becomes critical to the accuracy and success of the results.

The benefits of this model are:

- It is simple to interrogate and solve.
- No powertrain, so longitudinal motion is generated by simple application of torque to each axle.
- Both longitudinal and lateral dofs are modelled.

The main limitations of this type of model are:

- Pitch and roll accelerations are not modelled.
- The linear handling regime covered by the cornering stiffness approximation is not suitable for high speed manoeuvres.
- A small time lag is caused by the integration of the accelerations, thus it is limited by time step size.

2.3 9 Degree of Freedom Full Vehicle Model

The previous models provide a good platform to develop control systems. In order to fully investigate the system and its effects on vehicle and driver performance, it is necessary to examine the vehicle in a greater level of detail. Certain aspects of the vehicle that were not considered earlier, are now added to better simulate the vehicle motion, especially at high levels of acceleration. The most significant of these were longitudinal and lateral load transfer and rotational dofs of the body. The load transferred to and from each corner of the vehicle affects the amount of vertical load applied to each tyre. This in-turn affects the lateral and longitudinal forces that can be generated by each tyre, and hence the levels of acceleration that the vehicle can sustain. In previous models with no load transfer, the forces that each tyre could generate were dependent only on slip angles; with the addition of load transfer and variable vertical tyre loads, the calculation of tyre forces becomes more complex. At higher slip angles these relationships become non-linear. A tyre model was used to model these relationships, discussed in detail in Section 2.4. As well as these features rotation about the X-axis of the vehicle, termed roll, and rotation about the Y-axis, termed pitch, were both added to the model. The 9dof are: five body motions (longitudinal, lateral, roll, pitch, and yaw), and a longitudinal slip at each wheel. Heave was not modelled, as we were not concerned with the primary ride comfort of the vehicle. Figures 2.3, 2.4, and 2.5, show the vehicle and its dof.

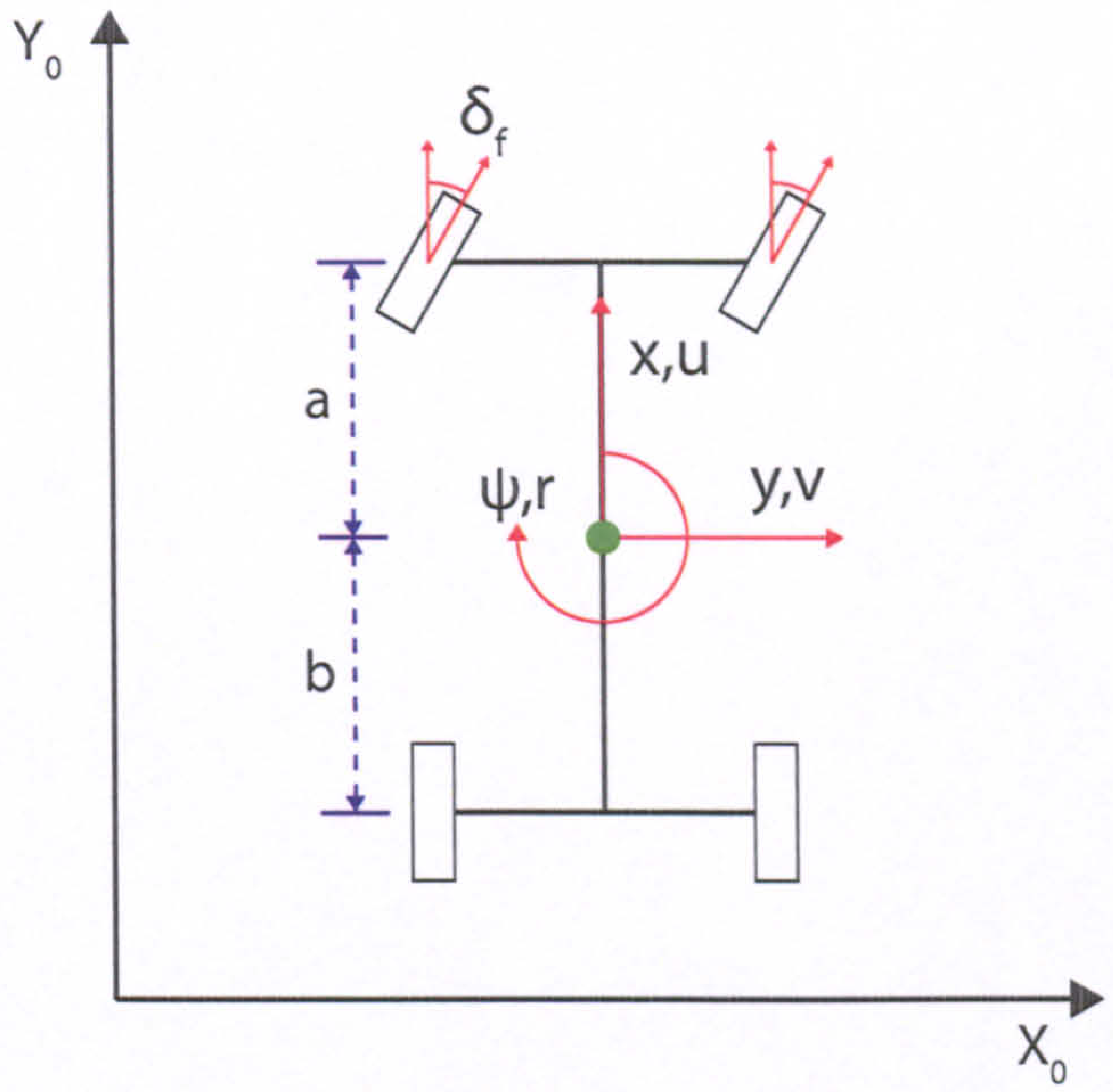


Figure 2.3: 9dof vehicle model, longitudinal, lateral and yaw dof's

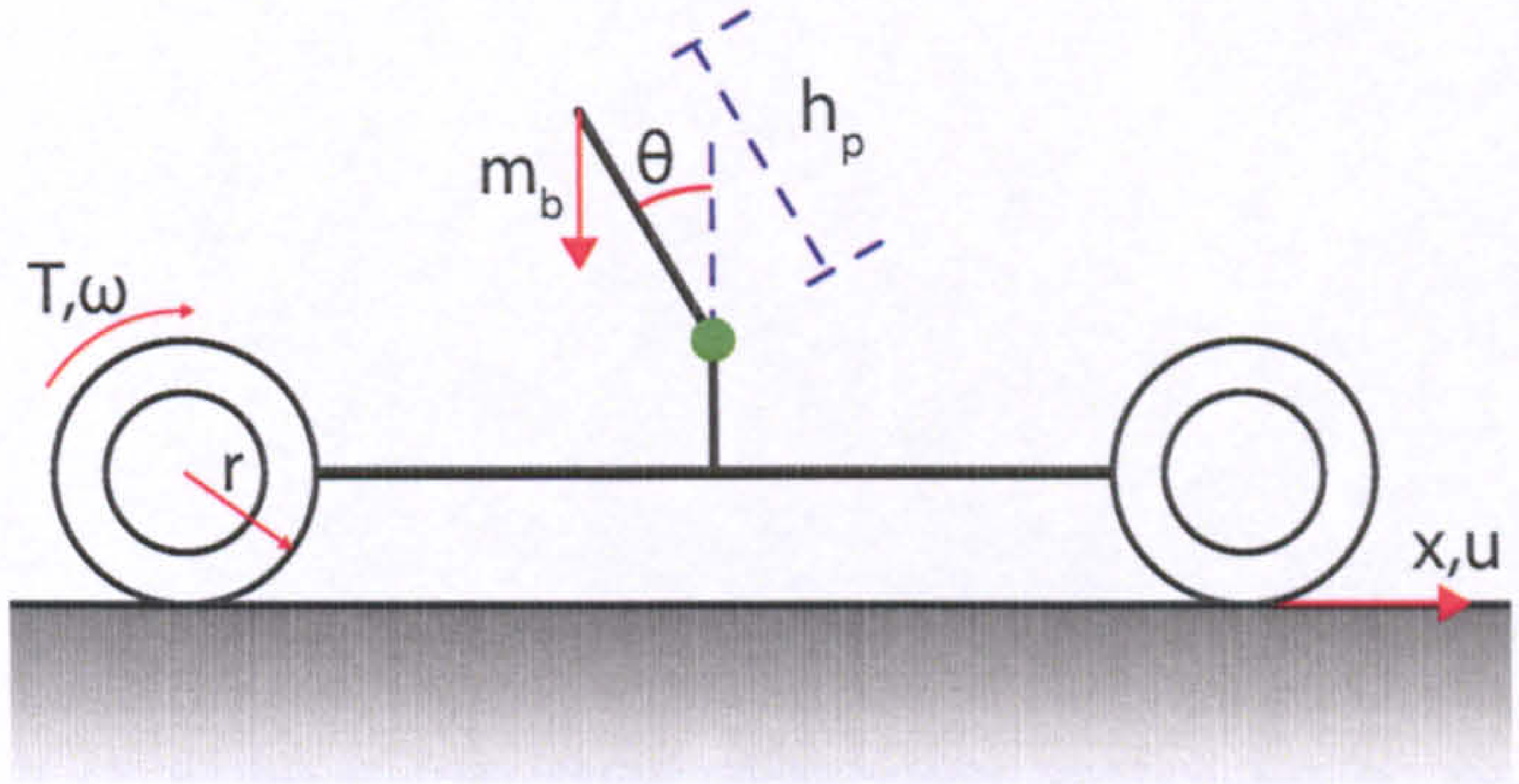


Figure 2.4: 9dof vehicle model, pitch, longitudinal and wheel dof's

The following equations of motion were derived for the system using Lagrangian Mechanics, where the kinematic and potential energy of the system are combined to simplify the formulation of the equations. Also shown are equations describing the vertical load on each tyre.

$$\sum F_x = m_t(\dot{u} - vr) - (am_f - bm_r)r^2 - m_b(h_r r\dot{\phi} + h_p\ddot{\theta}) \tag{2.12}$$

$$\sum F_y = m_t(\dot{v} + ur) - (am_f - bm_r)\dot{r} + m_b(h_r\ddot{\phi} + h_p r\dot{\theta}) \tag{2.13}$$

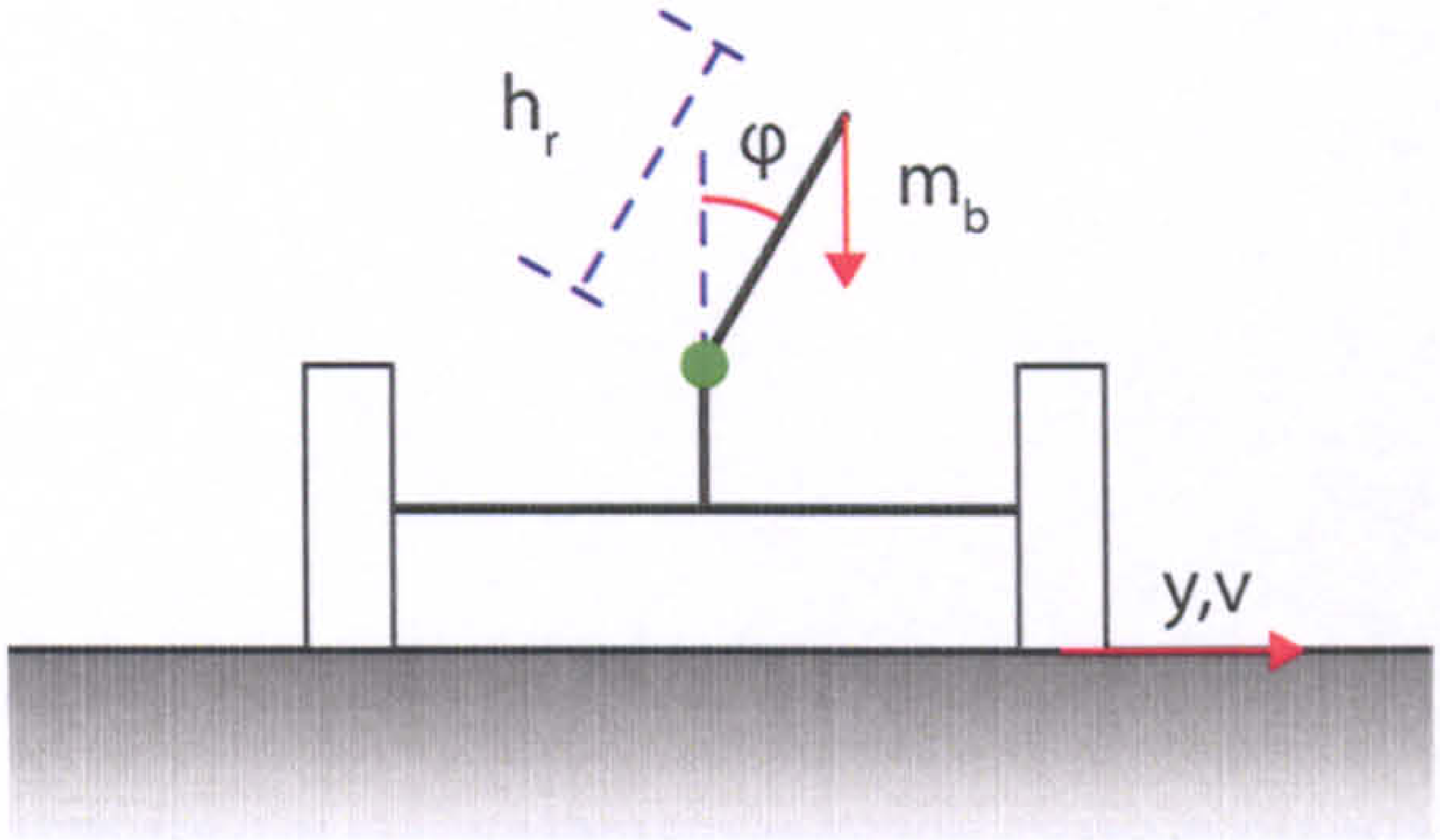


Figure 2.5: 9dof vehicle model, roll and lateral dof's

$$\begin{aligned}
\sum M_z &= (am_f - bm_r)(\dot{v}+ur) + (m_f a^2 + m_r b^2 + I_{zz})\dot{r} \\
&\quad + m_b(h_r u\dot{\phi} - h_p v\dot{\theta}) && (2.14) \\
\frac{\sum F_x}{m_t} m_b h_p - \sum F_{zf} a + \sum F_{zr} b &= (I_{yy} + m_b h_p^2)\ddot{\theta} + C_\theta \dot{\theta} + (B_\theta - m_b g h_p)\theta \\
&\quad + h_p^2 \dot{\phi} r + m_b h_r(\dot{v}+ur) && (2.15) \\
-\frac{\sum F_y}{m_t} m_b h_r + (\sum F_{zr} - \sum F_{zl})\frac{t_w}{2} &= (I_{xx} + m_b h_r^2)\ddot{\phi} + C_\phi \dot{\phi} + (B_\phi - m_b g h_r)\phi \\
&\quad - h_r^2 \dot{\theta} r + m_b h_r(\dot{v}+ur) && (2.16)
\end{aligned}$$

$$\begin{aligned}
F_{zfl} &= \frac{1}{2}\left(\frac{bm_t g}{l_{wb}} - \frac{m_t h_{cg}\dot{u}}{l_{wb}}\right) + \frac{B_{f\phi} m_t h_{cg}\dot{v}}{B_\phi t_w} - \frac{2B_\phi \phi}{t_w} - \frac{2B_\theta \theta}{l_{wb}} && (2.17) \\
F_{zfr} &= \frac{1}{2}\left(\frac{bm_t g}{l_{wb}} - \frac{m_t h_{cg}\dot{u}}{l_{wb}}\right) - \frac{B_{f\phi} m_t h_{cg}\dot{v}}{B_\phi t_w} + \frac{2B_\phi \phi}{t_w} - \frac{2B_\theta \theta}{l_{wb}} && (2.18) \\
F_{zrl} &= \frac{1}{2}\left(\frac{bm_t g}{l_{wb}} + \frac{m_t h_{cg}\dot{u}}{l_{wb}}\right) + \frac{B_{f\phi} m_t h_{cg}\dot{v}}{B_\phi t_w} - \frac{2B_\phi \phi}{t_w} + \frac{2B_\theta \theta}{l_{wb}} && (2.19) \\
F_{zrr} &= \frac{1}{2}\left(\frac{bm_t g}{l_{wb}} + \frac{m_t h_{cg}\dot{u}}{l_{wb}}\right) - \frac{B_{f\phi} m_t h_{cg}\dot{v}}{B_\phi t_w} + \frac{2B_\phi \phi}{t_w} + \frac{2B_\theta \theta}{l_{wb}} && (2.20)
\end{aligned}$$

This model had many advantages over the simple models constructed previously. One of the main areas that was not modelled for this stage of the research was the powertrain. Again torque could be applied directly at each wheel. Acceleration and braking were modelled to replicate the drive and brake split of the real vehicle, allowing controllers to be transferred between models easily. When using the model for lateral simulations it was sometimes necessary to ensure constant forward speed for repeatability of testing, this was performed using a simple PID controller on the torque input to each wheel. The base vehicle on which all controllers were tested was formed from this model. For some tests additional elements were added to capture certain aspects of the scenario.

2.3.1 Side Winds

In order for lateral control to be accepted by drivers, the system must be dependable and suitable for a wide range of driving conditions. One cause of traffic accidents in motorway scenarios is cross winds forcing the vehicle out of the lane. It is important to see how a lateral control system would react to such external disturbances. It was decided that a simple aerodynamic model should be used based on average aerodynamic data for a vehicle of this size. A projected side area was estimated at 3.5 m^2, and the side area's centre of pressure was assumed to be the centre of gravity of the body. This approximation prevented additional pitching motion. Given an estimated wind speed and angle of impact, the resultant lateral force and yawing moment were calculated (Equations 2.21 and Figure 2.6). The impact on the longitudinal motion of the vehicle was not observed.

$$\begin{aligned} F_{y(sw)} &= sin(\varepsilon)V_{sw}^2\rho A_s \\ M_{z(sw)} &= \frac{t_w}{2}cos(\varepsilon)V_{sw}^2\rho A_s \end{aligned} \tag{2.21}$$

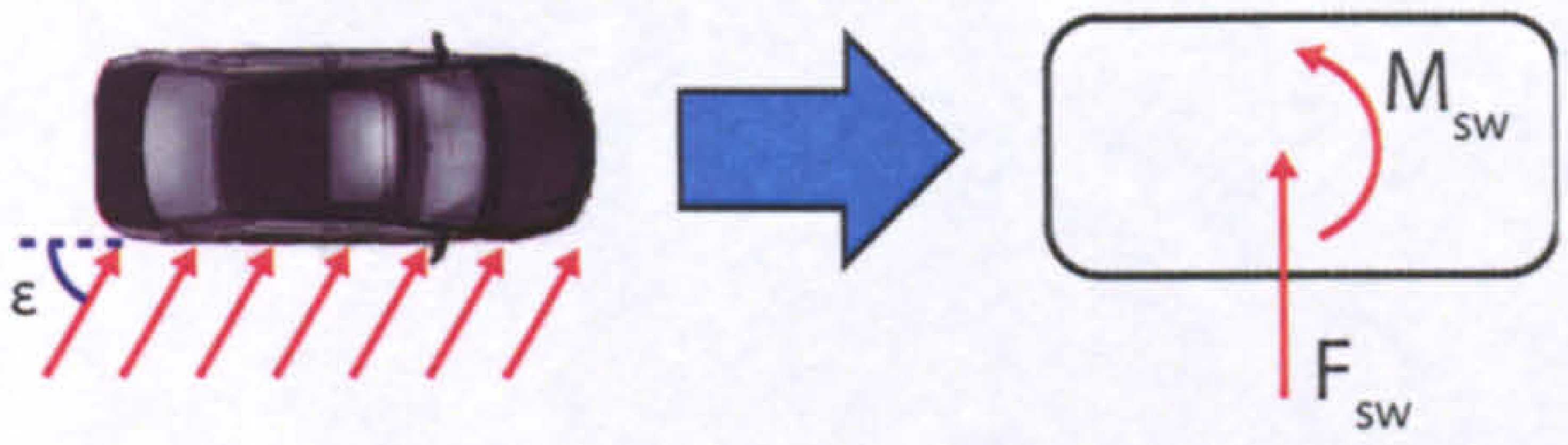


Figure 2.6: Side wind modelling

It may have been more accurate to take into account the rear area of the vehicle and investigate the variable side wind pressure distribution across the total exposed surface of the vehicle. This improved pressure distribution may have provided additional yawing moments, and may have allowed more investigation into the transient response of the vehicle to this inherently transient phenomena.

Straight-line aerodynamic forces (drag), were not considered in this model as it was hoped to investigate the impact of the control systems without the impact of another speed dependent force on the vehicle. While the model would be investigated at high speeds, resulting in high drag and downforce characteristics, the longitudinal velocity would remain relatively constant throughout the lateral control simulations. Therefore, the resultant net change in longitudinal drag should be minimal.

2.3.2 Superelevation

Superelevation, or banking is common in modern road design to assist in high speed cornering. By increasing the inclination of the road, the vehicle can generate additional lateral forces due to the rotation of its mass to the centre of the bend (Figure 2.7). It is vital that any lateral control system can perform in these conditions, so the ability to bank the vehicle was added to the model. An additional term is added to the F_y forces to replicate these banking effects. This is a highly simplified approximation, but as it was only used as an additional disturbance to the vehicle, a complete model of the effects of super elevation was not deemed necessary. While banking and side winds were important features of the model, there were many scenarios where they were not necessary. Switches were added to the model to enable and disable these features when required.

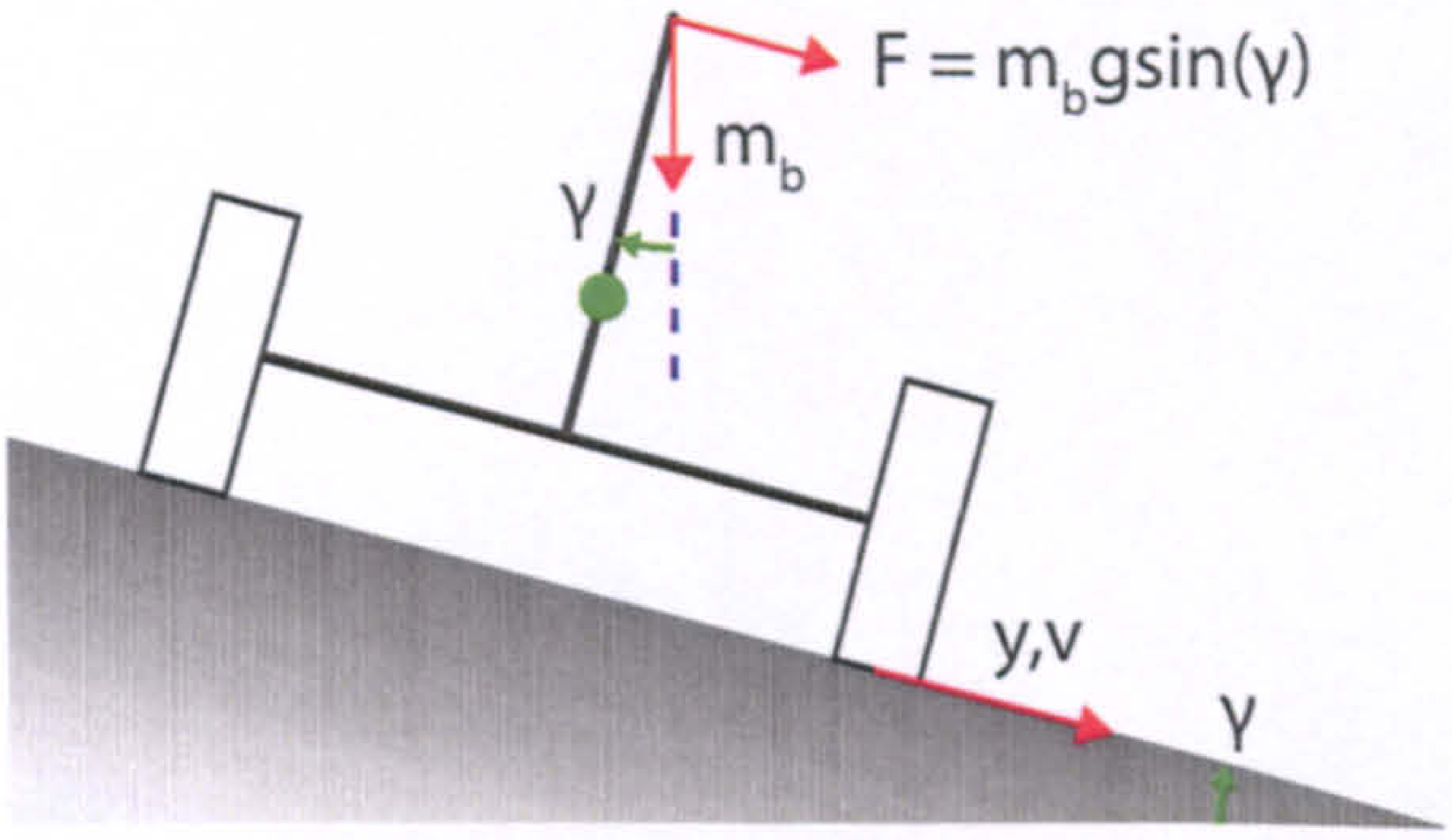


Figure 2.7: Additional lateral forces generated when the vehicle is banked

2.4 Tyre Modelling

To ensure the accurate modelling of tyre forces not only during high speed manoeuvres, but also towards the limits of linear handling, it was necessary to develop a non-linear tyre model that would capture the performance of the tyre over this range of conditions. During the off-line simulations, there was no need to consider the vehicle's performance from rest, simulations started at the desired speed, meaning that the original calculations of slip remain valid. In a driving simulator, starting from rest is important to create a realistic environment, therefore the original calculations are no longer valid as the vehicle speed tends to zero. Methods to overcome these deficiencies are discussed in Section 5.2.2.

While the calculation of slip differs between the two models, the tyre model used is otherwise identical. A range of tyre models were considered for this application, including Szostak et al. (1988) and Dugoff and Brown (1970) before it was decided to use the Magic Formula Tyre Model with Transient Properties given in Pacejka and Besselink (1997). This model was chosen as it encapsulated the dynamic performance of the tyre in more detail than other similar empirical models, it is widely used in similar vehicle dynamic research and tyre data is readily available. The model works by using a number of equations to generate an effective instantaneous 'carpet' plot for a given tyre (Figure 2.8). This plot can display the effects of a number of parameters, but most commonly it shows slip angle (longitudinal or lateral), vertical tyre load, and resultant tyre force (longitudinal, lateral or aligning torque). Slip angles are known from Equations 2.4 and 2.10, and individual vertical tyre loads can be calculated from longitudinal and lateral load transfer equations. The lateral and longitudinal forces and aligning torques of each wheel can then be calculated using the Pacejka equations.

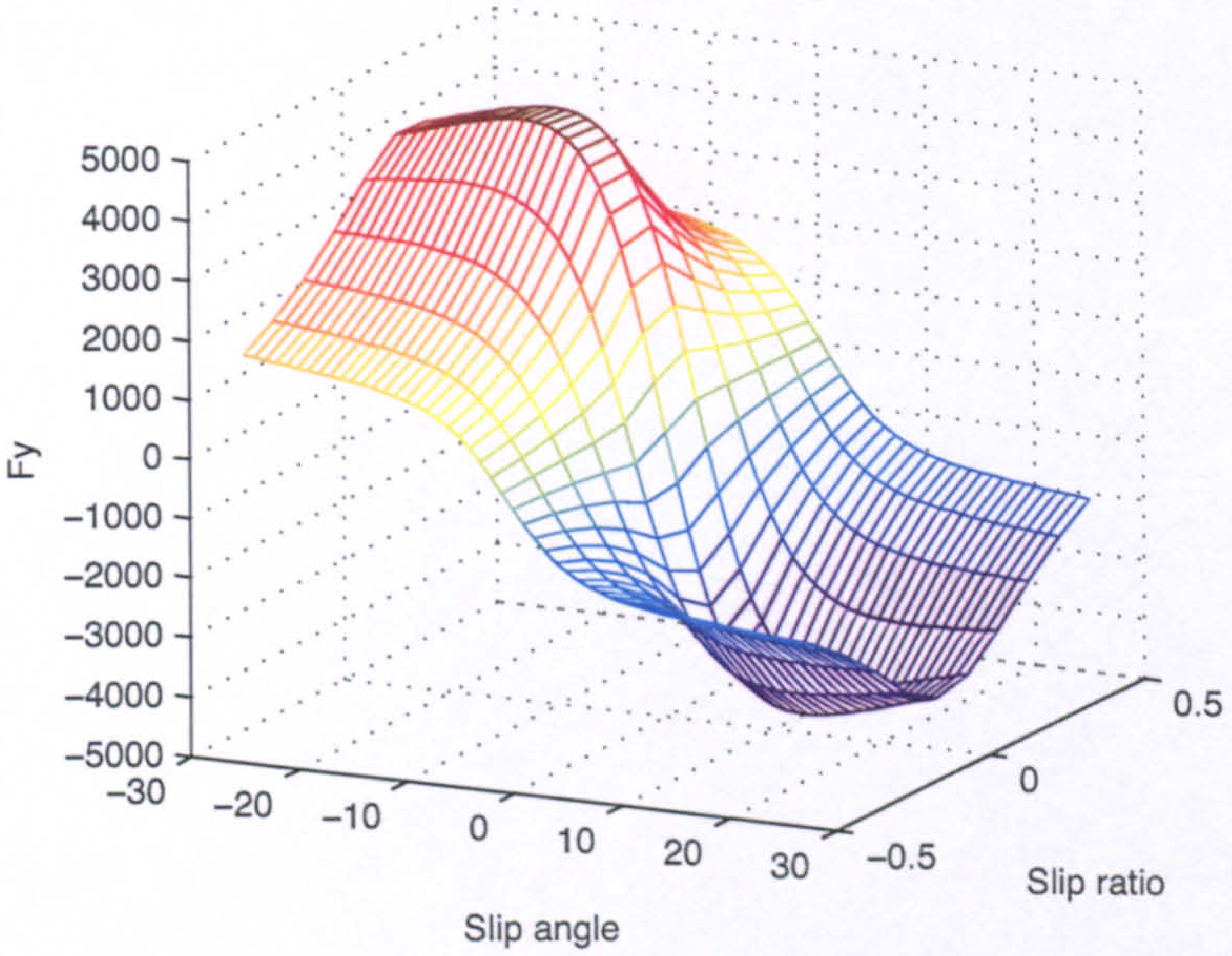


Figure 2.8: Example Pacejka 'carpet' plot

The Pacejka and Besselink (1997) model consists of over 50 equations,with 120 parameters and 20 scaling factors. In order to reduce simulation time, the equations were vectorised to allow all four tyres to be processed in parallel. The 120 parameters were used to describe the tyre's performance. The parameters generally come in full sets which can be obtained for certain brands and sizes of tyres; although the data is often difficult to obtain directly from manufacturers. For this research the data was taken from Pacejka (2002). The 20 scaling factors were used to adjust the results of the model for certain conditions. The most relevant of these were LMU_x and LMU_y, since they allowed a scaling coefficient of friction to be specified, which is vital when investigating the vehicles performance in a range of weather conditions.

To ensure consistency of modelling, the cornering stiffness used in the 2dof and 3dof models were approximated from the initial slop of the Pacejka plots used in the full model.

2.5 Validation

One of the most important aspects of vehicle modelling is ensuring the model provides a sufficiently accurate approximation to the real vehicle. While the model will always remain an approximation of the actual vehicle, it is vital that the key performance features for the desired scenario are captured in the model. Accuracy of the vehicle model can be affected not only by the vehicle data, but also by the equations and assumptions used. Ideally the model would be run through a range of relevant scenarios and its results compared to real world data obtained from the physical vehicle, but this is not always practical. Data obtained from physical testing can be affected enormously by environmental conditions, tyre degradation and numerous other factors. The instrumentation and physical testing of the vehicle can also be very expensive (This is one of the main reasons vehicle dynamics models have been developed). For these reasons it was not possible to validate this model against any real-world data. The other main method of validation, is to correlate the results of the vehicle model with that of other models and standards, that have themselves been previously validated and assessed by the wider vehicle dynamics community. Again, this method is not ideal as we are relying on the accuracy of previous validation, of which we have little or no prior knowledge. This method does allow a range of identical tests to be performed quickly and their results assessed without the interference of uncontrollable disturbances.

The widely used vehicle dynamics software package CarSim® was used to validate the vehicle model in this research. This software is used extensively throughout the academic and industrial automotive fields, and benefits from an easy to use graphical interface (GUI). While detail of the actual vehicle model used is not available publicly, the user guide provides some insight into the equations used in certain features of the model. The version used in these validation tests was CarSim® Education Version 4.51. Vehicle parameters from the 9dof model were entered into the CarSim® model. Unfortunately CarSim® did not allow for Pacejka coefficients to be used as a tyre model. Instead data points were taken from the Pacejka data used in the 9dof model and used in the CarSim® model as a cornering stiffness 'carpet' plot. While this would not allow the Pacejka calculations to be performed at each time step it would provide a sufficient approximation to the full Pacejka model.

With the software and models in place, the next task was to decide on a range of manoeuvres on which to test both models. Step steer manoeuvres provide the simplest means of assessing the transient lateral performance of the vehicle (e.g. the responsiveness and damping of the vehicle). They can be conducted at both low and high lateral accelerations to investigate the on-centre and near-limit handling behaviour of the vehicle. For these tests the speed should be kept constant, allowing more simple correlation to be performed. The variables of interest were lateral acceleration, yaw rate, and body roll. To fully capture the performance of the vehicle, it was also decided to look at a sine steer manoeuvre, which would assess the lateral acceleration and yaw rate gains of both simulation methods. Longitudinally the performance of the vehicle can be attained by straight line braking and accelerating manoeuvres. From these tests it should be possible to assess the pitching behaviour of the model. Finally to investigate the combined lateral and longitudinal performance, a corner lift off event was performed and the lateral acceleration, yaw rate and body roll were monitored.

2.5.1 Validation Results

Lateral Behaviour

The lateral behaviour of any vehicle is one key to the vehicle being accepted by the driver. It is important that the levels of yaw rate and lateral acceleration correspond between models. The speed of the responses of both of these parameters is generally affected by the type of vehicle, and loading conditions of the vehicle being modelled. Drivers will be able to notice differences in this response rate and so it is important that it correlates well. The oscillatory nature of the response also affects the driver's perception of the vehicle; more oscillatory behaviour would suggest a more unstable vehicle which may be unpleasant and unsafe for the driver.

The 10m/s 0.1g step steer manoeuvre represented the vehicle's 'on centre' handling performance. This included how the vehicle was affected by minor steering inputs, used to correct heading and the effects of minor disturbances. While the tests to be carried out in this research are more concerned with high speed driving, the vehicle performance at these lower speeds is still of some importance to the overall success of the simulations.

The main simulation results are shown in Figure 2.9. Results were positive. While the 9dof vehicle model displayed a slightly more oscillatory response, the steady state values of lateral acceleration and yaw rate correlated well. The response times appeared very similar, although it was difficult to accurately assess this due to the instantaneous nature of the response. The steady state roll angle was not within the same tolerance as the yaw rate, it displayed the same trends as that of the other vehicle model. Again the results

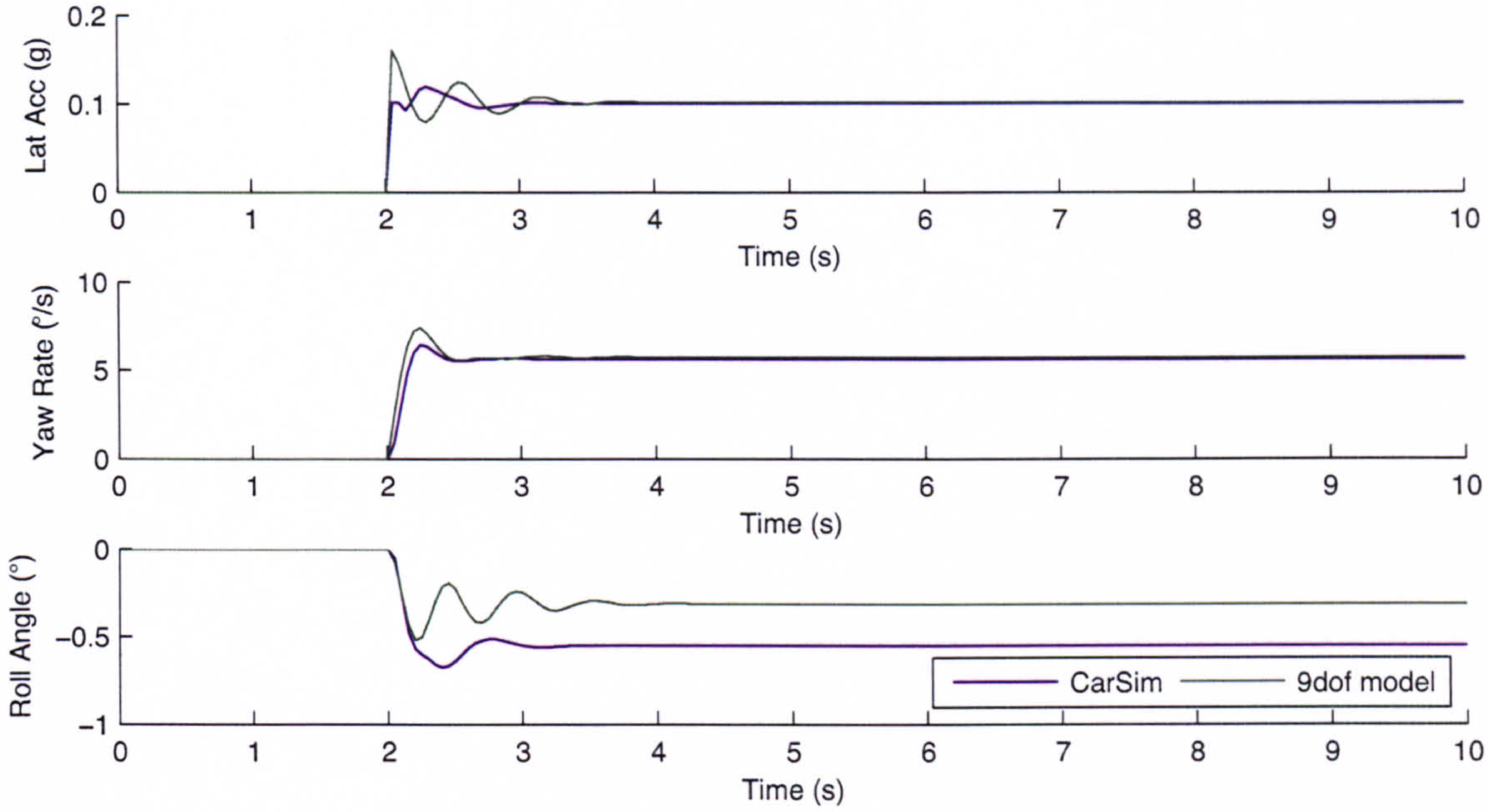


Figure 2.9: 10m/s 0.1g step steer - validation results

were more oscillatory for the 9dof model. These more oscillatory results may give the driver a sense of instability, which they may try to react by additional steering input, this in turn could compromise the stability further.

The other low speed test simulated the vehicle cornering at 0.3g. Again this type of scenario was not representative of the main focus of this study, but may play a part in the driver's acceptance of the vehicle, especially if used in the driving simulator study.

The vehicle displayed a very similar response to that of the 0.1g test. Again, the steady state levels of yaw rate and lateral acceleration corresponded well between models. The response of the 9dof vehicle model was still slightly more oscillatory, but the initial short-lived peaks were decreased at this higher level of lateral acceleration.

The next two step steer tests were more reflective of the type of conditions to which the test vehicle would be subjected. The 30m/s 0.1g manoeuvre covered the 'on centre' performance of the vehicle at motorway speeds. The accuracy of the model in this range is key, as this was one of the areas for which we would ask the driver to compare manual and assisted driving.

The results shown in Figure 2.11 are promising. Again steady state values of yaw rate and roll were near identical, but more interesting was the response rate of all parameters. As expected this was slower than for the low speed manoeuvres, meaning that differences would become more noticeable, both to us and the driver, but fortunately the rates appeared to correlate. The high initial peak and following undershot were noticeable in both

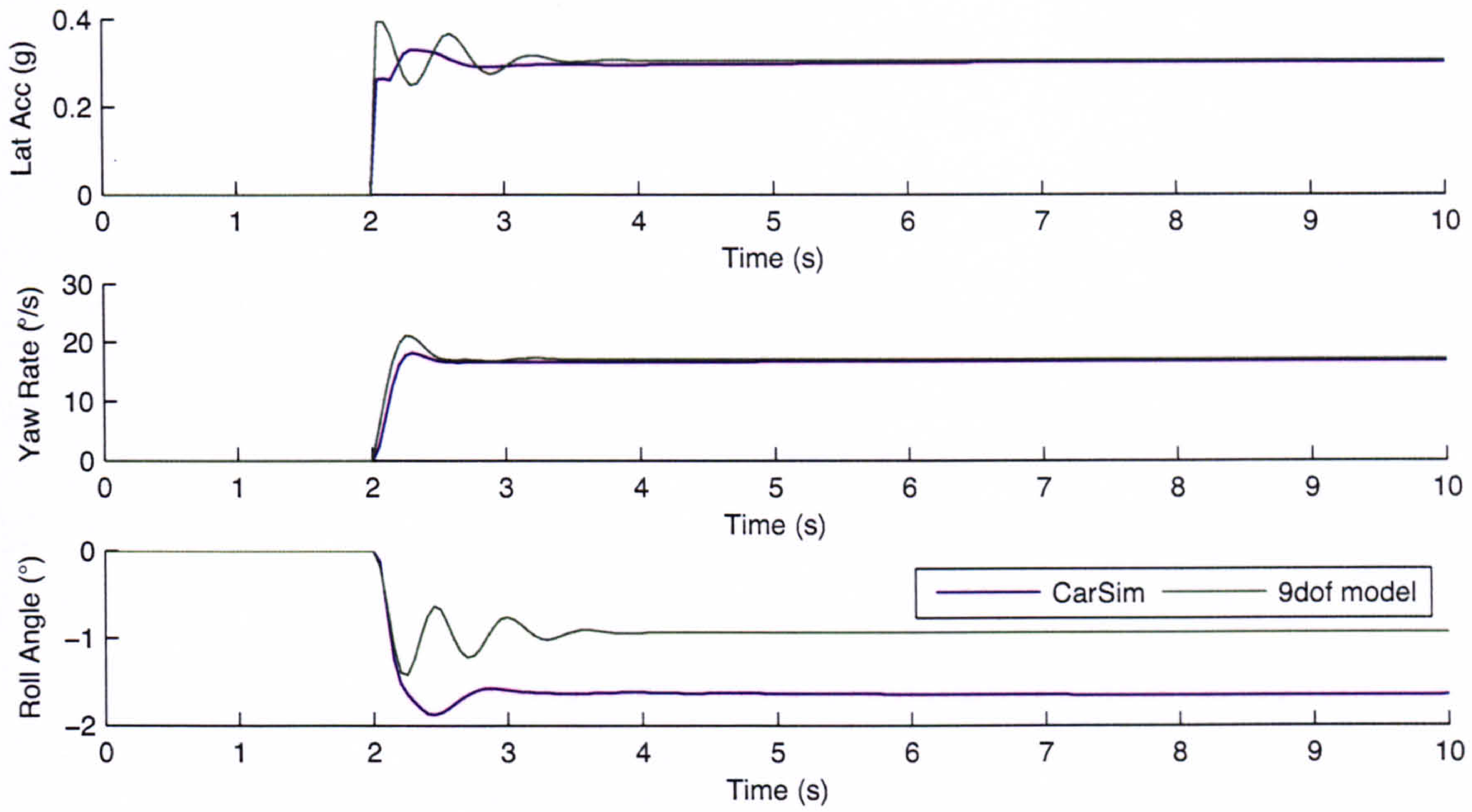


Figure 2.10: 10m/s 0.3g step steer - validation results

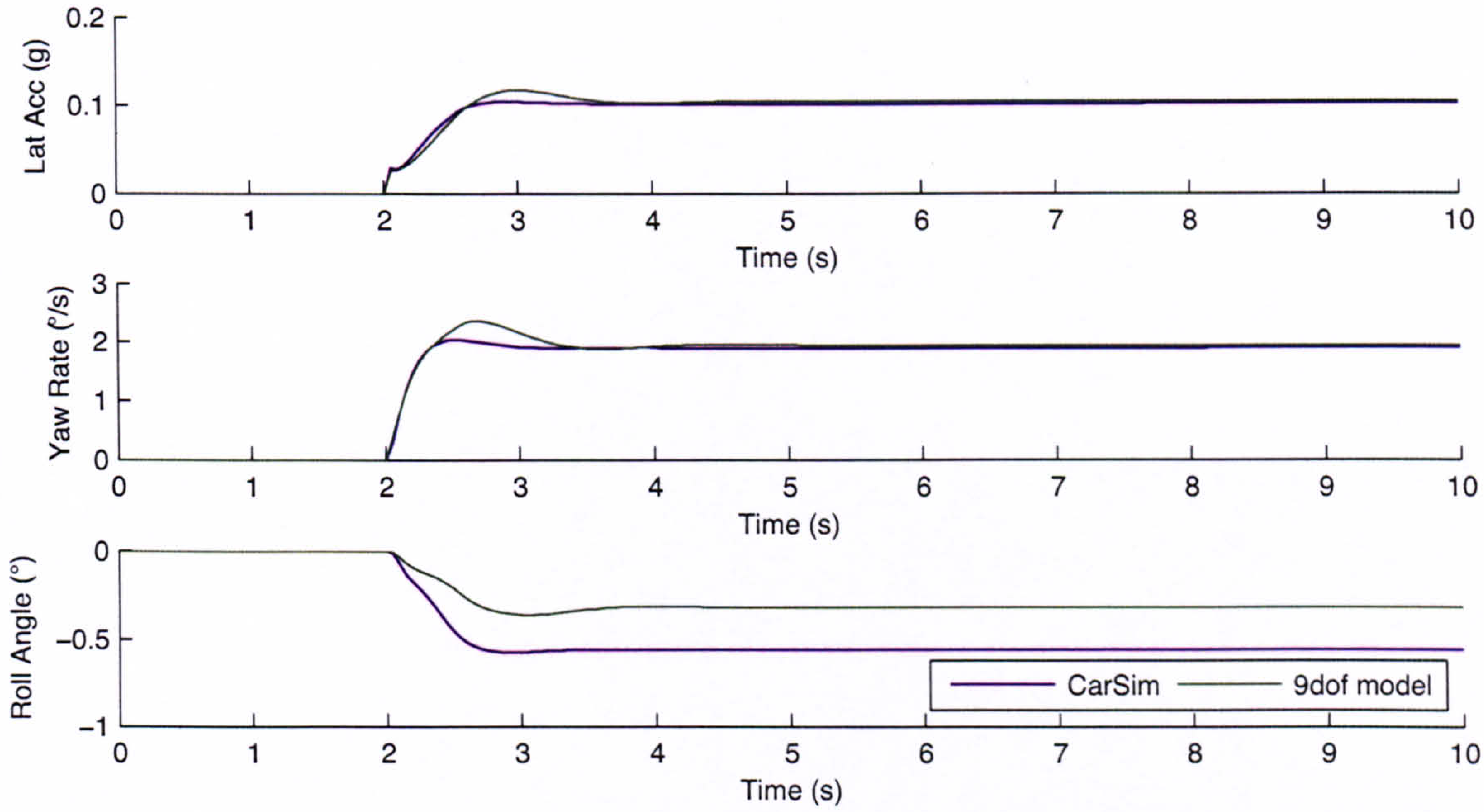


Figure 2.11: 30m/s 0.1g step steer - validation results

models, although this was more apparent in the 9dof vehicle model.

The final step steer simulation replicated a high level of lateral acceleration (0.5g), similar to that experienced in an evasive lane change manoeuvre. This will be investigated in Chapter 4, so again accurate vehicle modelling was required.

The results in Figure 2.12 suggest that this area of the vehicle handling is captured

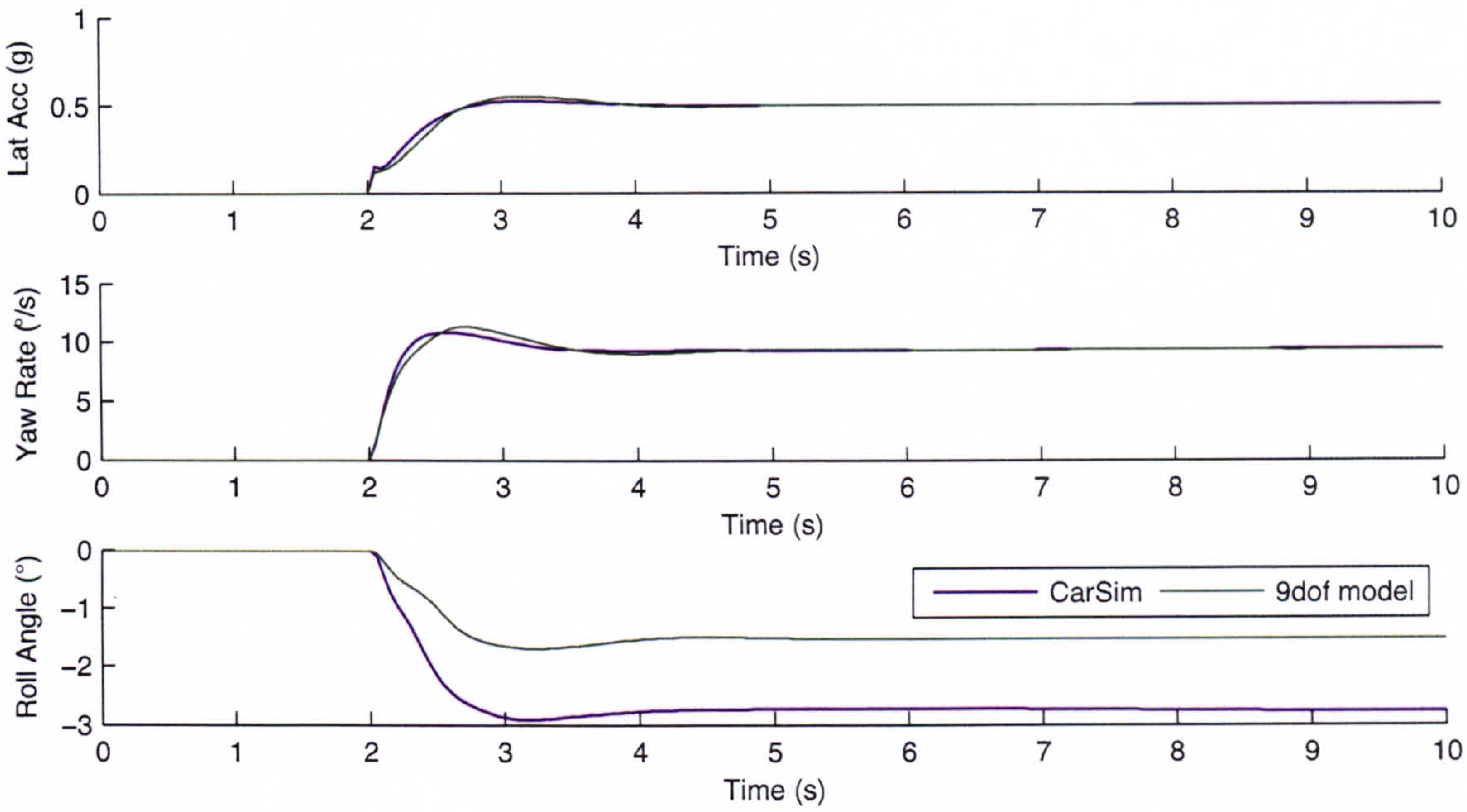


Figure 2.12: 30m/s 0.5g step steer - validation results

excellently. The steady state levels and response times were near identical between models. This manoeuvre reflected the vehicle performance near the limit of linear handling, and suggested that the tyre model and methods used provide a good approximation to this complex behaviour.

Considering the results for all step steer manoeuvres, it can be seen that the correlation of results seemed to improve as speed is increased. At lower speeds the 9dof model demonstrated more overshoot and oscillation in its response. This may be due to the methods used to calculate slip ratios. As u tends to zero, Equations 2.4 and 2.10 become unstable, making them impractical for applications where the vehicle needs to accelerate from rest. While it was not thought that this would impact on the vehicle at speeds of 10m/s, the reduced stability of the equations, combined with the increased influence of the tyre relaxation length at these low speeds, may produce a more oscillatory response. Other methods of calculating slip ratios proposed in Bernard and Clover (1995) and Genta (1997) were employed in the driving simulator (Section 5.2.2), but for the off-line simulations this was not deemed necessary, due to the high speed of manoeuvres.

While the step steer manoeuvres provided a good means of assessing the transient response of the model, they failed to fully capture the fixed frequency response of the vehicle. For this a sine wave steering profile was used, involving a 0.2g sine steering input at 0.25 Hz with a vehicle speed of 20m/s.

Considering the results of the test shown in Figure 2.13 it can be seen that there is

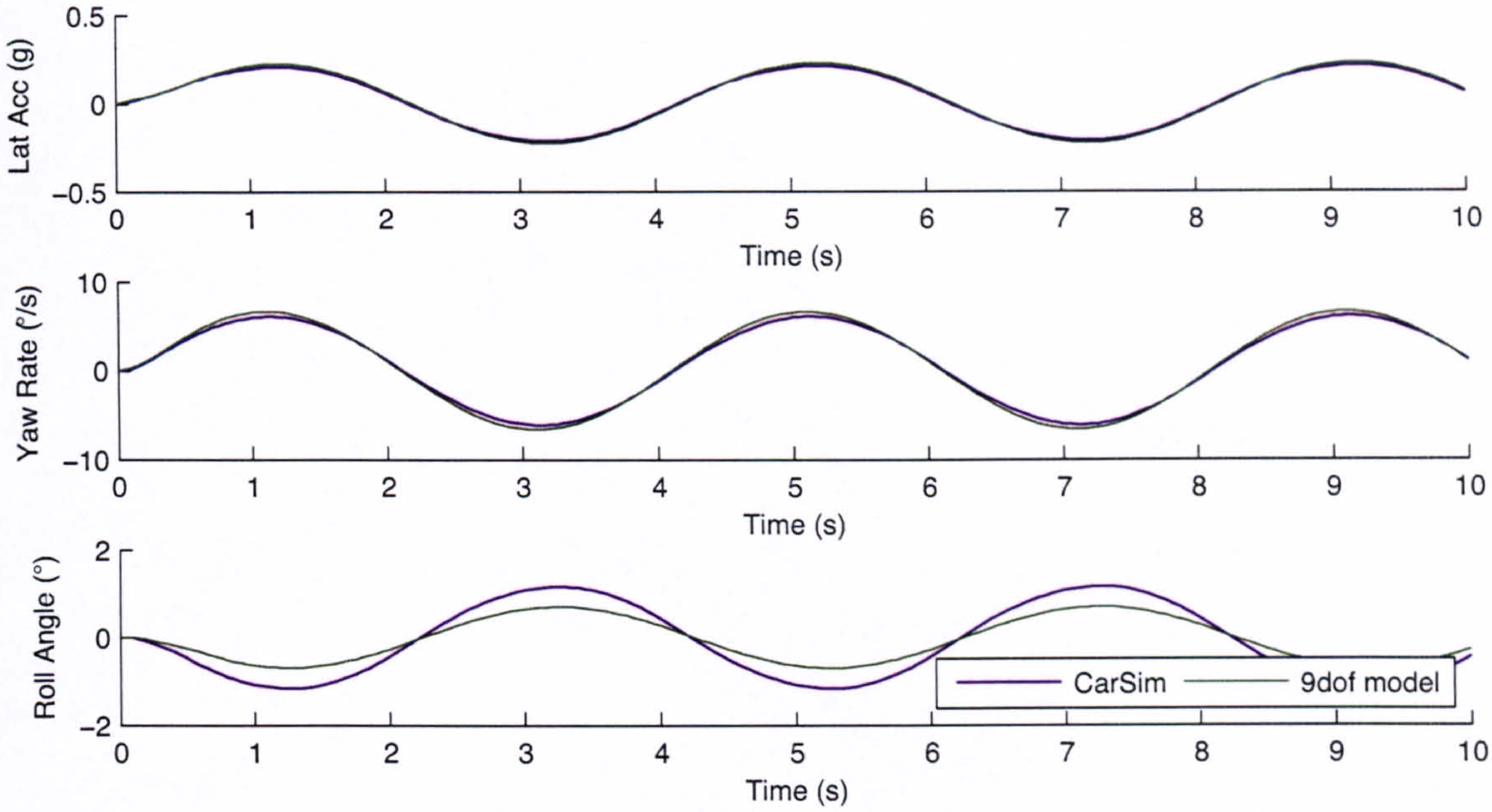


Figure 2.13: 30m/s 0.3g sine steer - validation results

very little difference between modelling techniques. The amplitude, and lag of responses were near identical.

Longitudinal Behaviour

To validate the longitudinal behaviour of the model, the powertrain model to be used in the simulator was removed, therefore allowing the response of the fundamental equations behind the model to be compared. The version of CarSim® used did not have powertrain modelling capabilities; instead driving and braking torques were applied directly at the wheels. In the 9dof model a simple controller was used to generate the required torque.

The straight line performance of the vehicle was investigated using an acceleration and braking event. During these events the main concern was with the pitch response of the vehicle.

Both acceleration and braking tests displayed very similar results (the only difference between the two was the front to rear ratio in which the torques are applied), and so the results are discussed together. Considering the acceleration traces in Figure 2.14 and 2.15 it can be seen that the CarSim® model generated a perfect step response at 2s. The 9dof model displayed a more damped response, which does not settle to the steady state value as quickly as the CarSim® model. This was caused by the controller used to generate longitudinal torque as it tried to match a desired velocity profile. Given the slight difference between inputs to the models the results show an excellent degree of correlation.

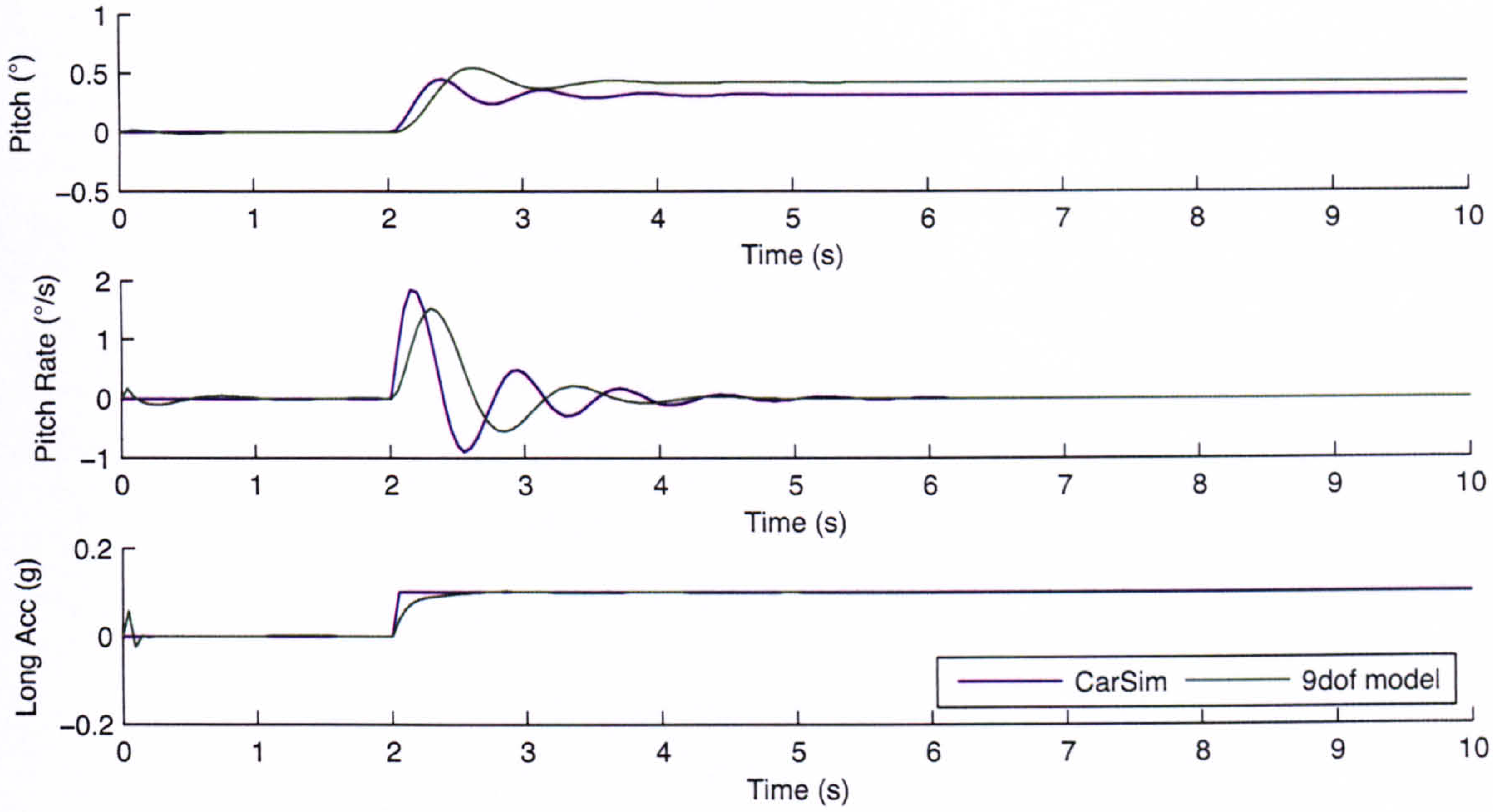


Figure 2.14: 10m/s 0.1g straight line acceleration - validation results

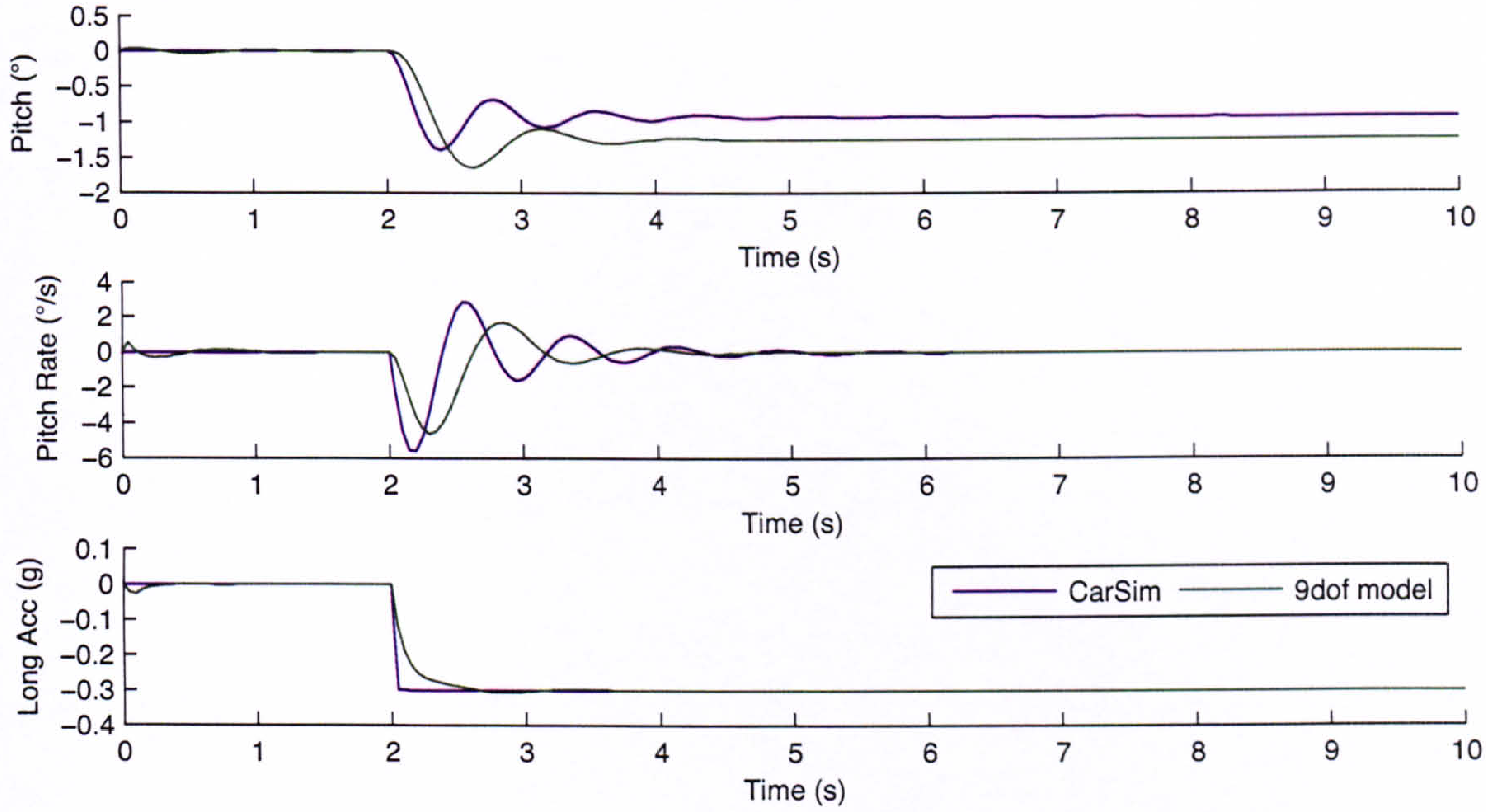


Figure 2.15: 30m/s 0.3g straight line braking - validation results

The steady state pitch angle of both models was proportional to the lateral acceleration although slight oscillation was noticed in the transient region of the response, due to the less than critical level of pitch damping of the vehicle. This was more pronounced in the CarSim® model as a result of the instantaneous nature of the torque application. The same can be seen from the pitch rate response, as both models appeared to take a similar time to settle back to zero, but the maximum rate experienced was large in the CarSim® model. The initial oscillation noticed in the 9dof model was caused by the influence of the speed controller. These oscillations were allowed to subside before any input was given to the model.

Combined Lateral and Longitudinal Behaviour

For certain simulations the vehicle will generally be performing a combination of lateral and longitudinal accelerations, which may have an effect on each other. For this reason it is vital to consider both types of motion in conjunction. This can be performed by a cornering lift-off simulation. Initially the vehicle was subject to a relatively high g step steer input at 30m/s. Once steady state cornering was reached, an engine braking event was simulated by applying a negative torque at the front wheels.

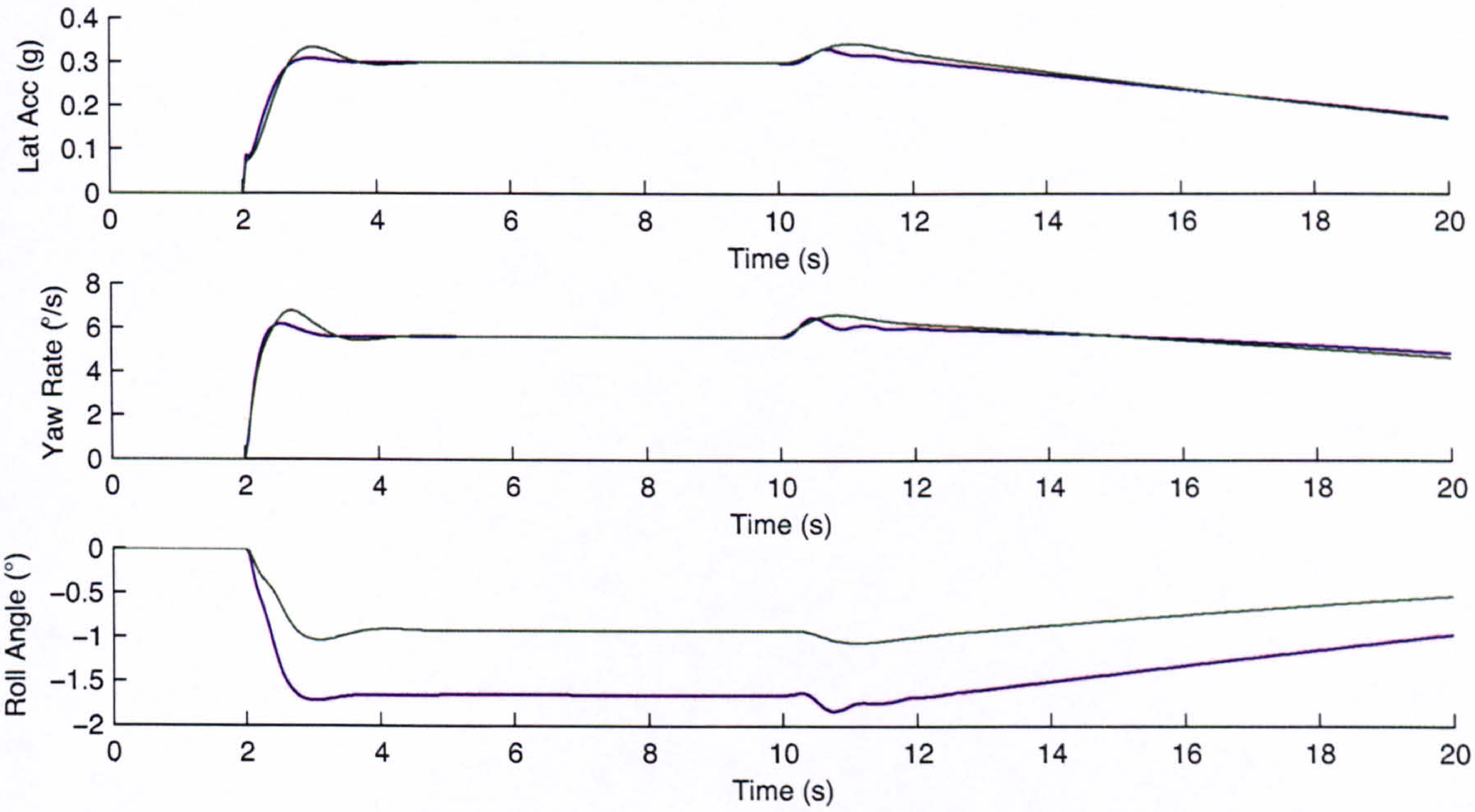


Figure 2.16: Cornering lift off - lateral validation results

The results shown in Figure 2.16 show the lateral behaviour of the vehicle models to such an event. The CarSim® model again displayed less overshoot than the 9dof model suggesting that it was more stable. This may be related to the damping present in the tyre model used. The CarSim® model also displayed a more oscillatory response after the braking part of the event was instigated. It is unclear what caused this prolonged oscillation but it is thought that it may be to do with the ability of the CarSim® model to generate instantaneous accelerations compared to the control torque response of the 9dof model. Apart from these issues the results of the two models were comparable. The lateral acceleration response was very similar once the initial overshoots were overcome. The longitudinal response shown in Figure 2.17 is similar to that experienced in the pure longitudinal tests as expected.

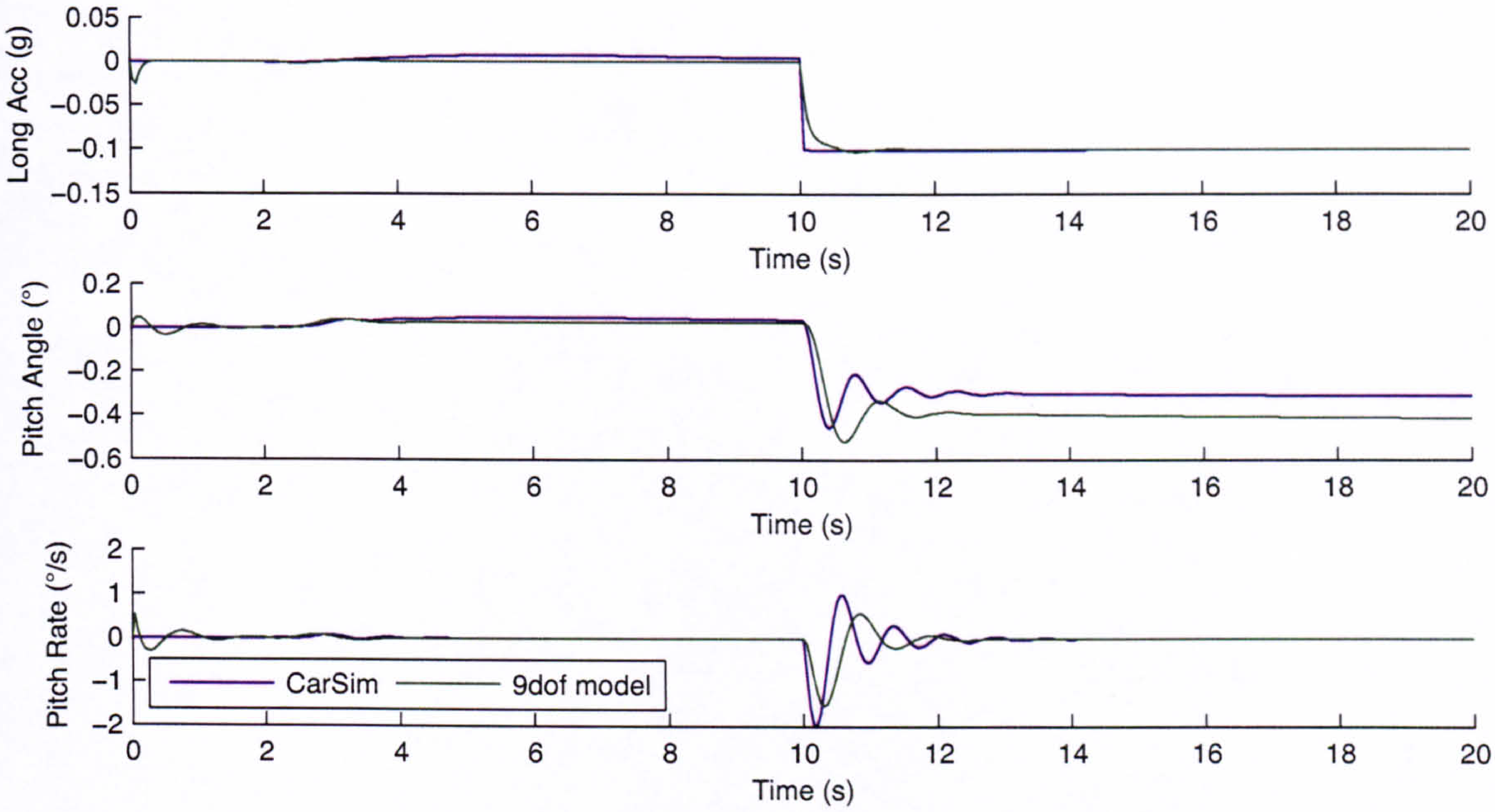


Figure 2.17: Cornering lift off - longitudinal validation results

Some of the vehicle parameters could have been tuned to reduce the oscilatory nature of the 9dof model's results, including roll stiffness and roll damping. While this would have produced results more inline with that of the CarSim® model, it is not to say that these results would have been any more correct. The CarSim® model may have misrepresented nuances of the vehicle that were considered in the 9dof model. Given the general similarity of the results, it was decided to use the inital set of vehicle paramters for all further experimentation.

Validation Conclusions

The main purpose of the research conducted in this chapter was to construct a vehicle model capable of capturing the performance of a vehicle for the full range of conditions that an ADAS system could be subjected to. These range from low and medium g acceleration and braking events, to the on-centre lateral behaviour and higher lateral acceleration scenarios of similar severity to that of an evasive lane change. When results from the 9dof vehicle model were compared to those from an industry standard software package, only minor differences were discovered:

- Generally there was a good correlation between models for both longitudinal and lateral motions.
- Lateral response was more oscillatory at lower speeds with the 9dof model, due to tyre model and slip calculations. This does not effect the success of this research, as we are more concerned with the high speed performance of the vehicle.
- High speed responses were more similar, with less overshoot generated by the 9dof model.
- The longitudinal performance of both methods was again similar. Differences noticed can be put down to the differing torque control methods of the two models.
- Combined lateral and longitudinal motion also showed good correlation.

Chapter 3

Longitudinal Control

Chapter 3 discusses the development and testing of longitudinal control systems. The fundamental headway control part of an ACC is initially investigated at a detailed level, isolated from the influence of other components. For the first time in the field, the performance of the system and its effects on the vehicle dynamics are considered in adverse environmental conditions. Initial findings from this work were presented at the SAE World Congress 2005 (Auckland et al. 2005). The system is made adaptive with the integration of a set speed control, to explore how the performance of the full system would translate through the vehicle dynamics, and back to the driver. Testing of the system is performed using a wide range of manoeuvres, to fully capture possible scenarios that the system may be subject to during motorway driving.

The first type of Advanced Driver Assistance Systems (ADAS) that are investigated in this research are those that control the longitudinal behaviour of the vehicle. Section 1.4.1 detailed the functions of these systems, and investigated the current state of the art. Conclusions from this earlier work have shown that critical factors which may impact on the control system, and its interaction with both the vehicle and driver, have been underdeveloped. It is the aim of this research to tackle some of those issues.

This chapter looks at the development of an Adaptive Cruise Control (ACC) system, that will play the part of our longitudinal control system. Initially the control is considered at a detailed level, where it is tuned, and its performance assesssed using the range of vehicle models developed in Chapter 2. The influence of external disturbance sources (i.e. surrounding traffic), are simplified to allow us to focus on the basic control logic.

The same tuned algorithm is then investigated in a more extensive traffic environment. Here enabling and disabling of the ACC are considered, as well as the impact of the surrounding vehicles on the system. This section also details the modifications that are necessary to integrate the controller with the UoLDS.

3.1 Detailed Controller Design and Analysis

Longitudinal control is a crucial part of the automated vehicle roadmap, and many systems are now available on production vehicles. The current state of the art of longitudinal control is discussed in detail in Section 1.4.1, with reference given to systems which are in production, and available on current vehicle models. Many of these commercial systems are based on algorithms which have not yet been published, but there are still a large number of longitudinal control theories available in the literature from academic sources. For the purpose of this research it was decided to use one of these academic algorithms and investigate its impact on the vehicle dynamics.

The most common type of longitudinal control for passenger vehicles is Adaptive Cruise Control (ACC), as it is a single vehicle solution that can be added as an option to production vehicles at relatively low cost (though not for after market sales). ACC systems are usually installed on vehicles as an extension to the basic cruise control system, that has been common on many vehicles since the 1980s. There are many factors which impact on the safe and successful operation of the ACC, including the methods in which the system is enabled and disabled, and how it switches between speed control and headway control. These topics are investigated in detail in Section 3.2, but for now only ACC operating in following mode (simple tracking of the vehicle in front) will be considered. This allows us to develop a well tuned algorithm without the interference of other traffic factors. The impact of the crucial component of any ACC system can then be investigated, to provide a good platform from which to develop a fully integrated ACC solution.

3.1.1 Controller Design

With many published algorithms available, it was decided to use the one developed in Ioannou et al. (1993) as it was based on two simple principles, which could easily be adapted to work well with a range of vehicles. Ioannou et al. (1993) has also been referenced by numerous research publications, which suggests it is a well respected piece of work. The simple nature of the system meant that any results obtained would show the system's impact on the vehicle dynamic performance, without the added influences of complex control logic.

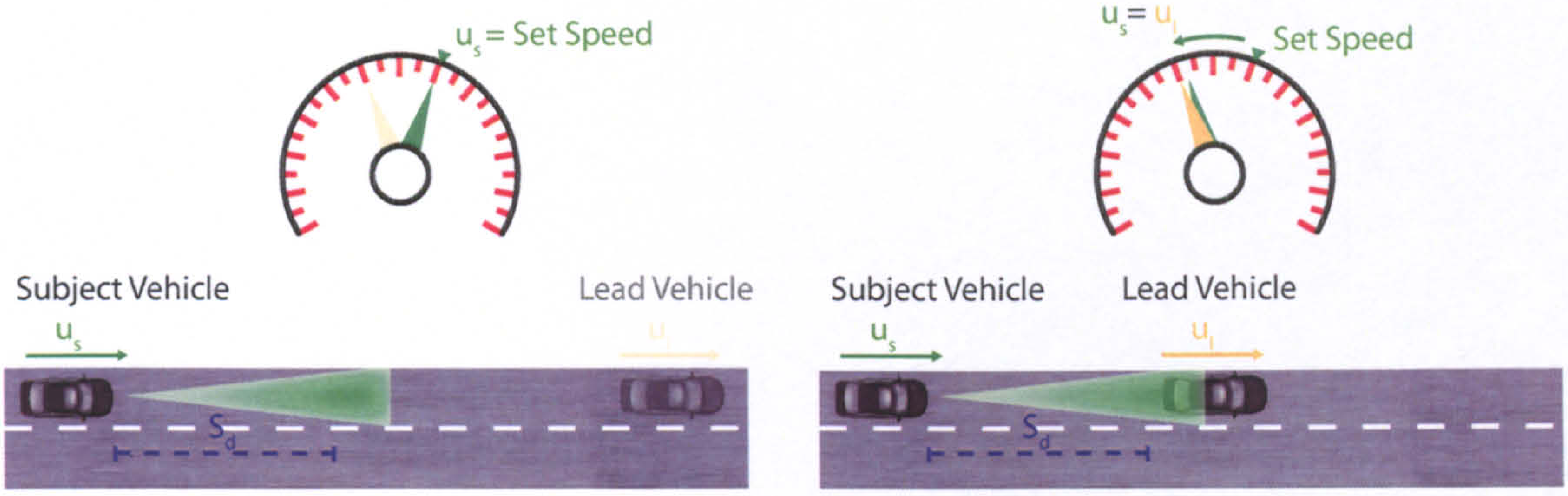


Figure 3.1: Longitudinal control description

Figure 3.1 identifies the key components of the longitudinal control system at this level of detail. The subject vehicle is the one under control of the system, whereas the lead vehicle provided the input to the system. The core part of the control logic from Ioannou et al. (1993) was used to actuate this control. It consisted of two control objectives or principles:

1. To keep the desired vehicle spacing (headway) S_d
2. To ensure similar lead and subject velocities

Two secondary control objectives were given, to ensure the ride comfort requirements of the driver are met:

- The maximum levels of acceleration and deceleration applied by the system should be no greater than and 0.1g and 0.2g respectively.
- The absolute value of jerk should be as small as possible.

These objectives can be defined by the following equations, where h_w is the desired time gap between vehicles, and the subscripts $_l$ and $_s$ denote lead and subject vehicles.

$$S_d = h_w u_s \tag{3.1}$$

$$u_l = u_s \tag{3.2}$$

$$-0.2g < \dot{u}_s < 0.1g \tag{3.3}$$

$$\ddot{u}_s \rightarrow 0 \tag{3.4}$$

A simple fixed gain PID method was developed to work with the the control logic taken from Ioannou et al. (1993). This meant that models of the complex powertrain and braking systems were not required. Instead the ACC system directly controlled the amount of torque applied to each axle. The non-linear relationships required to model the powertrain and braking systems were beyond the scope of this initial research, as the dynamic performance of the vehicle is more important than the intricacies of the controller. The acceleration limits were set by limiting the amounts of torque that the control system could demand from each axle at any given time.

The radar used in the ACC system was also simplified for the purpose of these preliminary tests. It was assumed that the sensor functioned without problem, and could provide the controller with the lead vehicle's velocity, at a rate equal to that of the simulation time step.

With knowledge of the speeds of both the lead and subject vehicle (obtained from wheel speed sensor or similar), the following control equations were derived, where T_{out} is input to the vehicle model:

$$T_{sp} = K_{Psp}(u_l - u_s) + K_{Dsp}\frac{d(u_l-u_s)}{dt} \tag{3.5}$$

$$T_h = K_{Ph}(x_l - x_s - h_w u_s) + K_{Ih}\int(x_l - x_s - h_w u_s)dt \tag{3.6}$$

$$T_{out} = T_{sp} + T_h$$

Gains K_{Psp} and K_{Dsp} provide control to maintain the same vehicle speed, and gains K_{Ph} and K_{Ih} and provide inter-vehicle spacing control. Intergral speed control is not required as it is equivalent to proportional headway control. Derivative inter-vehicle spacing control is not required as it is equivalent to proportional speed control. This inter vehicle spacing is termed headway and can be referred to as the distance or time between vehicles. In this research we consider headway in the time domain, as a fixed time headway allows the distance between vehicles to vary with speed, reducing distances between vehicles at low speeds, and allowing longer safe braking distances at higher speeds. Much research has been conducted into acceptable levels of headway, for manual and automated driving including Hoedemaeker and Brookhuis (1998). For these systems to be commercially successful it is important that drivers are comfortable with the levels of headway used by the system, too close and they may feel unsafe, too long and they may disable the system. Some systems have variable settings for headway so that the driver can choose a setting they are comfortable with. It is hoped to include this feature into this system, but for now we will use a headway setting of 1.5s. This level is deemed acceptable for motorway driving (ISO/FDIS 2002).

3.1.2 Control Tuning

In order to provide accurate and stable control, it was important that the gains were tuned to the specific vehicle data-set to be used throughout the range of simulations. The six gains used in the system would require significant permutations to investigate possible solutions. Due to the simulation time required with the detailed 9dof model, it was decided to begin tuning using the simplified 3dof vehicle model. This model was populated with the same vehicle data-set to be used throughout all the simulations. The benefit of reduced simulation time, was that results could be viewed quicker than real time. Results from these simulations could then be used as the basis for tuning the full 9dof model.

Before tuning was undertaken, it was important to consider the performance characteristics that are desirable for an ACC system:

- Comfort
    - Levels of acceleration and jerk generated by the system should be minimised.
    - Oscillatory accelerations should be avoided.
- Safety
    - Actual headway should remain at, or above the desired level.
    - The system should not generate positive acceleration to regain the desired headway, when the lead vehicle is travelling slower than the subject.

Given the maximum deceleration of the system was set to 0.2g, a scenario was set up where both the lead and subject vehicles were initially travelling at 70mph (31.3m/s) with a constant time headway of 1.5s. The lead vehicle then decelerated at this maximum level for 2s. Initial tests were conducted to find a rough set of gains; sufficient enough to prevent collision and ensure vehicle stability. The gains were then finally tuned iteratively using the 9dof vehicle model. Results from these tuning tests are presented and discussed in this section. Concern was raised over the necessity of the speed control part of the system; surely if the headway part of the control system worked successfully then the speed of the subject vehicle would have to match that of the leader to maintain this gap. With this in mind, an initial set of simulations was run to monitor the effect of increasing $K_{P_{sp}}$ from zero to double K_{P_h}. Results are shown in Figure 3.2 for the tuning manoeuvre described above. With low $K_{P_{sp}}$, the headway between the two vehicles was reduced by up to 0.05s.

While this may appear to be only a slight deviation from the desired value, it compromised the safety of the subject vehicle, and at higher speeds and deceleration levels the effect may be increased. This is caused by the systems slow reaction to the deceleration of the lead vehicle, as the initial headway change was only calculated through integration of the lead vehicle's velocity signal. With increased influence of the speed control, the subject vehicle was able to react to the change in the lead vehicle's velocity more quickly. This can be seen in the longitudinal acceleration trace, where by the increased K_{Psp} gave a more pronounced acceleration. This would also lead to more jerk being experienced which may be uncomfortable for the driver. This quick response actually leads to increased headway during the manoeuvre, which improved the safety margin, also positive acceleration was not required to regain the desired headway setting.

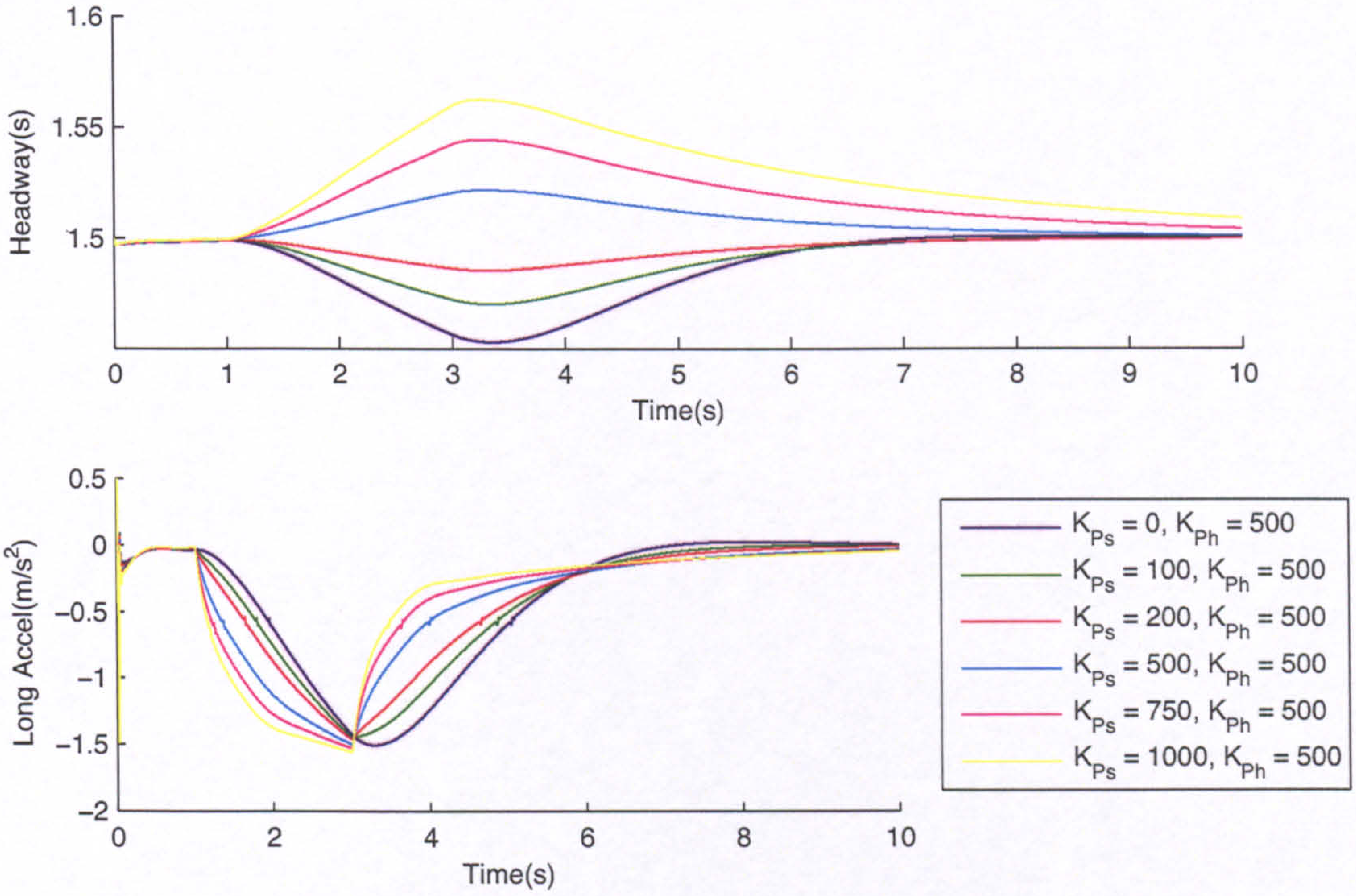


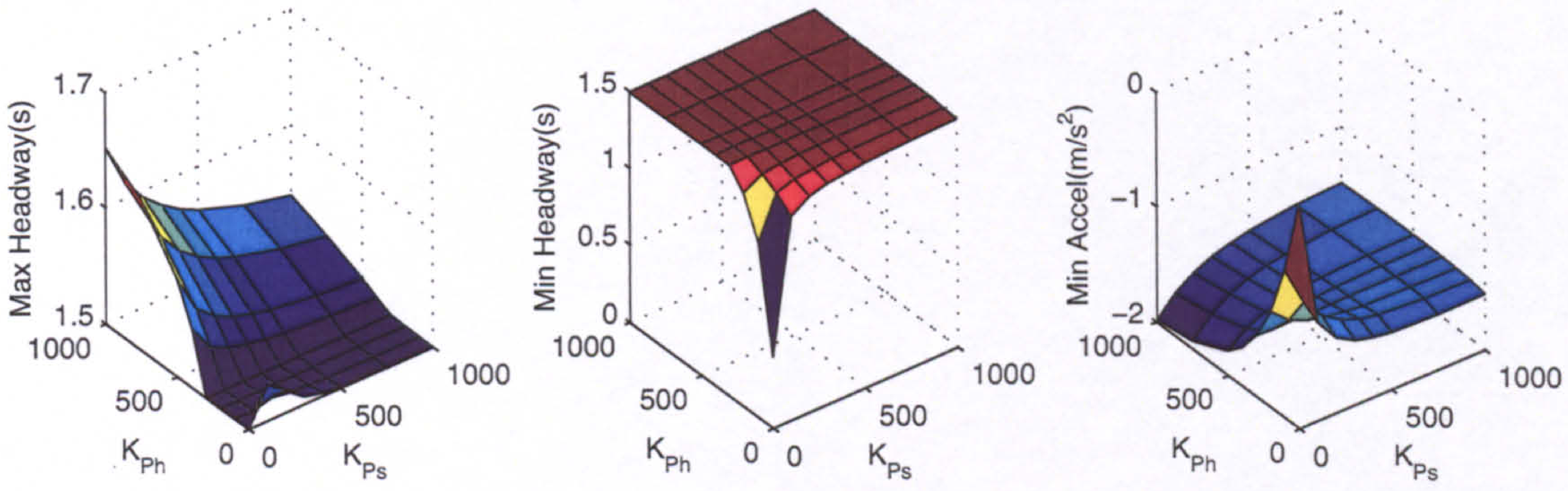
Figure 3.2: Influence of speed control on control objectives

Given the two control laws governing the system, the tuning problem was more complex than that of a Single Input Single Output (SISO) system. While this research was not concerned primarily with control tuning, it was necessary that the system was tuned effectively to maximise the system's potential. With this in mind, a simple logical approach was taken. It was decided to run a batch of simulations where the influences of K_{Psp}(for now referred to as speed control) and K_{Ph} (headway control) were varied over a wide range. Given 14 values of each K_{Psp}, and K_{Ph}, 196 simulations were required to formulate a 'map' showing the effects of each for a given metric. Again, the tuning manoeuvre described previously was used. Three metrics are chosen to best summarise the controllers performance, the results of which are shown in Figure 3.3.

Max Headway demonstrates to what extent the system deviated from the desired headway, increasing the safety margin. Ideally the value should remain at 1.5s but slight increases are tolerable.

Min Headway demonstrates to what extent the system deviated from the the desired headway, low values reduce the safety margin. Any value below 1.5s is undesirable.

Min Acceleration demonstrates the minimum acceleration (maximum deceleration) experienced. This relates to the comfort levels perceived by the driver. Ideally this should be as close to zero as possible, but obviously a certain level must be attained to change the velocity of the subject vehicle.



(a) Max Headway (b) Min Headway (c) Min Acceleration

Figure 3.3: Surface plots of the influence of K_{Psp} and K_{Ph} on control objectives

The maximum headway shown in Figure 3.3a depends highly on K_{Ph}, at low gain levels the maximum headway was acceptable at 1.5s, but as the gain was increased (>300), this maximum headway increased. While this would not compromise the safety of the system, it is preferable to track the desired headway throughout the manoeuvre. Larger maximum headway can be related to a slow response of the system, and the deceleration of the subject vehicle may be unnecessarily transmitted to other following traffic. With K_{Ph} at a low value, an increase in K_{Psp} caused a slight increase in maximum headway, as the controller reacted quickly to the change in lead vehicle velocity, but overshot the desired headway causing this increased maximum headway. As K_{Psp} was increased beyond 500 this subsided.

Figure 3.3b shows the minimum time headway experienced during the simulation. At low gain levels this dropped below the acceptable threshold of 1.5s, affecting the safety margin of the subject vehicle. With both gains set at levels of 200 and above the desired safety margin was regained. The minimum acceleration experienced during the manoeuvre is displayed in Figure 3.3c, and should ideally be as close to zero as possible. This was the case for low K_{Psp} and K_{Ph} but only because the system did not react quickly enough, causing undershoot of the desired headway. As K_{Psp} was increased, this level of acceleration decreased (became more severe) and plateaued at -1.5m/s^2. Increases in K_{Ph} caused the severity of the acceleration to increase at a faster rate than K_{Psp}, as this speed control element reacted to the change in lead velocity. Maximum levels of K_{Ph} yielded higher levels of severity than those experienced with maximum K_{Psp}. These higher levels of deceleration suggest higher jerk levels, and a more uncomfortable experience for the driver.

Following these tests, K_{Psp} was set at 200 and K_{Ph} at 300. These levels are the lowest values at which all desired control objectives can be met. For this initial tuning test there was little, or no steady state error experienced in either the headway, or subject vehicle velocity, leading to no intergral control component (K_{Ih} = 0). There was also little or no oscillatory response experienced in these simulations. This may have been due to the simple powertrain and brake models allowing torques to be generated quickly. With this in mind, initial derivative control values were also set to zero (K_{Dsp} = 0). Both intergral and derivative gains were reconsidered when integrated with full powertrain and brake models, but for this initial work they were simply unnecessary. Torque output from the controller was limited to prevent acceleration levels outside the desired range.

3.1.3 Test Scenarios

With a simple ACC system tuned to provide effective performance, a range of test scenarios were required to investigate the system's impact on the dynamics of the vehicle. The extensive literature review in Section 1.4, highlighted a number of possible issues with the longitudinal control systems that have not been fully investigated in previous research. These issues form the objectives of the initial tests as detailed in the list below.

- Investigate the effect of different environmental conditions on the headway response and stability of the vehicle under control.

- Examine pitching behaviour of the vehicle under ACC operation and its impact on driver comfort.

- Assess the performance of the ACC system when cornering, and its impact on the handling of the vehicle.

Simple simulations were set up to tackle these issues. All simulations only considered the lead and subject vehicle, other traffic was disregarded. For the purpose of all simulations, it was assumed that the lead vehicle was not equipped with an ACC system. It was therefore able to generate accelerations larger than the subject vehicle. At the start of each simulation, both lead and subject vehicles were travelling at 31m/s (70mph), with a constant time headway gap of 1.5s (46.5m at 31m/s).

Environmental Conditions

As discussed earlier there is some inconsistency in the acceptable range of environmental conditions in which ACC systems can be used. The radar systems used have been tested in rain and foggy conditions and have shown favourable results (Russell et al. 1997). But little research has been carried out to investigate the effects of these conditions on the vehicle when under the influence of these systems. For this reason, it was decided to investigate ACC system performance through a range of environmental conditions, characterised through coefficients of friction μ, given in Table 3.1, for the pure rolling case. As the tyres are the vehicle's only means of transmitting lateral and longitudinal forces to the road, these coefficients play a crucial role in the level of performance achievable by the vehicle.

This may seem a trivial result, especially from a vehicle dynamics point of view. When the surface co-efficent of friction is 0.2 the maximum acceleration the vehicle can achieve is 0.2g. This research aims to consider not only the vehicle dynamics issues but also the human interaction with these controllers. It is entirely possible that drivers may assume that ADAS may improve the acceleration capabilities of the vehicle, they may therefore trust it to perform in situations beyond the vehicles limits. From this point of view it is interesting to see how the system's perform in these scenarios. In these tests the acceleration limits are low due to the capabilities of the system but we will return to this idea of environmental conditions later in the thesis.

Table 3.1: Surface coefficients of friction (Khatun et al. 2002, Sakai and Hori 2000)

Surface	Co-eff of friction
Dry Asphalt	0.85
Wet Asphalt	0.4
Icy or Snowy Road	0.2

The lead vehicle was subjected to a range of decelerations from -0.5m/s^2 to -2.0m/s^2, and the subject vehicle's headway and velocity performance were monitored.

Comfort Impacts

Currently ACC systems are marketed as a comfort aid, rather than a safety device. When using ACC, driver workload is reduced (Iijima et al. 2000), but the comfort levels of the driver depend not only on their workload, but also the accelerations experienced. For this reason, the pitching behaviour of the vehicle was investigated, as well as the longitudinal acceleration and jerk, to measure any differences between the unlimited response of the vehicle, and that of the vehicle with an ACC system.

In the test, the lead vehicle decelerated at 3m/s^2 for 4s after which time the resultant speed (21.3m/s) was maintained. A control case was set up where the subject vehicle was equipped with an unlimited ACC system.

When limited with ACC, the vehicle was unable to maintain an acceleration of 3m/s^2 (without driver intervention), and so it was thought that the system may cause undesirable accelerations to be passed to the driver, as it tried to cope with this exceptional input.

Operation While Cornering

While the longitudinal performance of the system was considered in the previous tests, it was also necessary to look at the effects of ACC on the cornering of a vehicle. Given the ACC system is a purely longitudinal control device, any lateral control of the vehicle must be performed by the driver (or other control system). Any change in longitudinal speed of the vehicle caused by an ACC system, will have a direct effect on its lateral response. These effects are investigated in the following tests.

From the International Standard for ACC (ISO/FDIS 2002), the minimum bend radius around which the system should work is a curve of radius 125m. While this was deemed too tight a corner for usual motorway driving, radiuses approaching this can be found on rural and urban roads. Both the lead and subject vehicles were given a constant speed of 31m/s (70mph) to simulate high speed driving. The steer angle was then found with which the subject vehicle followed a path of radius 200m (equivalent to an extremely tight corner). Simulations were then undertaken to demonstrate the subject vehicle's lateral and longitudinal performance when the lead vehicle accelerates or brakes through the curve. The path tracking performance was observed, as well as the effect on vehicle roll accelerations, which have an adverse effect on the level of comfort perceived by occupants.

3.1.4 Analysis

Environmental Conditions

The first set of tests concerned the impact of environmental factors on the controller and vehicle. Results are shown for these tests in Figures 3.4 - 3.7. For this and proceeding analysis, the simulations were conducted using the full 9dof vehicle model,but again the complex effects of the powertrain or brake systems were not modelled.

Results for the three coefficients of friction (μ) are shown on the same axis to allow direct comparison of their effects. Results for the low acceleration manoeuvres (± 0.1m/s^2) are summarised by Figures 3.4 and 3.5. It can be seen that at these low levels of acceleration, the performance of the system was not affected by the surface friction. The longitudinal acceleration and headway response of the system were near identical for all three μ conditions. This was because the longitudinal force required to generate the desired longitudinal acceleration was achievable in all conditions. There was no excessive wheel slip, as the torques demanded by the control system were relatively low. The slight peaks noticed at 2.5s and 3.5s were caused by the switching of the controller between simulated engine braking and the hydraulic braking system.

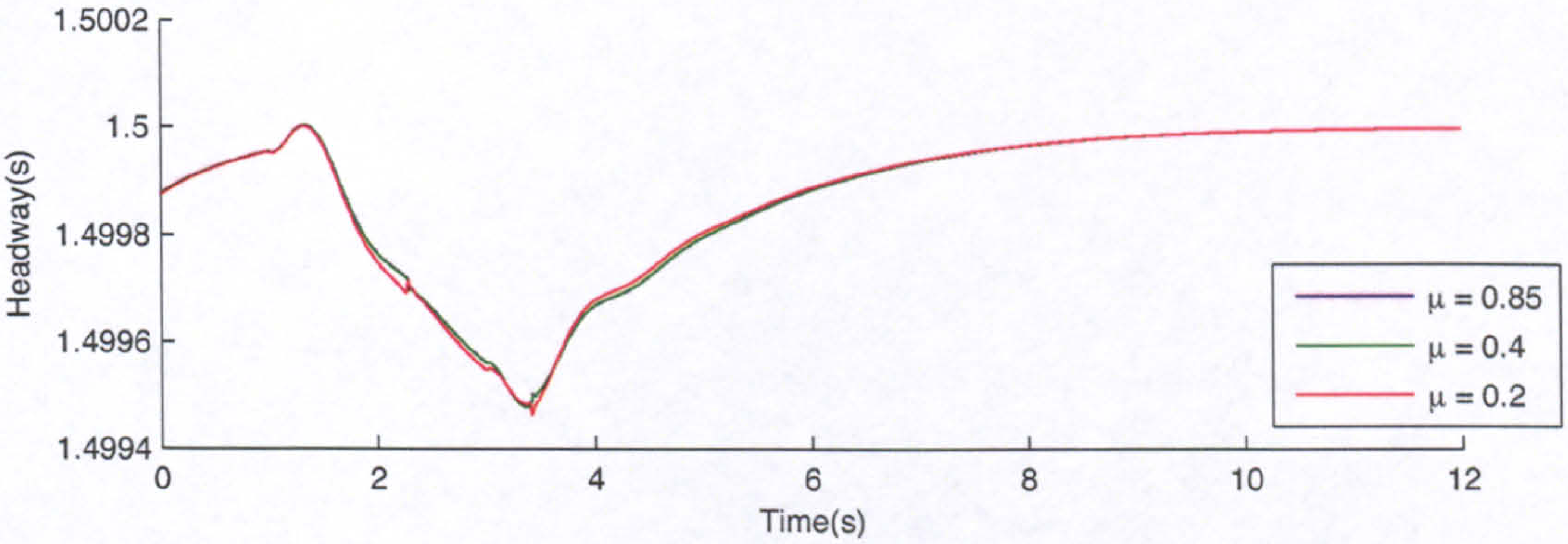


Figure 3.4: Headway response of the ACC system to low accelerations

The controller's performance was tested at higher levels of lead vehicle deceleration, results from these tests are shown in Figures 3.6 and 3.7. It can be see that in dry and wet conditions, the vehicle was able to generate sufficient traction to maintain a desired level of headway. In icy conditions, even though the sensor system would work without problem, the vehicle was not able to maintain the desired level of headway. Initially (1-2s) the headway was acceptable at 1.5s, but as time increased the vehicle was unable to generate the desired level of longitudinal acceleration and the headway dropped to 1.4s. This may appear an insignificant undershoot but it has serious implications for the vehicle,

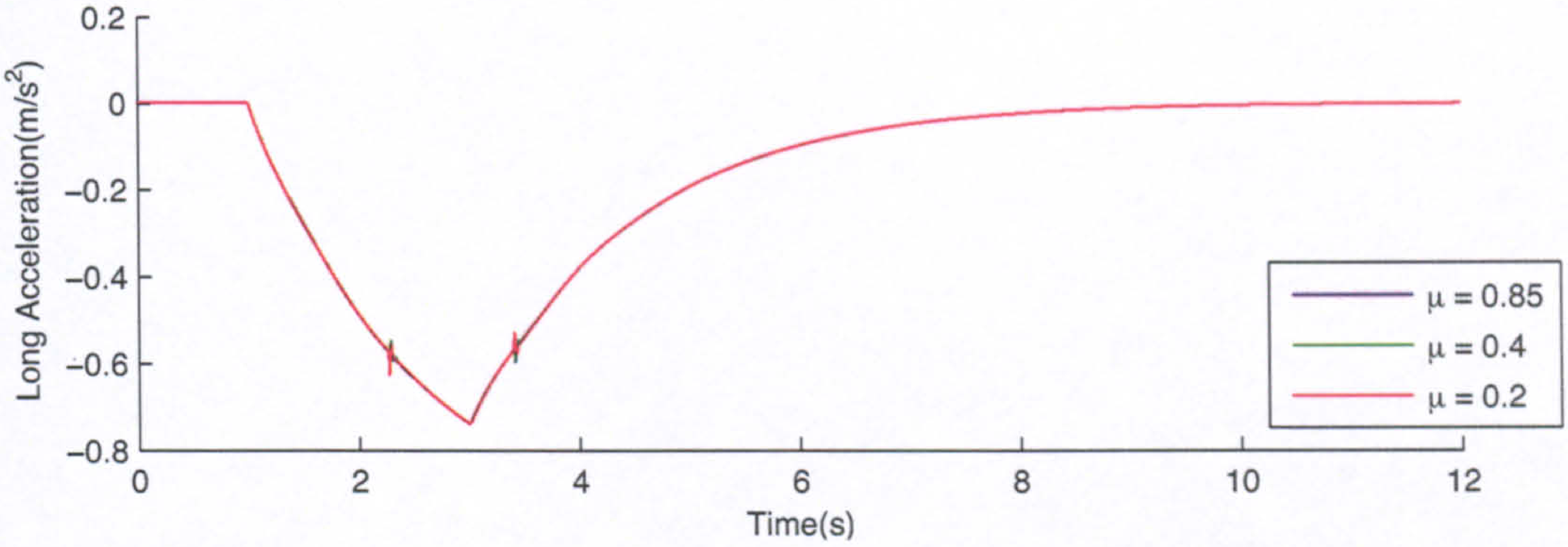


Figure 3.5: Longitudinal acceleration response of the ACC system to low accelerations

as the safety margin has been reduced to a level lower than that expected by the driver. This would be exacerbated at higher speeds, with lower headway settings. As the lead vehicle stopped decelerating, the subject vehicle was able to increase its headway to the desired level of 1.5s, but it then overshoots and continues in this oscillatory trend until settling within 1.49-1.5s in 30s.

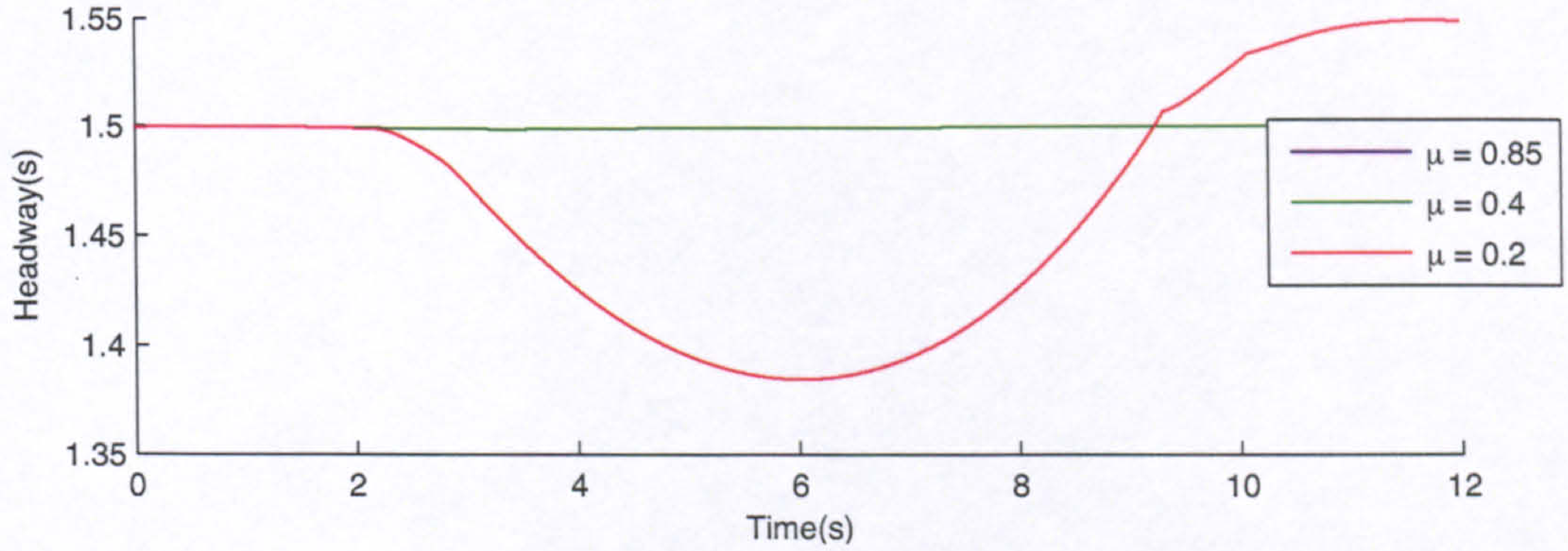


Figure 3.6: Headway response of the ACC system to 0.2g accelerations

This oscillatory behaviour was caused by the vehicle's inability to generate the required longitudinal forces and apply them to the road. Looking at Figure 3.7, it can be seen that in icy conditions, the vehicle maintained the same longitudinal acceleration profile as the other conditions, even after the brakes were applied (shown by the small spike at 1.5s). At about 2s the vehicle was unable to generate the larger longitudinal acceleration required as the front wheels 'lock up' with the increased brake torque applied. Some longitudinal acceleration was still achievable, through forces generated by the rear tyres. The front wheels remained locked until 9s, as the brake torque is increased in an attempt to slow the vehicle. This problem would be helped by the addition of an Anti-Lock Braking System (ABS), which as the wheel begins to lock, would momentarily reduce the brake torque, allowing the wheel to spin and generate longitudinal force, before again applying brake torque. This type of ABS system rapidly repeats the process over a short period of time, which generates an uncomfortable judder, often passed to the cabin and occupants. ABS is only usually required in safety critical events, and its use in this scenario may promote a lack of trust in the ACC system. The integration of the two systems requires further investigation, especially with the development of stop and go ACC systems that will operate over the full range of vehicle speeds.

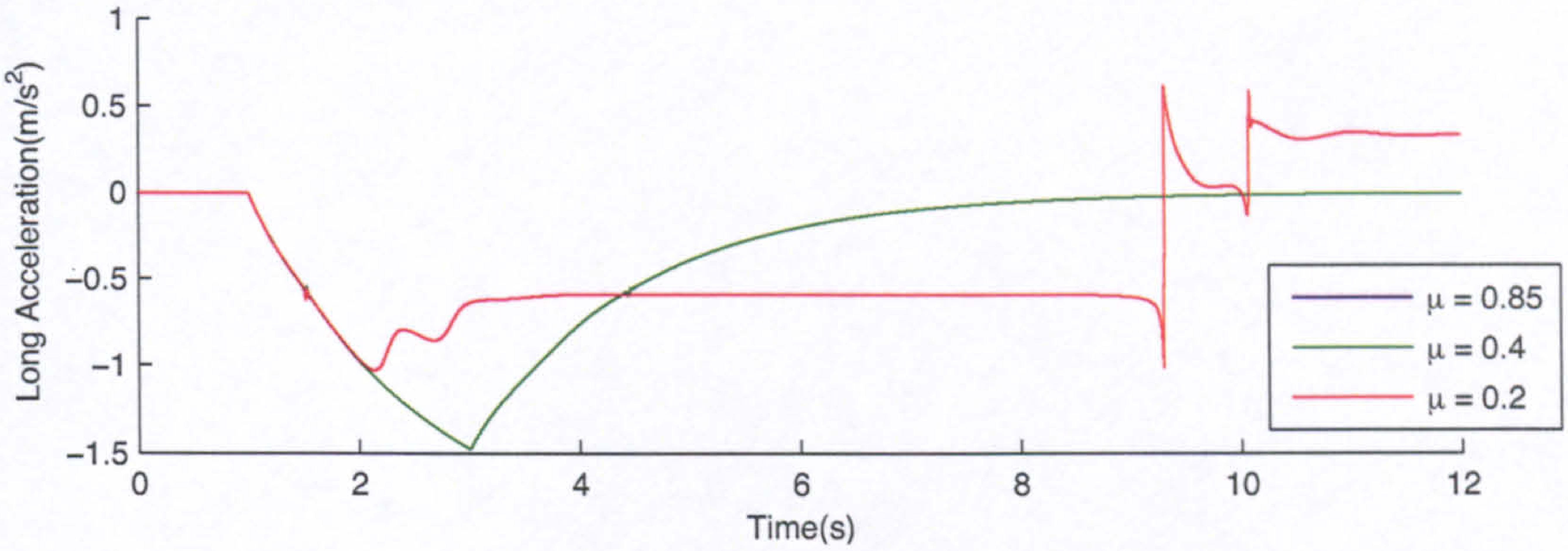


Figure 3.7: Longitudinal acceleration response of the ACC system to 0.2g accelerations

The headway begins to increase as the lead vehicle maintains a constant speed (after 6s), from this point the applied brake torque is reduced, allowing the front wheels to rotate, generating some braking force (which actually slightly slows the vehicle). As the headway reaches 1.5s, the controller applies drive torque to the front wheels, which causes the large spike in acceleration, as the sign of the acceleration of the vehicle changes direction. This would result in a large, if short lived, jerk which would be uncomfortable for the driver. This acceleration was quickly reduced, as the wheels began to slip and generate substantially reduced longitudinal drive forces. As the subject vehicle speed increased the drive torque was reduced, until wheel slip was reduced to a normal level (about 10s). This allowed larger longitudinal forces to be generated and again jerk would be perceived as the longitudinal acceleration of the vehicle was increased. The vehicle continues with this trend as the headway error oscillates about zero. These accelerations and jerks would obviously have an negative impact on the driver's comfort throughout the event.

It should be remembered that this simulation encompasses a rare and unusual situation. It is unlikely that drivers will be travelling at high speeds with small headway's in icy conditions. But when we consider that many novice drivers may not be aware of the available grip levels, and they may have enhanced trust in the system (believe it is more capable than it is), the situation becomes more plausible. As a human factors issue the response of the system to this kind of situation is valid and interesting, where as the vehicle dynamics element of the test is more obvious and less interesting.

Comfort Impacts

In the second set of simulations, the pitching performance of the vehicle was investigated by forcing the subject vehicle to react to a lead vehicle deceleration of 3m/s^2 (just beyond the controller's limits). A control case was also set up, to replicate human driving, where the limits were removed from the control system, allowing the control subject vehicle to achieve the acceleration level of its leader. It was thought that the jerks involved as the controller reached its limits would translate into uncomfortable pitching accelerations. Looking at the headway response in Figure 3.8, it can be seen that the limited ACC system caused a larger undershoot than the control system in the desired level of headway, but both still remained within an acceptable 0.01s.

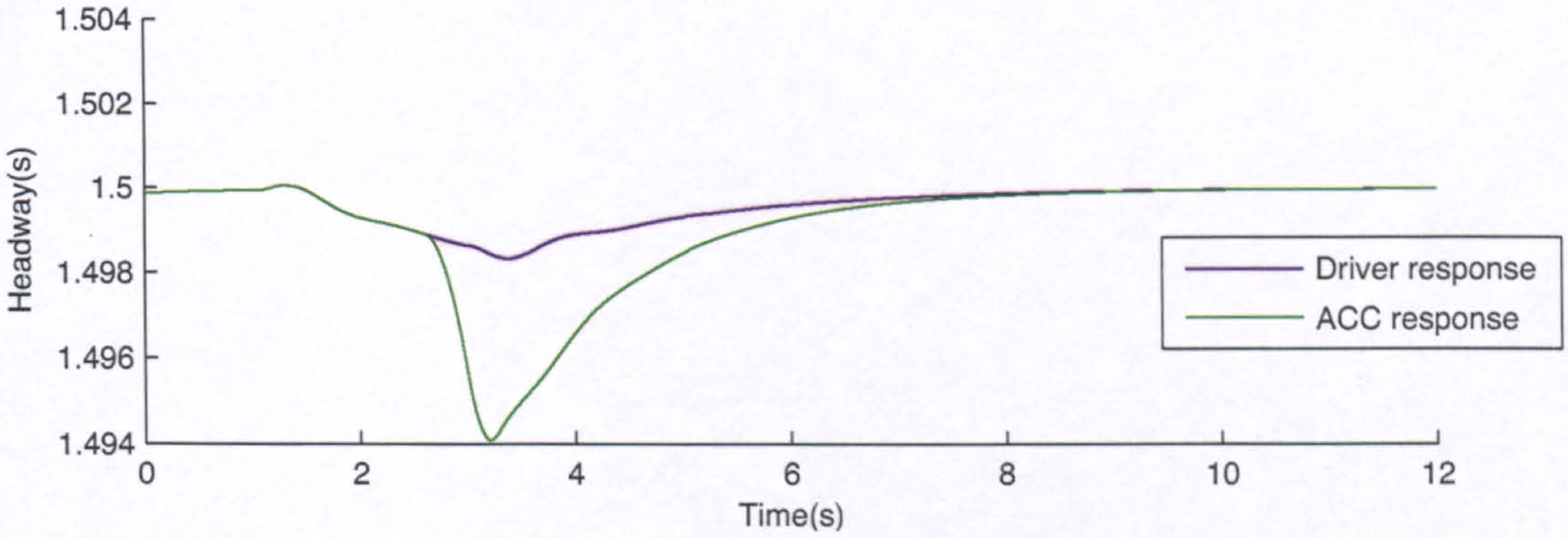


Figure 3.8: Headway response of the ACC system to out of range accelerations

The effects of the acceleration limits were more apparent in the acceleration profile shown in Figure 3.9. Here it can be seen that the ACC vehicle was limited to -2m/s^2, and while the control vehicle did not reach the 3m/s^2 of the lead vehicle, the limit was enough to cause the undershoot in headway noticed in Figure 3.8. The limits were controlled by limiting the amount of torque that the controller could demand, through both the drive and braking systems.

While these limits may cause additional longitudinal jerks to be experienced by the vehicle, it was unlikely that their magnitudes would be larger than those experienced in the uncontrolled vehicle. This was validated by the pitch accelerations shown in Figure 3.10. In the ACC enabled vehicle, it was noticeable that there were more peaks in acceleration. These occur as the system reached its limit and again, when the acceleration was reduced

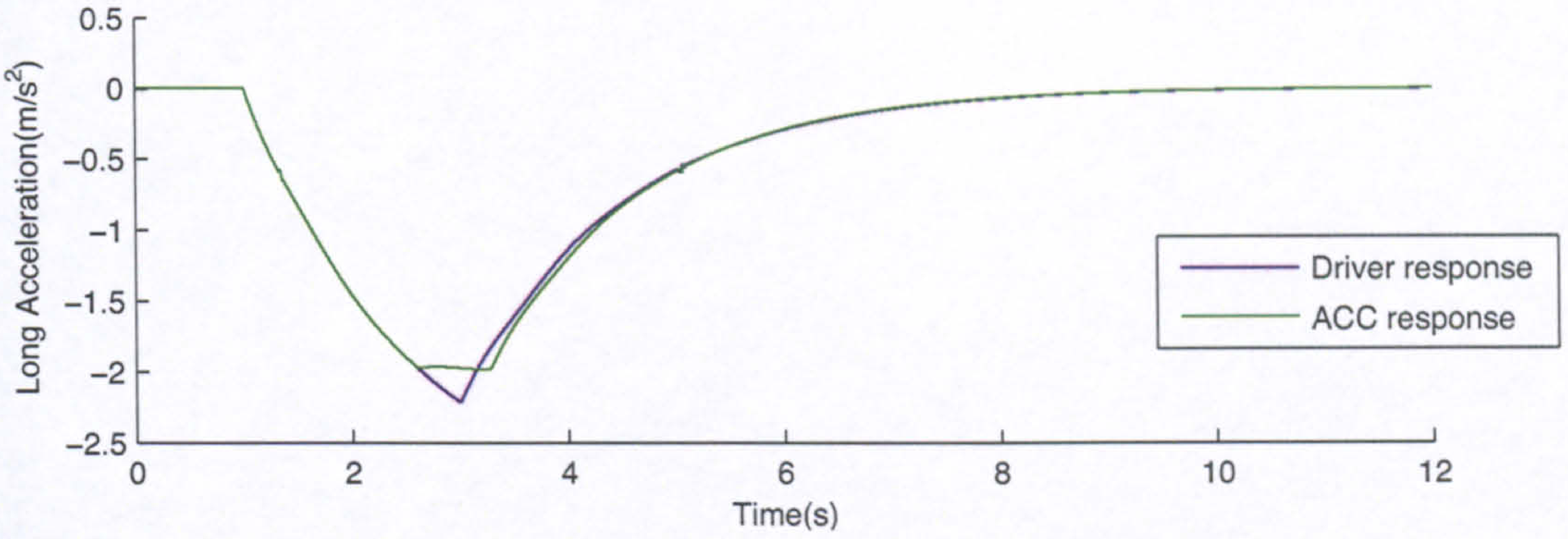


Figure 3.9: Longitudinal acceleration response of the ACC system to out of range accelerations

from this level. But these peaks were of a smaller magnitude than those experienced in uncontrolled driving, and were therefore unlikely to cause uncomfortable sensations for the driver. As the pitch accelerations were closely linked to the second time derivative of the longitudinal acceleration of the vehicle, it was fair to say that the jerk and snap (2nd time derivative) of longitudinal acceleration may also be reduced in the ACC enabled vehicle.

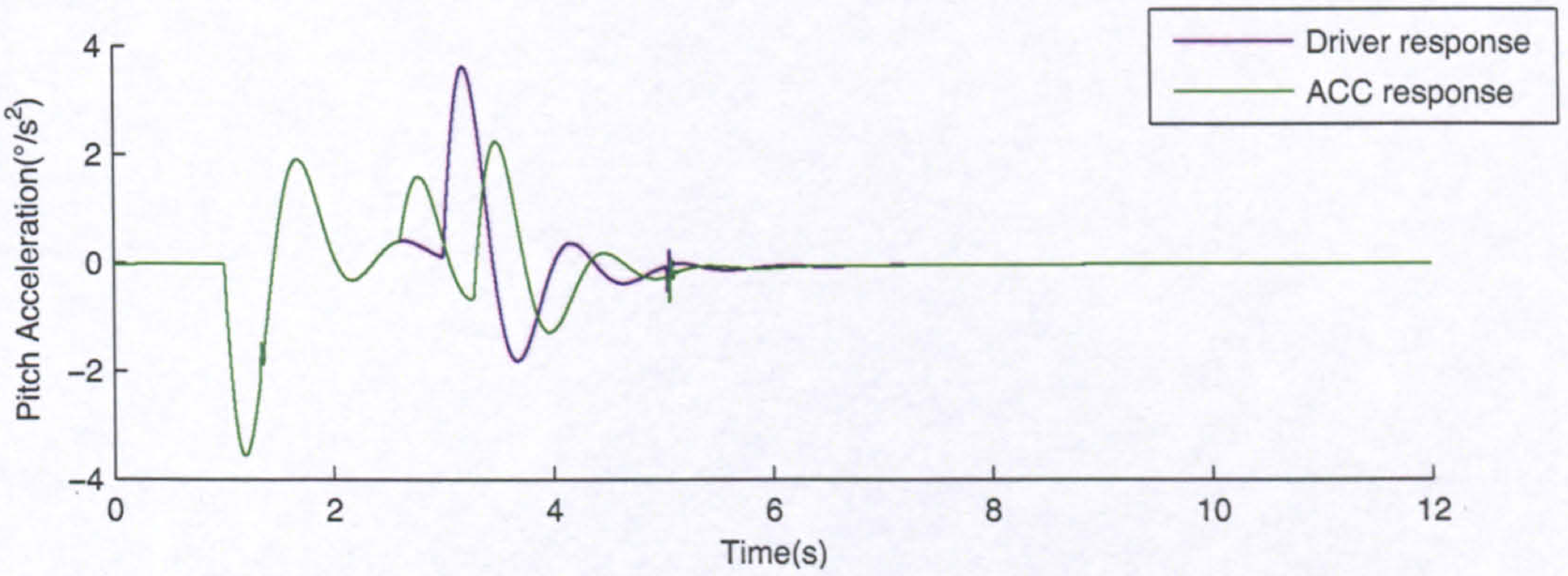


Figure 3.10: Pitch acceleration response of the ACC system to out of range accelerations

Operation while Cornering

The aim of this range of simulations was to investigate the performance of the vehicle around a curve, when its ACC system generated a longitudinal acceleration. We shall consider the effects of the ACC system on the path taken and the levels of roll acceleration experienced by the driver. Looking at Figure 3.11 it can be seen that the desired trajectory of the subject vehicle was significantly affected by the introduction of longitudinal acceleration during the manoeuvre. Whilst the stability of the vehicle was never in question, the lateral position of the vehicle on the road may vary by over 5m at the exit of a 200m radius bend. This error would result in lane departure, unless the driver counteracted the lateral motion caused by the ACC, using either a change in steer angle or longitudinal input (throttle/brake). While this test described was an extreme case (200m radius corners are much tighter than those on UK motorways), drivers could be subject to a similar scenario on less major motorways or rural roads. While it is expected that the driver would intervene, this cannot be guaranteed. It would be interesting to see if removal of one of the control tasks from the driver allowed more concentration on other tasks (steering), or if the driver relaxed more and concentrated less overall. The driver's approach to this event will be investigated further using driving simulation experiments in Chapter 6.

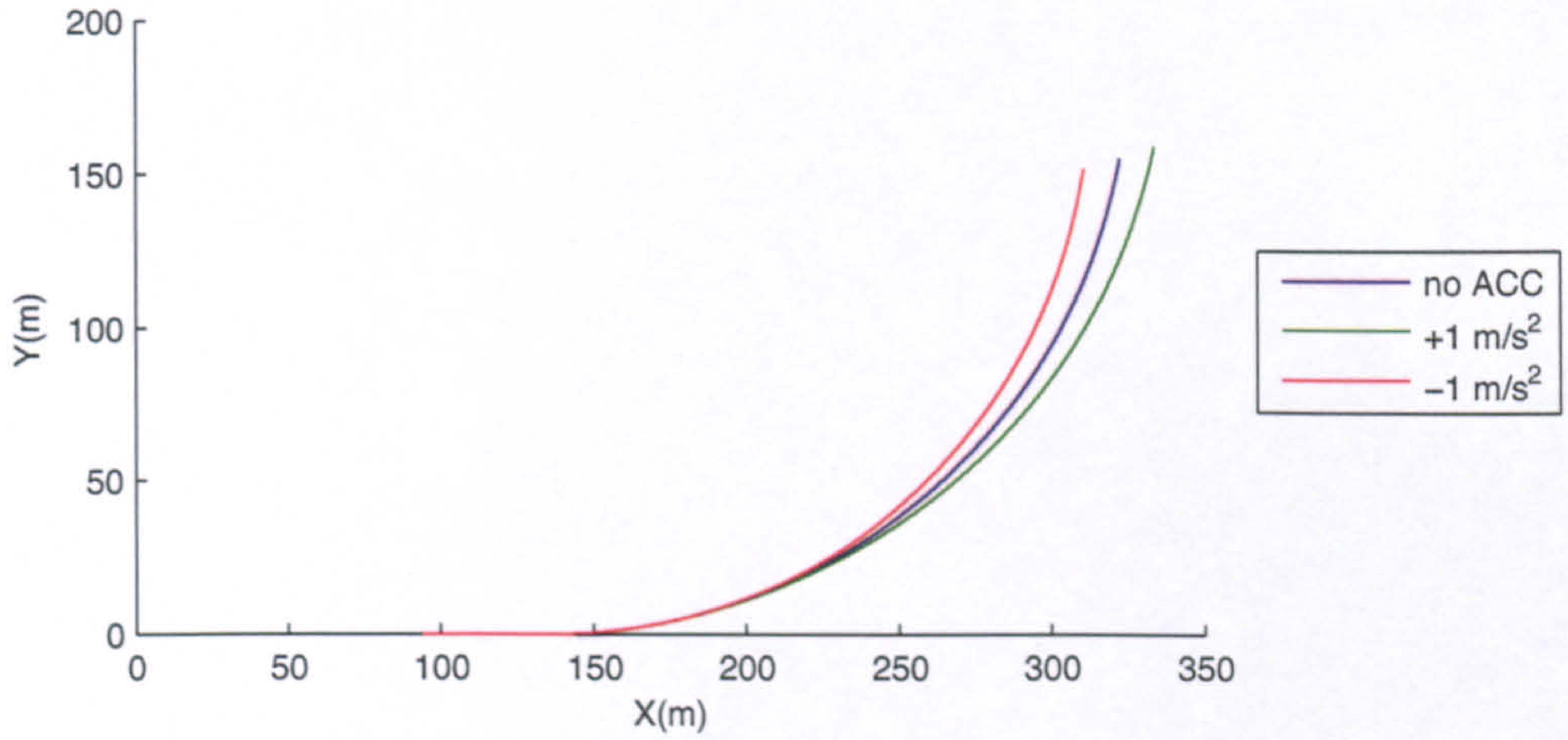


Figure 3.11: Trajectory taken when ACC system caused vehicle to accelerate

The body roll accelerations were monitored throughout these combined lateral and longitudinal accelerations; Figure 3.12 shows that there was little variation in these values due to ACC interaction. The spike noticed at 1s was caused by the step steer input. Little other variation in roll acceleration was noticed at the point where the ACC system causes the vehicle to accelerate (2s). It can therefore be assumed that ACC systems do not cause a decrease in driver comfort levels, due to roll accelerations.

3.1.5 Conclusions

From these initial tests it was possible to draw a number of conclusions about the performance of the ACC system under investigation. Some of these conclusions require further

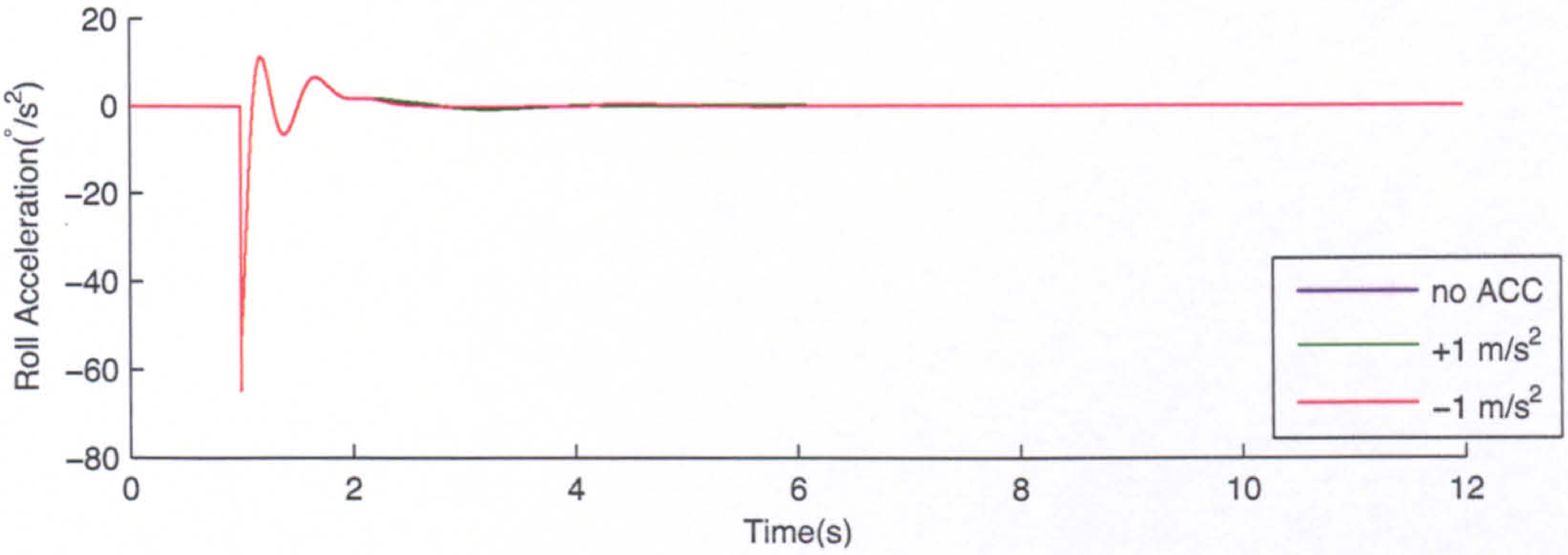


Figure 3.12: ACC effects on roll acceleration

investigation as to their impact on the driver, which is covered in later chapters of this research. These test results have shown that:

- The system was capable of a good performance through both dry and wet conditions.
- The system failed to maintain a desired level of headway in icy conditions due to a lack of available grip, further investigation is required to look at the system used in conjunction with ABS.
- There was no impact on the comfort of the vehicle caused by pitch accelerations with the out of range operation of the ACC.
- The system could cause lane deviation while cornering, if the lead vehicle accelerates/brake, and the subject driver fails to intervene.

3.2 Hierarchal Control Scheme Design and Analysis

With the detailed design of the ACC headway control in place, the focus of the work moved on to the design of the other elements of the control system. This included the standard cruise control element of the system, issues involved when switching between the two modes, and integration of the powertrain model required for successful driving simulator operation. Again, attention was paid to vehicle dynamic issues, and comfort impacts to ensure a driver centred approach was taken at all times, to both the design and implementation of the system.

3.2.1 Integration of Speed Control to ACC

ACC systems are an extension of a conventional cruise control system. For most of the their operational period they behave as a standard cruise control, maintaining the vehicle's speed as set by the driver. Only when a lead vehicle is within a predefined control bound and travelling slower than the subject vehicle, will the system enter headway control mode. Cruise control systems have been on the market since the 1980's and much research has been carried out to ensure their safe operation (Tanigawa et al. 1984). The more interesting question posed by ACC, is when and how to switch between conventional cruise (speed) control and and adaptive (headway) control. While it may at first appear that the speed control element of the ACC could be used to maintain a cruising speed, an additional controller allows the the cruise controller to be tuned for the small errors it will experience, providing a smooth sedate response in cruise operation; compared to the quicker more severe response that may be required from the ACC. We know that the radar system used in ACC can function accurately with headway distances of up to 150m (Abou-Jaoude 2003), but should this be the distance at which headway control begins? Will drivers get annoyed by the car beginning to slow for a vehicle that is over 100m in the distance? The other extreme is that the ACC system maintains speed control (i.e. a constant speed), until the last possible safe opportunity to begin headway control. This would result in a late braking system with higher longitudinal accelerations. This type of system may reduce the driver's confidence in the ACC, as they may want the system to begin to reduce its speed before it does. It may also reduce comfort levels due to increased levels of acceleration, and may even reduce the fuel efficiency of the vehicle.

It is thought that the optimal headway control range will lie somewhere between these two extremes. To discover this optimum range a set of simulations was performed where the lead vehicle speed and headway control range (control bound) were varied to investigate the effects of this range on the headway and acceleration of the subject vehicle.

Before these experiments could be performed the following features were added to the control system.

Cruise (Set Speed) Control A simple PID controller was added, the input of which was the vehicle speed error (given the desired speed), the output was the torque required to minimise this error.

Control Switch An 'if' statement was included which selected either speed or headway control depending on the current headway of the subject vehicle. This threshold is investigated in the following tests.

Control Output Limited When subject speed is greater than the leader speed, torques were limited to negative values to prevent the subject car accelerating, when it enters the control bound defined by the control switch.

Lower Desired Headway For the purpose of these tests the desired headway was set at 1s. In the driving simulator experiments, a range of headway options will be available, so this lower headway is used to highlight any problems that may be caused by its variation.

For these tests the subject vehicle had an initial velocity of 31.3m/s (70mph), this was also set as the desired velocity (set speed). The initial headway was set at 3.0s. So the speed controller would initially be activated and try to maintain the desired 70mph. The lead vehicle maintained a constant velocity of 22.4m/s or 26.8m/s (50 or 60 mph). The subject vehicle was therefore travelling faster than the leader and would reach the control bound, which was varied between 2, 1.5 and 1.2s for each lead vehicle speed. The headway and accelerations results are shown for the more extreme 22.4m/s lead speed in Figures 3.13 and 3.14, and for both speeds in Table 3.2.

Considering Figure 3.13 the effects of the headway bounds are immediately obvious. With a control bound of 2s the subject vehicle decelerated over a period of 12s, gradually decreasing headway to the desired level of 1s. With a control bound of 1.5s the system was also able to achieve the desired headway without undershooting the target. Critically, with the control bound set at 1.2s the system did not have enough time to generate the maximum level of acceleration to prevent the vehicle undershooting the desired headway.

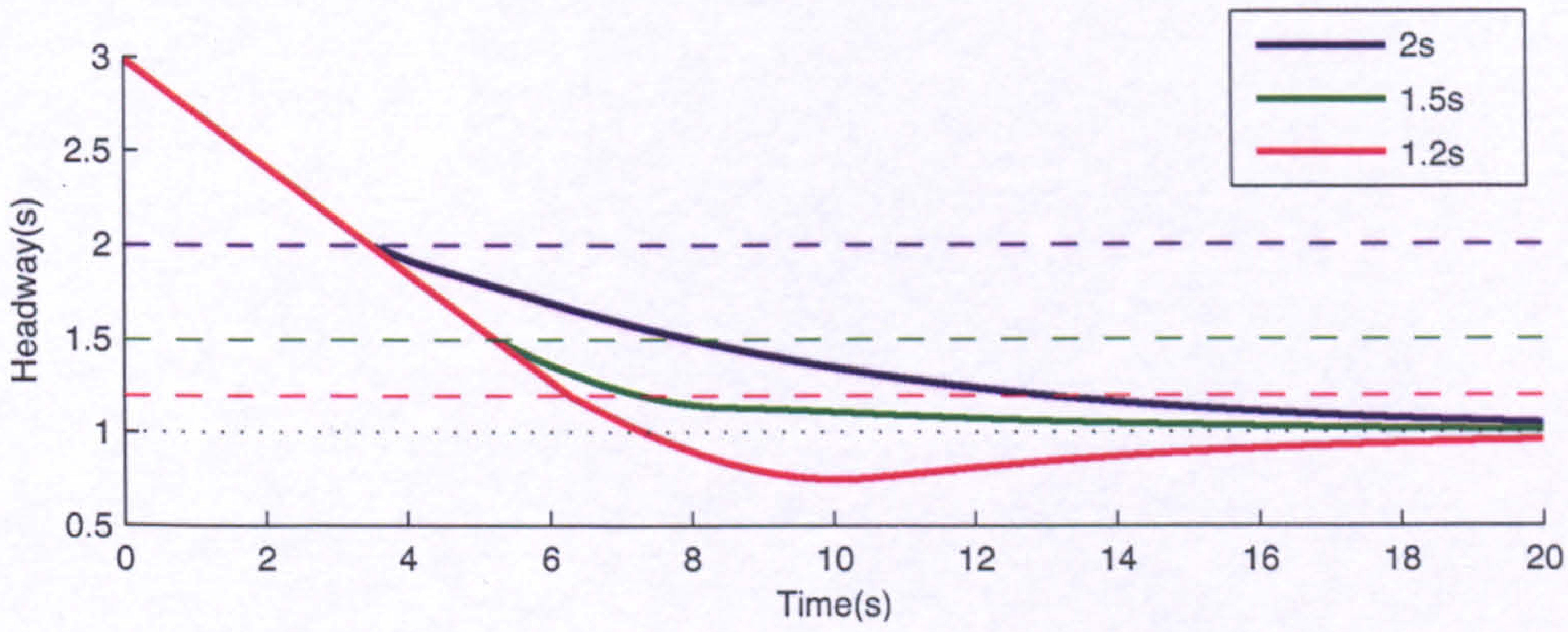


Figure 3.13: The effects of the control bound on the headway of the vehicle

The acceleration response of the system is shown in Figure 3.14, as expected the larger the control bound the earlier the acceleration began. What is more surprising is that the peak acceleration was the same for each speed. This was due to the acceleration of the system being limited to -2m/s^2. The initial larger spikes were short lived and were generated as a result of the step change in input to the control system. While the magnitude of the acceleration appeared similar between models, its duration was markedly different. With a control bound of 2s the maximum level of deceleration lasted for less than 1s, this was then gradually reduced over a long period. It is thought that the driver may find this long period of acceleration annoying. With a control bound of 1.5s the maximum acceleration was sustained for a longer period ($\approx$3s), but the acceleration returned to approximately zero much more quickly than with a control bound of 2s. These trends were maintained as the control bound was reduced to 1.2s. In fact for this control bound, the acceleration actually became positive (at 13s), due to the undershoot in headway and speed.

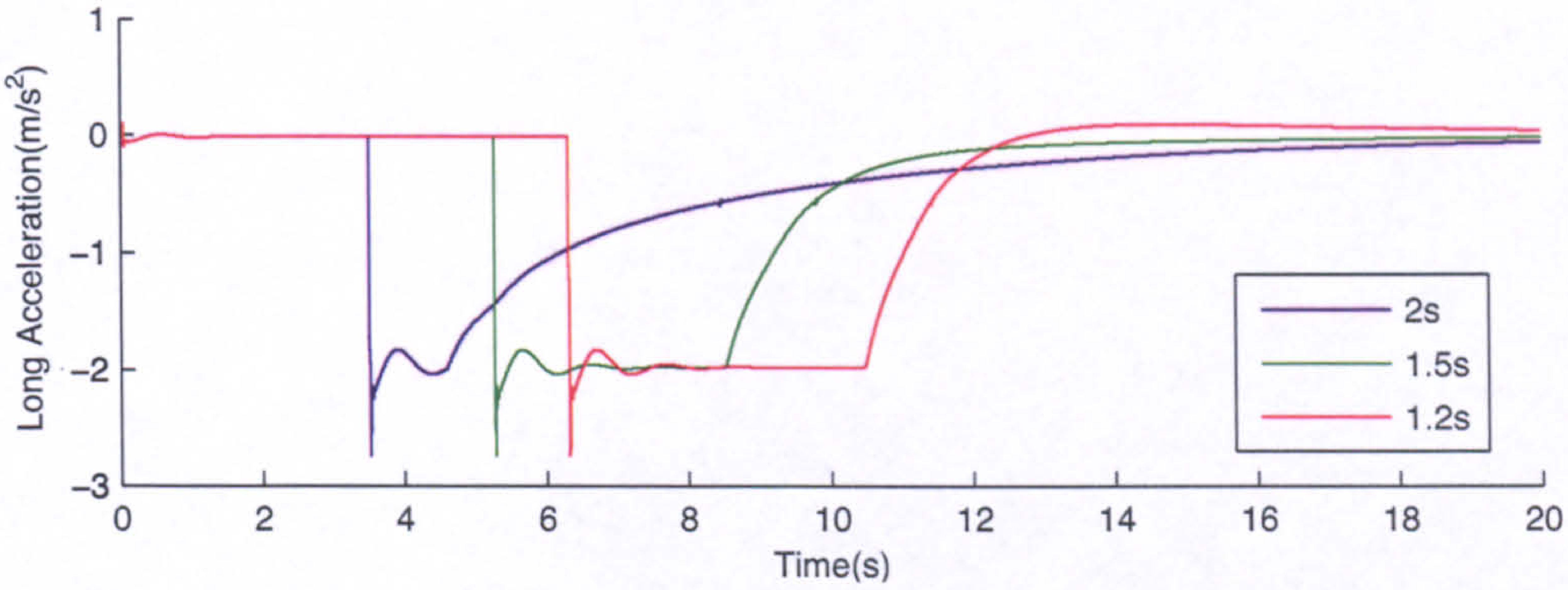


Figure 3.14: The effects of the control bound on the longitudinal acceleration of the vehicle

With the length of the deceleration period of concern, a metric was set up which monitored the time that the vehicle spent accelerating at a level greater than 0.1m/s^2. This is included in Table 3.2 along with the minimum headway and maximum acceleration experienced throughout the event. Considering the minimum headway experienced by the vehicle; it can be seen that all simulations remained above the minimum desirable level, apart from the 22.4m/s and 1.2 combination (also shown in Figure 3.13). With increased control bound the minimum headway became larger, as the system took longer to settle. As seen in Figure 3.14, the minimum acceleration of all control bounds was the same for the 22.4m/s events. This was not the case for the 26.8m/s events; as expected the maximum acceleration falls as the control bound increases, suggesting that comfort levels would increase as the control bound is increased. But considering the deceleration period of each simulation, the 2s control bound took a much longer time period to bring the vehicle to the desired headway level. This may result in a system which reacts early, but appears slow to respond. With these ideas in mind, the control bound was set at 1.5s. As we later may consider driver defined headway intervals, it is more accurate to say that the headway control bound is defined as the desired headway + 0.5s.

Table 3.2: The effects of headway control bound on control response

U_l	**Control Bound**	**Min Headway**	**Min Acceleration**	**Decel Period**
m/s	s	s	m/s^2	s
22.4	1.200	0.751	-2.742	6.029
22.4	1.500	1.017	-2.742	7.232
22.4	2.000	1.054	-2.741	13.738
26.8	1.200	1.050	-2.744	5.680
26.8	1.500	1.087	-2.105	9.611
26.8	2.000	1.092	-0.612	11.047

3.2.2 Powertrain Integration and Controller Design

All longitudinal control simulations throughout this research have used a simple model of the powertrain and braking system which allowed the desired level of torque to be applied to each axle. While this assumption is fairly valid, as the relatively low levels of acceleration mean that these levels of torque can easily be generated by both systems, the delays involved in generating these torques, especially in the powertrain system are not taken into account. These delays may cause complications when the control system has to react quickly to changes in lead vehicle velocity. Given parts of this research will utilise a driving simulator, it is important that the system works effectively with a powertrain to replicate real driving. The automatic powertrain used in CarSim® (Mechanical-Simulation 2006) was coded into Simulink® and used in conjunction with the 9dof vehicle model. This powertrain model included an automatic gear box, torque converter, and 2.5L engine, representative of a vehicle of the luxury class (where these systems are initially marketed). The automatic gear box also meant that a greater range of accelerations could be achieved, without the need for the driver to change gear during the controller operation.

Initial integration proved simple, gains were adjusted to take into account the desired throttle position rather than the torque output. Also, only a small amount of engine braking was attainable so the threshold below which the brake system was activated was adjusted accordingly. Initial results showed promise; the system was not as quick to respond to lead vehicle accelerations, but responses remained acceptable with only slight overshoots and comfortable accelerations.

Acceleration Limits / Short Headway Gains

The control logic described in Figure 3.15 was used for ACC simulations with no powertrain, with success. When the same logic was integrated with the powertrain vehicle model, again positive results were obtained.

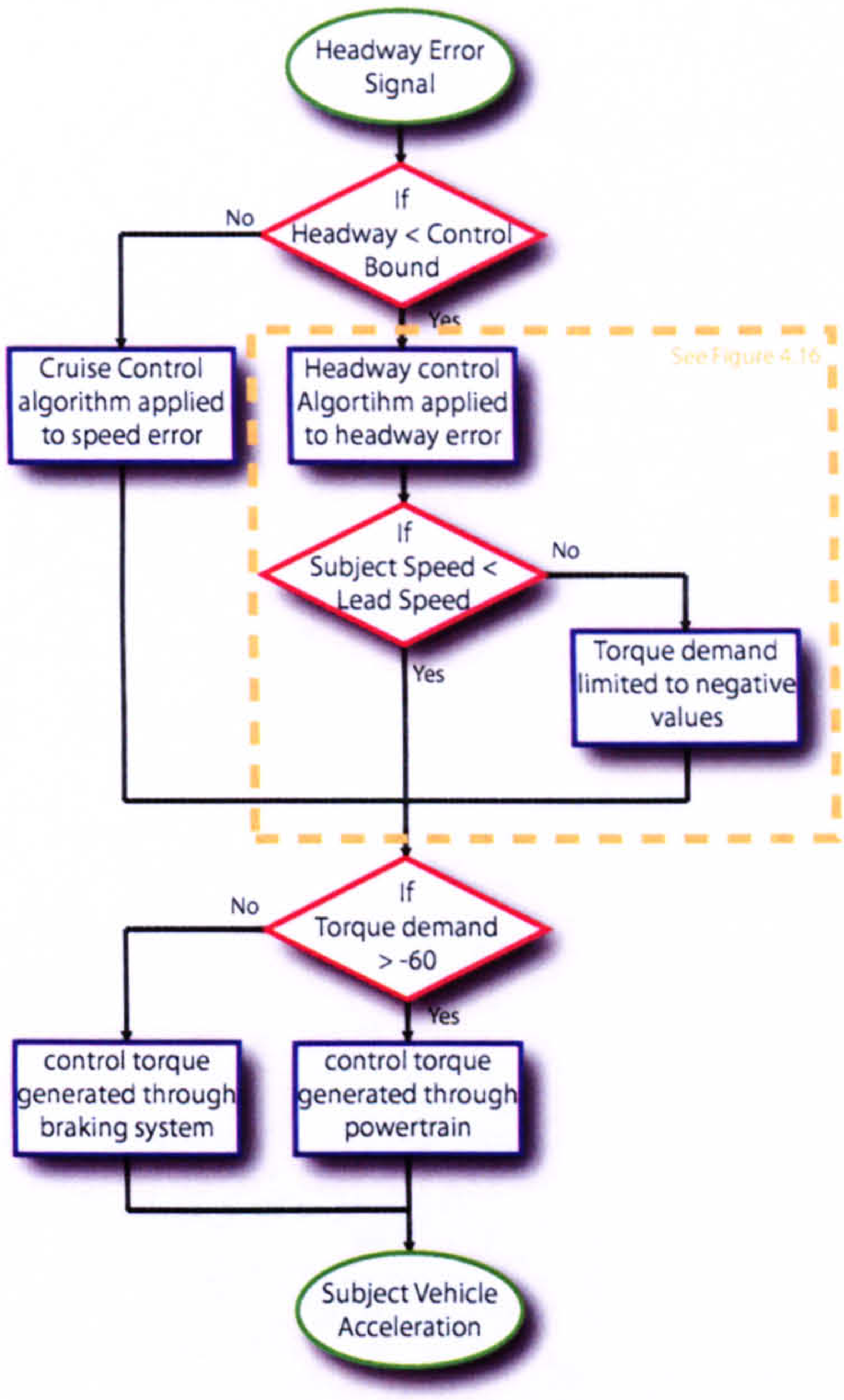


Figure 3.15: ACC control flow diagram

But when integrated with the driving simulator, small oscillations were noticed in the longitudinal acceleration of the subject vehicle, when tracking a lead vehicle that was maintaining a constant speed. It was found that the limit that prevents the vehicle accelerating if the subject speed is larger than the lead speed, caused a degree of longitudinal acceleration and jerk. This was due to the subject vehicle not being able to accelerate, to maintain the leader's velocity. Once the velocity of the subject fell below that of the leader's, relatively large control inputs had built up, resulting in a large initial peak in acceleration. This acceleration quickly died away as the desired velocity was reached. Resistances and losses in the model meant that the velocity could not be maintained, and so the process started over. This all happened over a small period and resulted in a perceived oscillatory acceleration (the phenomenon is visible in Figure 3.17). While not critical to the system's performance, it was thought that these accelerations could be uncomfortable for drivers, and so a new control approach was developed to eradicate them.

Instead of the limit which prevented positive acceleration when subject speed was greater than leader speed, two headway control states were set up:

Long Gains When the headway is within the control bound, but not approaching critical or desired levels the control gains were set up to increase the influence of the leader's speed. This meant that the system would try to match the leader's speed, whilst gradually reducing headway to the desired level.

Short Gains As the headway approaches the desired or critical level, the gains were switched to provide increased headway control. These gains would also be activated if a lead vehicle cuts in in front of the subject vehicle.

To switch between these two control states a condition was required that would provide a smooth transition imperceivable by the driver. Initially a headway criteria was used but this focused solely on the subjects speed and did not take into account the wide range of leader speeds possible, especially when considering other vehicles which may cut in front of the subject. Instead the Time To Collision (TTC), of the subject vehicle was used to switch between these two states. TTC is commonly used in transportation research as an alternative metric to headway, which describes the safety of the subject vehicle dependant on the leader's position and velocity. It is the time it would take for the subject to collide with the lead vehicle given their relative speeds and headway (Equation 3.7).

$$TTC = \frac{S_d}{u_s - u_l} \tag{3.7}$$

A range of thresholds were tried, before a TTC of 3s was selected as the limit below which the short headway gains would be used. A revised flow chart is shown in Figure 3.16 which highlights these changes.

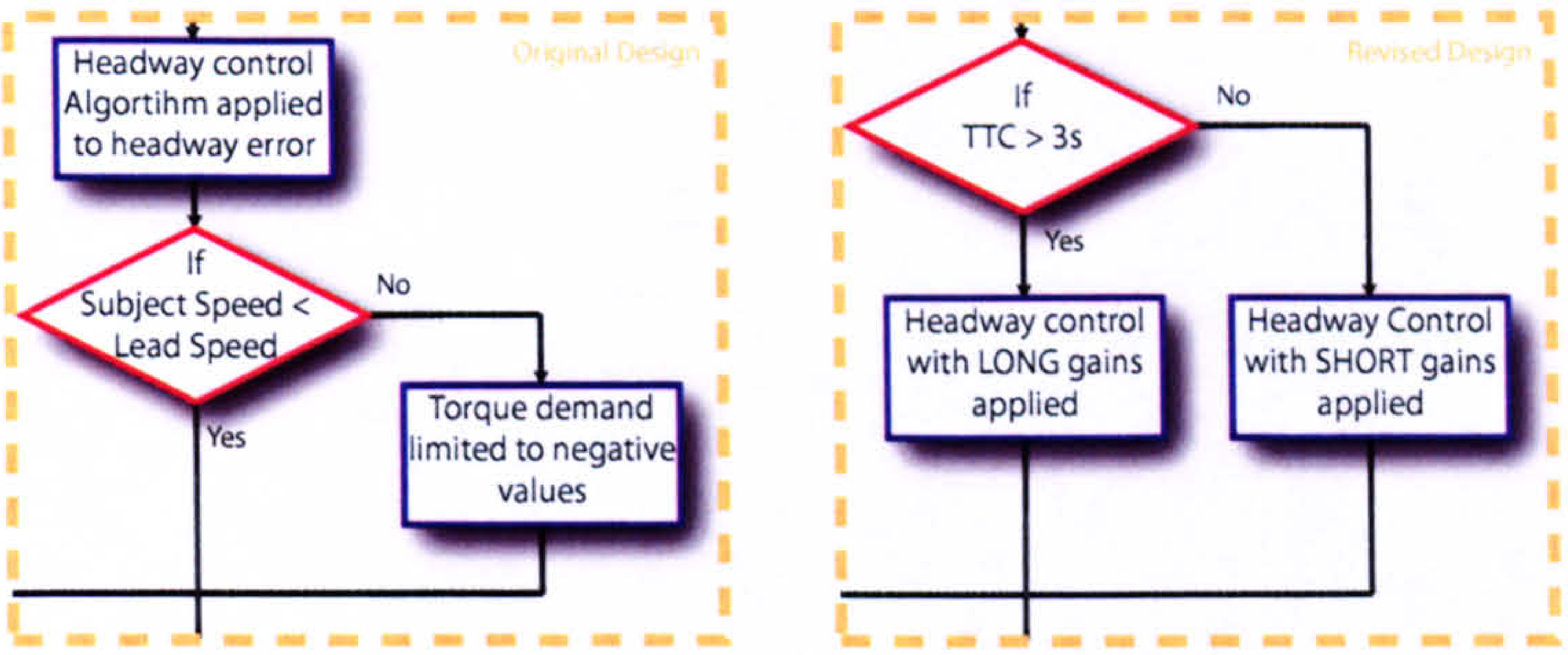


Figure 3.16: Revisions to ACC controller design

To demonstrate this cyclic acceleration and the effects of the revisions to the control logic, a simple simulation was run. In the simulation, the lead vehicle had an initial velocity of 55mph, and the subject was travelling at 70mph with an initial velocity and a headway of 1.75s.

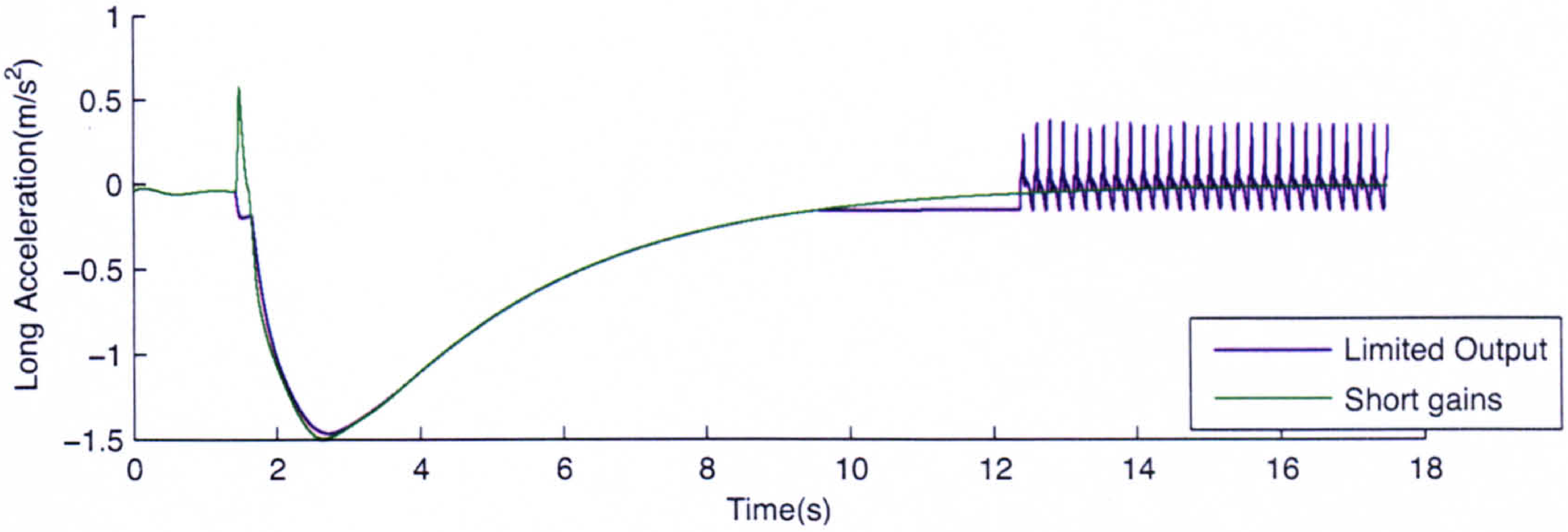


Figure 3.17: Effect of control limits on acceleration when maintaining headway

If we first consider the acceleration response of the system (Figure 3.17), the oscillation caused by the control limits is clearly visible from 12s onwards. The first important fact to note, is that this same oscillation was not present in the controller with the two sets of headway gains. The other major factor to note, is the initial acceleration at 1.5s; with limits the system initially decelerated. This was caused by engine braking, the step that follows this initial acceleration was caused by the lack of torque that could be generated by the engine alone, before the brake torque threshold was reached. In the unlimited control scheme the system initially accelerated due to the large headway error. This is short lived as the increased speed control gains counteract this, and caused the vehicle to decelerate. The response then followed a similar trend as the limited controller, and actually settled more quickly, due to its ability to accurately track the lead vehicle's velocity. The initial spike in acceleration may cause a strange sensation for the driver, as the vehicle may appear to try to catch up with the vehicle in front. But in this instance it was very short lived and it was hoped to tune this further out of the system, especially for relatively small speed differences.

The headway response shown in Figure 3.18 supports the findings in the acceleration response. The initial response of both systems was near identical. The unlimited controller appears to settle quicker with less steady state error than the limited scheme. The fluctuations in acceleration were also just about visible in the limited headway response.

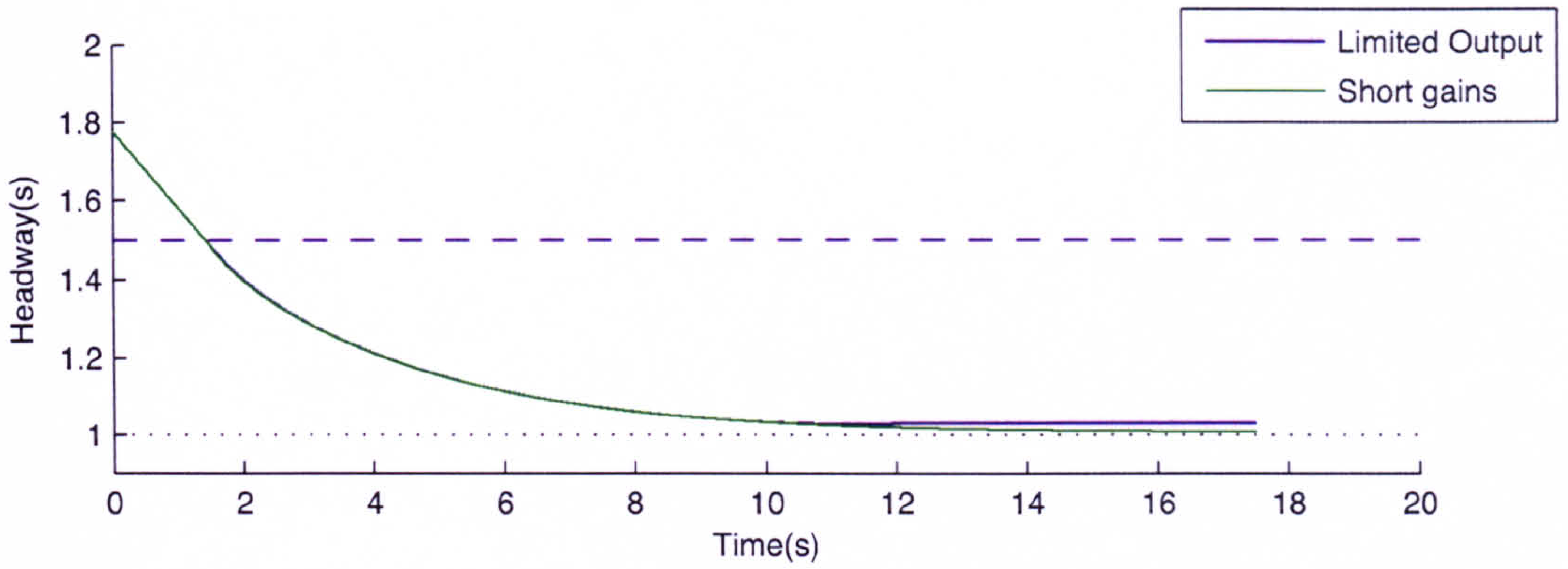


Figure 3.18: Headway of vehicles with control limits and TTC dependent gains

3.2.3 Test Scenarios and Analysis

To validate the success of the tuning measures discussed throughout this section, a range of simulations were conducted. The scenarios cover simple decelerations caused by the system through to more extreme manoeuvres; including sinusoidal lead vehicle acceleration. The most interesting of these results are discussed in this section. The control system used throughout these simulations is that which was designed in the previous sections, although the gains used were decided upon after a final online tune in the driving simulator; which allowed us to subjectively assess the effects of any accelerations perceived.

Lead Vehicle Acceleration Tests

Previous tests have shown the ability of the control system to switch between speed and headway control, and track the lead vehicle's constant speed accurately and smoothly. But what happens when the lead vehicle accelerates or decelerates? This type of test was considered in the earlier part of this chapter, but the integration of the powertrain and extended control logic may have effects on the system's performance. In these tests we were especially concerned with the response of the vehicle to 'out of range' accelerations and decelerations. To investigate this, a simple test was set up where the subject was tracking the leader at a constant speed and headway of 1s. The lead vehicle then underwent an impulse change in acceleration. The headway and acceleration profile of the subject vehicle were monitored. Results are shown for a lead vehicle acceleration of +3m/s^2 and -5m/s^2. These tests also were also performed using the original control system with no powertrain to asses the impact of the additions made.

The headway response shown in Figure 3.19 and the acceleration profile in Figure 3.20 demonstrate the success of both controllers. There were minor fluctuations noticed in the

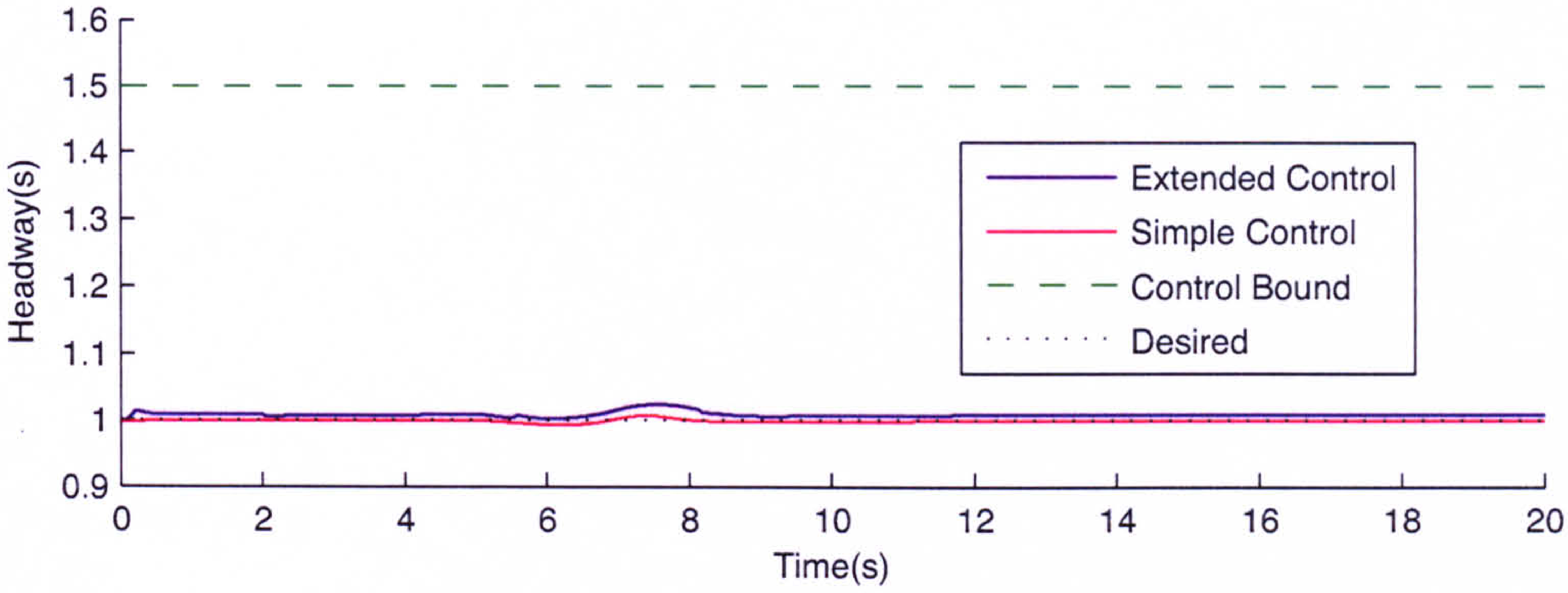


Figure 3.19: Headway response of vehicle to 3m/s^2 lead vehicle acceleration

headway response of the vehicles. These are expected, as the subject vehicle was not able to accelerate at the same level as the leader and so falls away. This slight increase was quickly reduced as the leader stopped accelerating and the subject was able to catch up. The headway was not undershot and safety was not compromised. Differences between the two control systems become more clear when we consider the acceleration results.

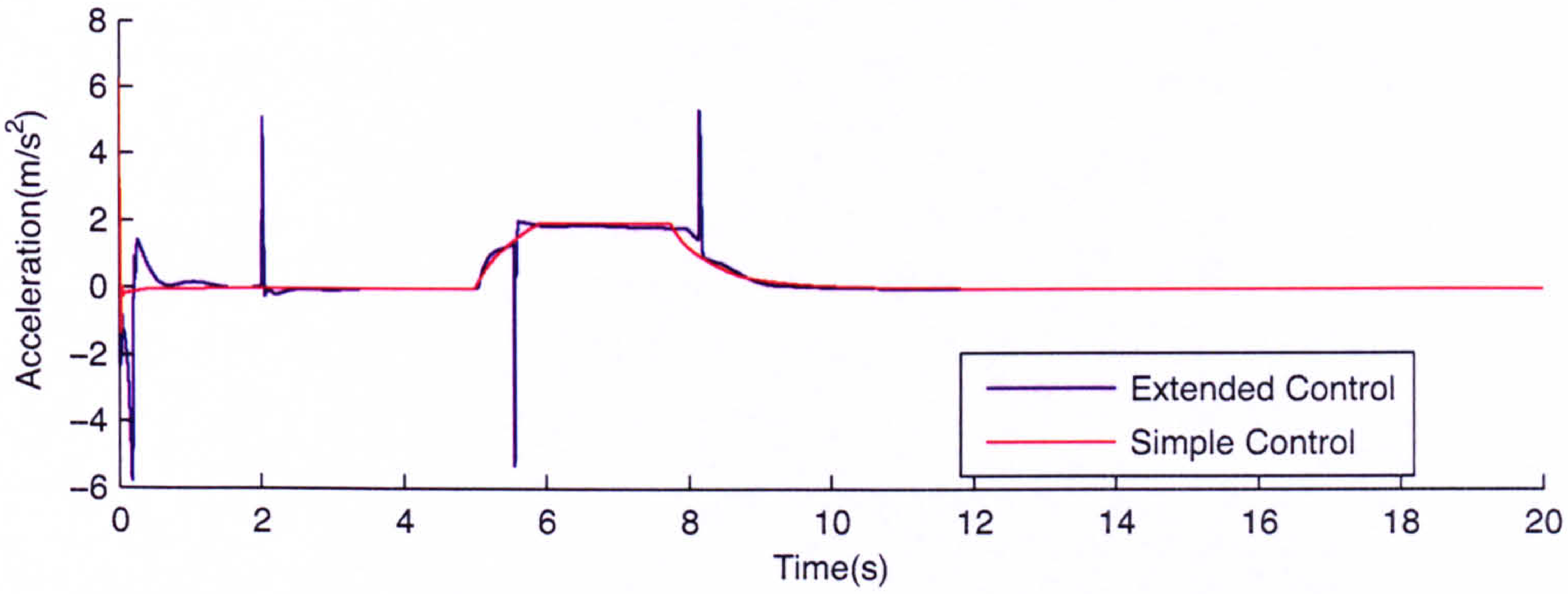


Figure 3.20: Acceleration response of vehicle to 3m/s^2 lead vehicle acceleration

When the extended control methods acceleration response is examined the first thing that is noticed is the large spikes at 2, 5.5, and 8s, caused by automatic gear changes. These accelerations were only noticeable due to the small time step used in the simulation and are due to the large instantaneous change in speed at the torque converter, which is transmitted back through the powertrain. The spikes are so short lived that they are not rendered by the motion base of the simulator used in later experiments. They can be disregarded from the results of this and proceeding simulations. The only significance of these spikes is that they show the time of gear changes in the simulation. The first gear change occurs as the system found equilibrium and no longer required acceleration to track the leader's velocity. As the system reacted to the lead vehicle's acceleration it changed down a gear to generate the maximum allowable acceleration. A constant acceleration of just over 1.5m/s^2, is then maintained, until the lead vehicle was caught and the subject vehicle shifts up a gear as no further acceleration was required. Apart from these spikes, the acceleration response was as expected and demonstrated the effective upper limit of the system. These levels of acceleration are nearly identical to those generated the simple control system, obviously there are no gear changes - hence no spikes in this system, but the fundamental acceleration profile of both systems is very similar.

The results of the maximum deceleration test are shown in Figures 3.21 and 3.22. It is immediately obvious that there was a much larger deviation in headway than experienced in the previous test. This was due to the larger magnitude of the leader acceleration. In this case the headway undershoot was detrimental to the safety of the vehicle, as the subject became closer to the lead vehicle than desired. The system was not able to maintain the desired headway, as the torque exerted by the system was limited to generate a maximum deceleration of 2m/s^2. In this scenario the driver did not need to intervene to prevent collision, but if the leader were to decelerate for a prolonged period of time intervention would be required. It should also be noticed that the responses of both the simple and extended controllers are again similar, The simple control system is able to react slightly quicker to the event due to less powertrain losses.

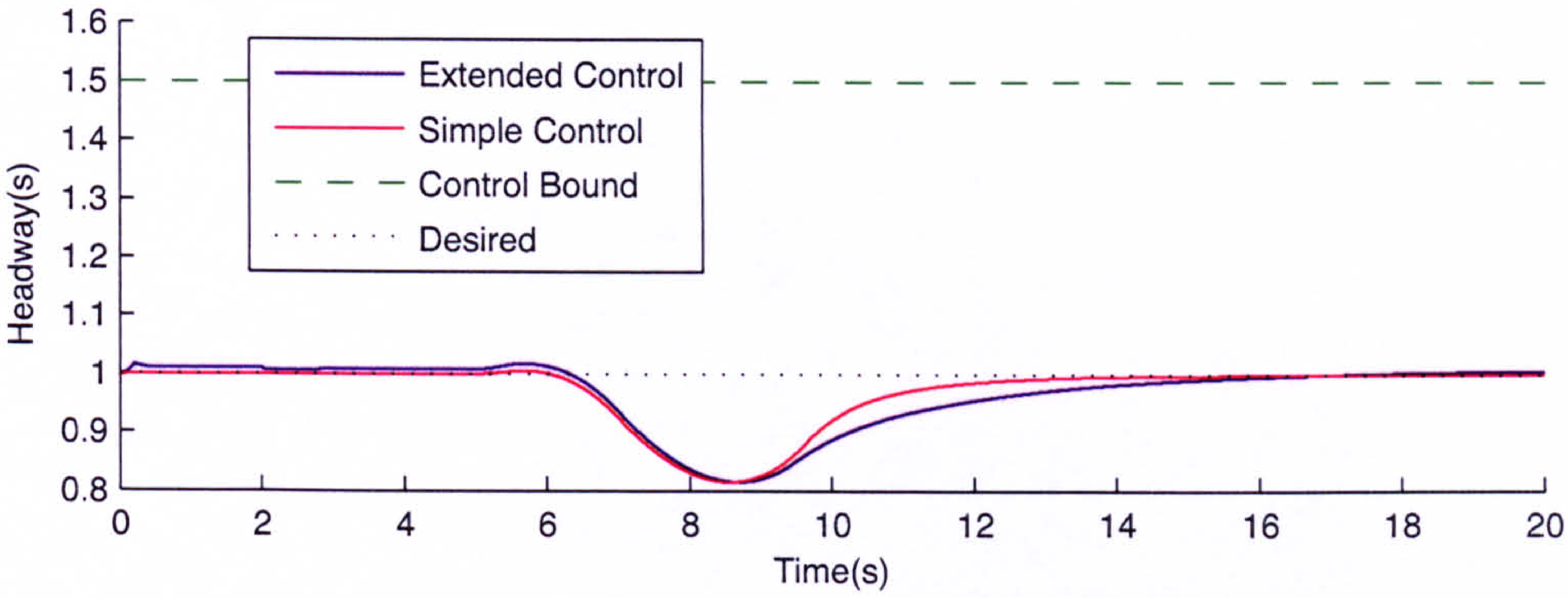


Figure 3.21: Headway response of vehicle to -5m/s^2 lead vehicle acceleration

The acceleration profile of the subject vehicles were similar to those obtained in the previous test. This time the extended control system displayed no gear changes, as the system did not demand high positive accelerations. Instead the deceleration was performed by the braking system. The maximum level of deceleration was quickly reached and maintained, until the leader speed was attained. Then brake torque was gradually reduced so that the desired headway could be achieved without undershooting the leader's velocity. The result was a smooth, comfortable acceleration profile near identical to that

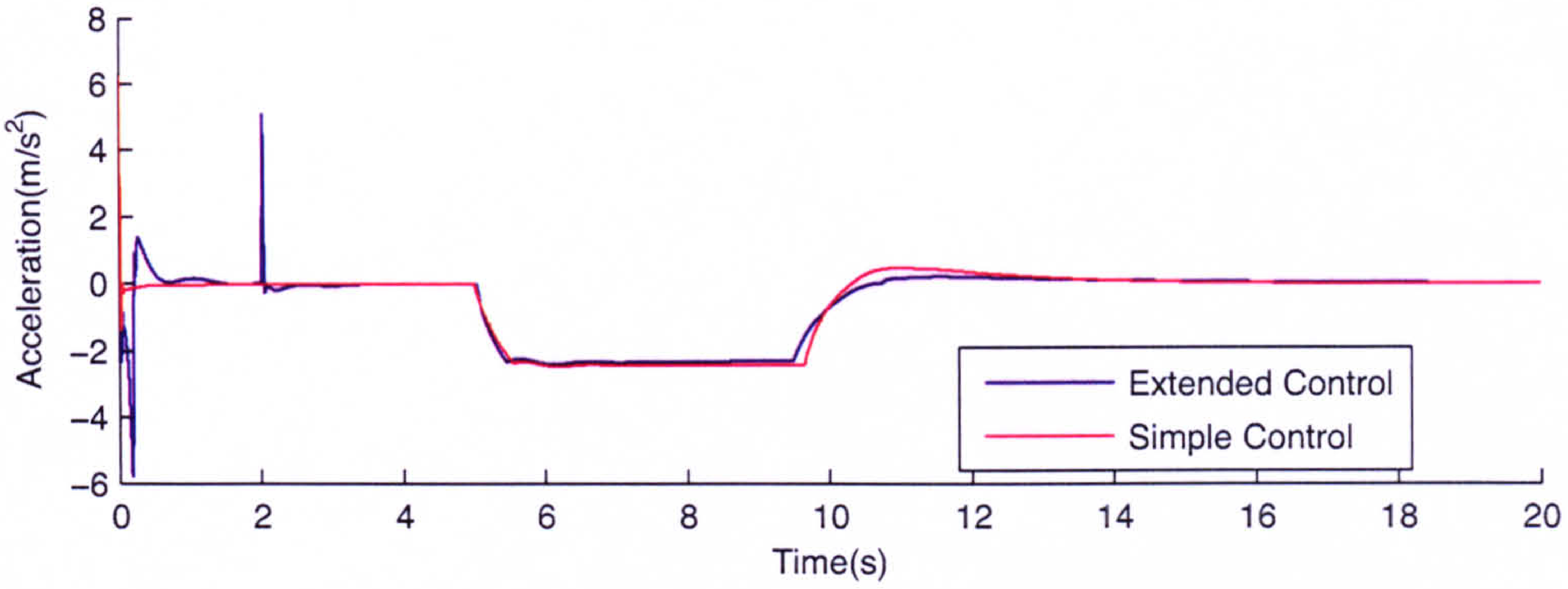


Figure 3.22: Acceleration response of vehicle to -5m/s^2 lead vehicle acceleration

of the simple system. And while the headway response undershot its desired target, safety and stability of the vehicle were maintained at all times.

Sinusoidal Lead Vehicle Acceleration

One area of interest that has received a lot of research is the string stability of ACC vehicles (Liang and Peng 2000). While in this research we are only considering the effect of the ADAS on the subject vehicle and driver; it is important to consider the impact of lead vehicle oscillatory accelerations, both from a string stability point of view, and also the impact of oscillatory lead vehicle behaviour.

To test this, a simple simulation was constructed where the lead vehicle had a sinusoidal velocity profile. The subject vehicle initially had a higher velocity than that of the leader, and a headway just outside the control bound. As the subject vehicle caught up with the leader, the ACC system had to initially reduce the subject's speed and then try to maintain the sinusoidal lead velocity profile. This test was carried out for two frequencies of lead vehicle velocity, 0.1Hz and 1Hz, both with a peak to peak amplitude of 2m/s. While the low frequency test mimics possible lead vehicle behaviour, the high speed test involves instantaneous lead vehicle accelerations of over 6m/s^2. these accelerations are beyond the capabilities of the control system, but the test allows us to asses the ultimate stability of the system.

The velocity profile for the low frequency test is shown in Figure 3.23. It can be seen that the initially high subject velocity was linearly reduced once the subject entered the control bound. As the leader's velocity was approached, the sinusoidal velocity was tracked, with minimal phase lag (26°) and amplitude reduction ($\frac{amp_{sub}}{amp_{lead}} = 0.837$). These losses in the system were caused by the speed of the control system, and more noticeably the latency created by the powertrain. It is important to note that the system remained stable throughout this simulation.

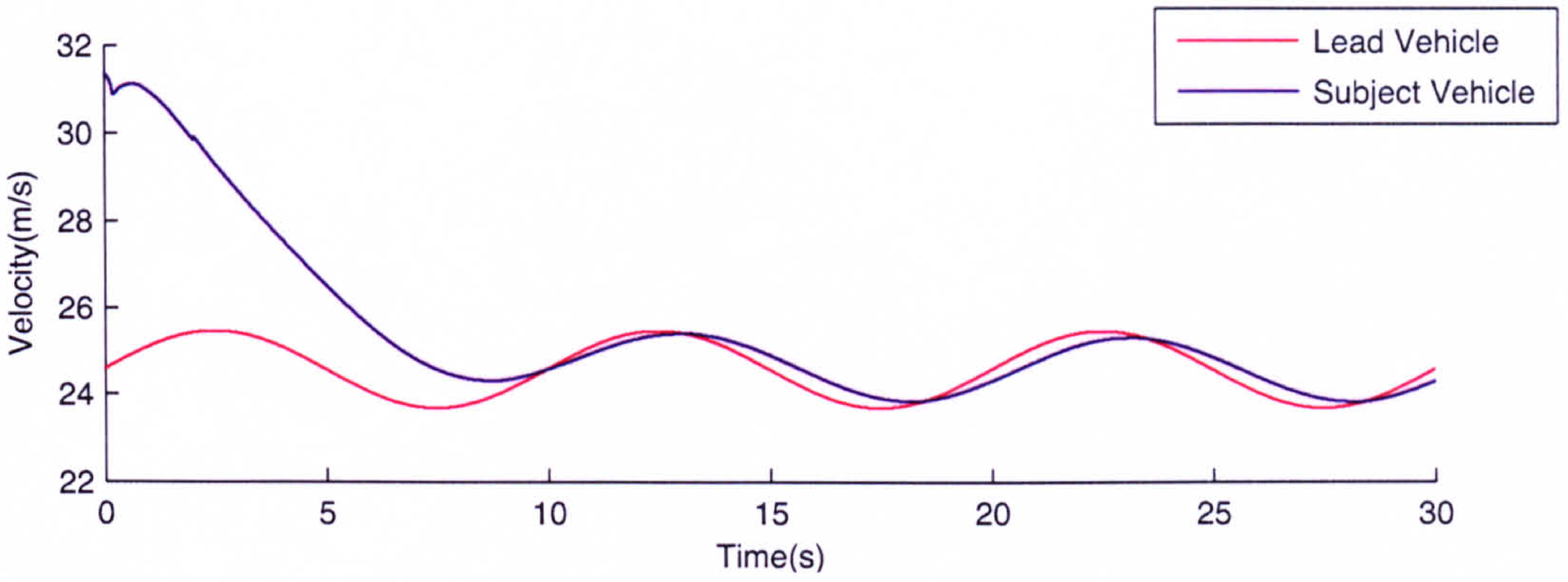


Figure 3.23: Velocity response of vehicle to low frequency sinusoidal lead vehicle velocity

The headway response of the system in Figure 3.24 shows the ability of the system to accurately maintain the desired headway of 1s with a sinusoidal fluctuation in lead vehicle velocity. After the speed had been reduced the headway of system did not fall below 1s, maintaining the safety of the subject vehicle.

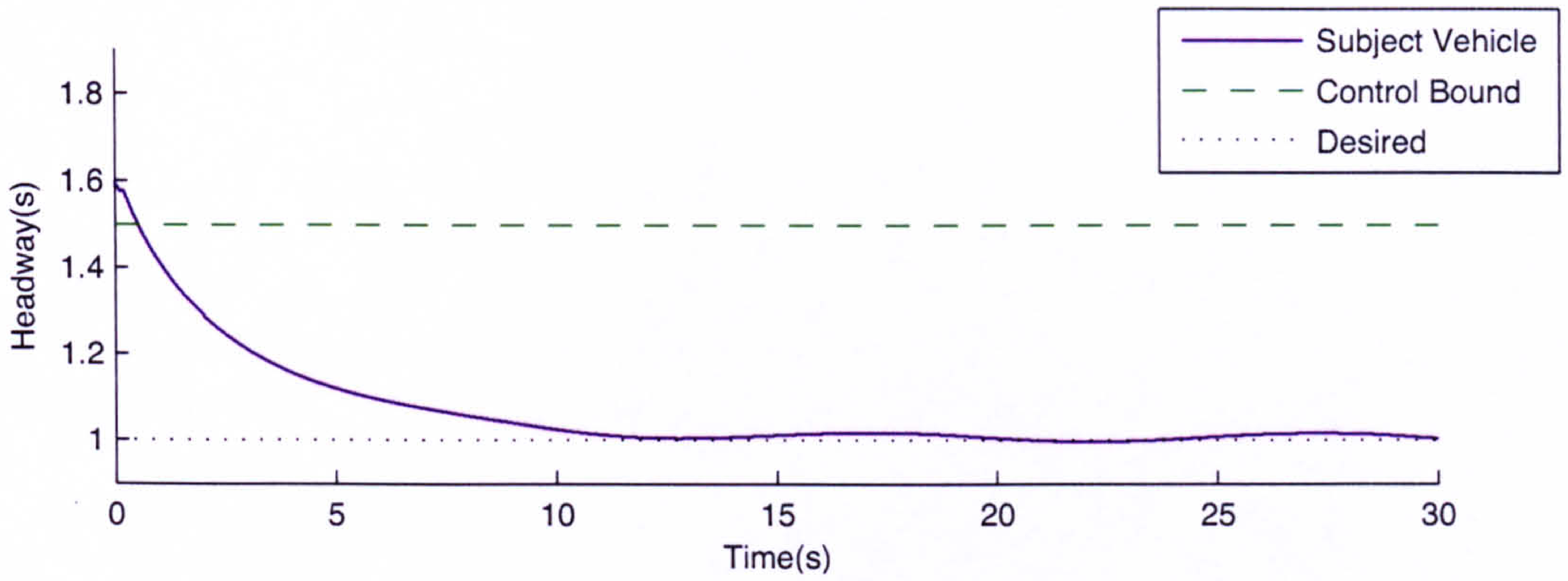


Figure 3.24: Headway response of vehicle to low frequency sinusoidal lead vehicle velocity

Results for the high frequency (1Hz) simulation are shown in Figures 3.25, 3.26 and 3.27. Considering the velocity response of the subject vehicle, it is immediately obvious that the amplitude of the subject's velocity was reduced from the leader's (amplitude ratio = 0.23). This was mainly due to the speed of response of the powertrain, which could not generate the desired level of acceleration quickly enough to match the velocity of the lead vehicle. The phase lag (49°) was also much larger than experienced at the low frequency, as a result of the same powertrain lags. The performance of the system still remained stable throughout the simulation. These results were expected given the magnitude of accelerations experienced, and demonstrate the stability of the controller when subjected to this high freqency input.

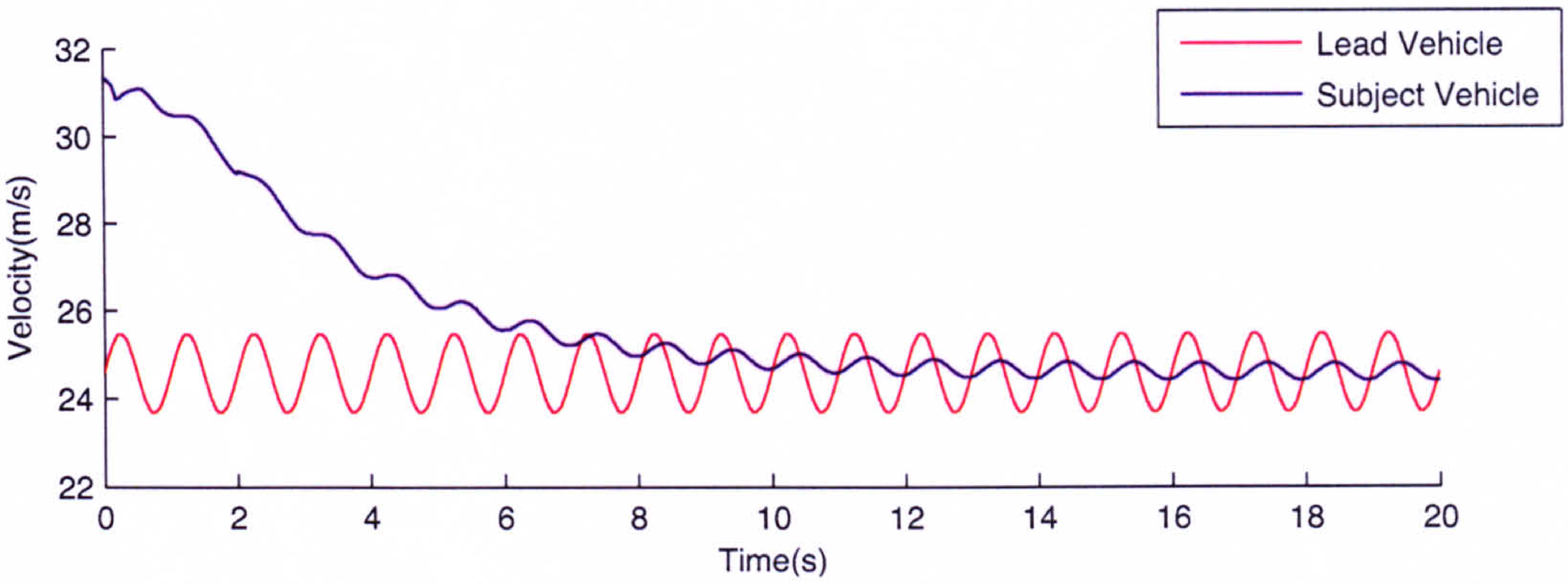


Figure 3.25: Velocity response of vehicle to high frequency sinusoidal lead vehicle velocity

The headway of the subject vehicle was acceptable throughout the simulation, only minor oscillation was noticeable, and the value always remained slightly larger than the desired value of 1s. This was even the case when the system was slow to respond to the troughs (decelerations) in lead vehicle velocity.

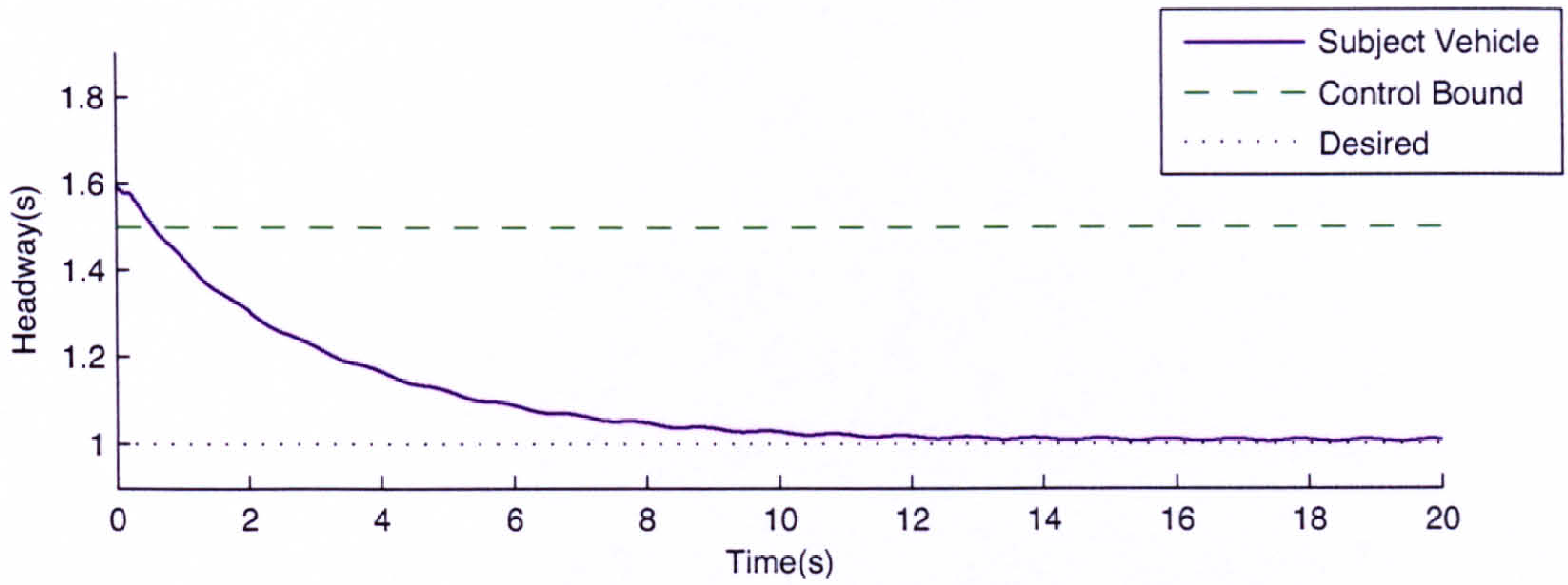


Figure 3.26: Headway response of vehicle to high frequency sinusoidal lead vehicle velocity

The acceleration profile is shown in Figure 3.27 for reference. Ignoring the sinusoidal acceleration, the first order response was similar to that noticed in previous tests, where the initial sharp deceleration was smoothly reduced back to zero. The sinusoidal nature of the leader's velocity did not affect the stability of the vehicle when undergoing this fundamental transition. The slight steps noticed in the positive slope of the sinusoid were caused by the transition from the braking system to the powertrain, and the lags involved in the generation of the desired level of torque. But again this was not detrimental to the safety of the vehicle. the high accelerations experienced by the systems mean this would not be a comfortable event for the driver, but the relatively slow response of the system mean that some of the lead vehicle behaviour was effectively filtered out, reducing the impact on the driver without compromising safety.

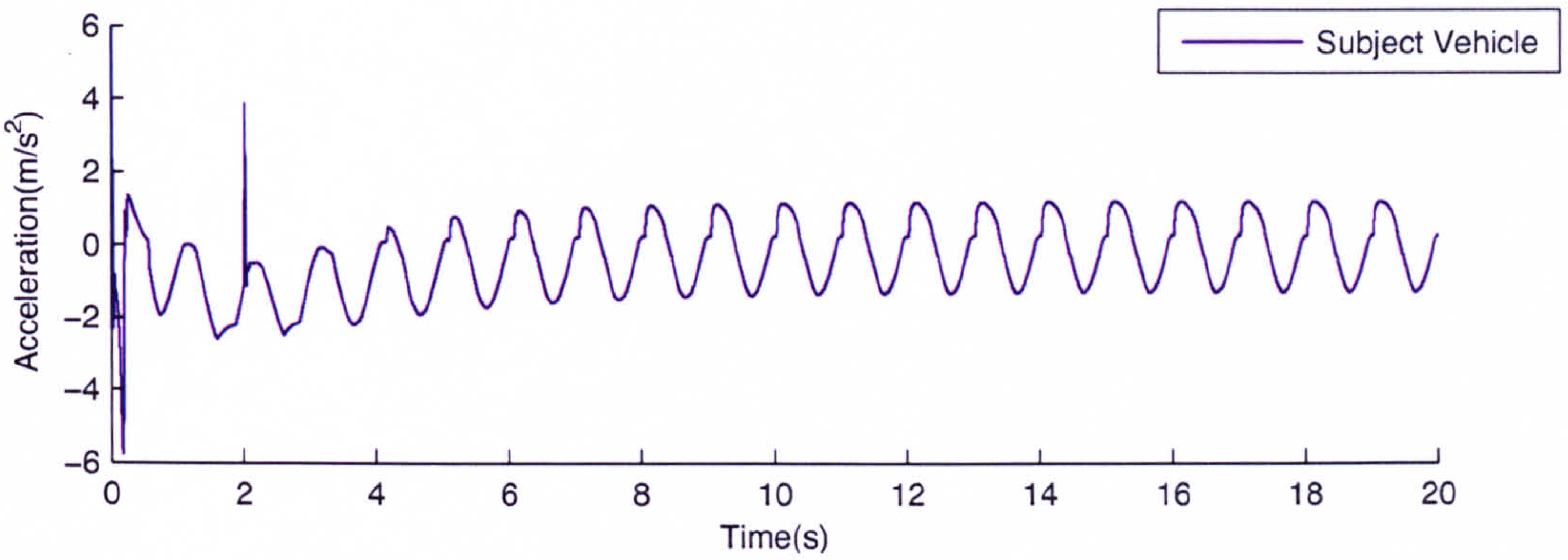


Figure 3.27: Acceleration response of vehicle to high frequency sinusoidal lead vehicle velocity

Lead Vehicle Cut In

One area of the ACC performance that has not been investigated so far in this research, is the effect of a lead vehicle cutting in in front of the subject vehicle, with a slower velocity than the subject, and a short time gap between the two vehicles. For the purpose of this research we term this type of event 'Car Cutting In' (CCI). While severe, this scenario is not uncommon in motorway driving. It could also be an area where the system can help mitigate against collision. As the system can react quickly to start deceleration, and then if necessary, warn the driver to apply additional braking.

To replicate this scenario a simulation was set up where the lead vehicle's velocity was lower than the subject and the initial headway was set at 0.6s, lower than the desired level of 1s. Results from this simulation are shown in Figures 3.28 and 3.29.

The first thing to notice from the headway response is that collision was avoided, a minimum headway of 0.15s was obviously much lower than desired, but given the low initial headway and velocity differential it was impressive that the system could avoid collision without driver intervention. After the minimum headway was reached the subject slowed further to attain the desired vehicle speed and headway.

The acceleration response of the vehicle shows that the maximum deceleration of

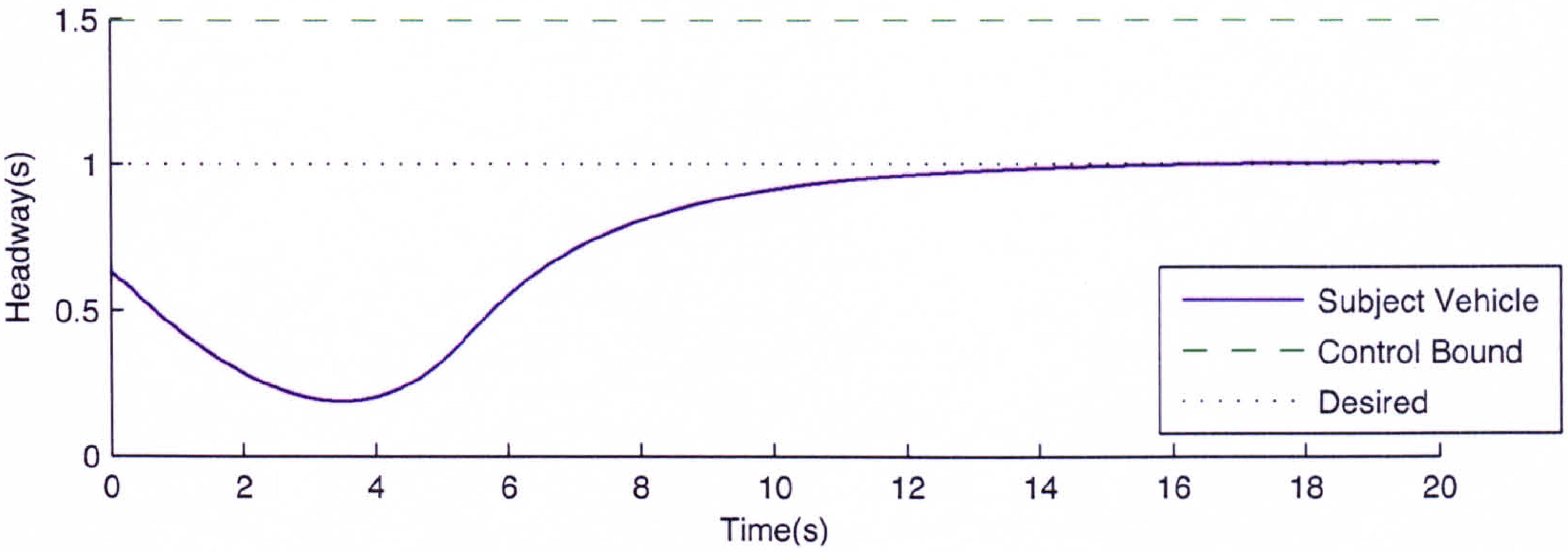


Figure 3.28: Headway response of vehicle to CCI event

2m/s^2 was initially maintained (ignoring gear changes) by the braking system. This was then gradually reduced as the headway was achieved. At 6s, the braking system was disabled and the required torque was generated through the powertrain. Initially, this was still a decelerating torque, but as the velocity of the lead vehicle was undershot a slight accelerating torque was generated to catch up with the lead vehicle.

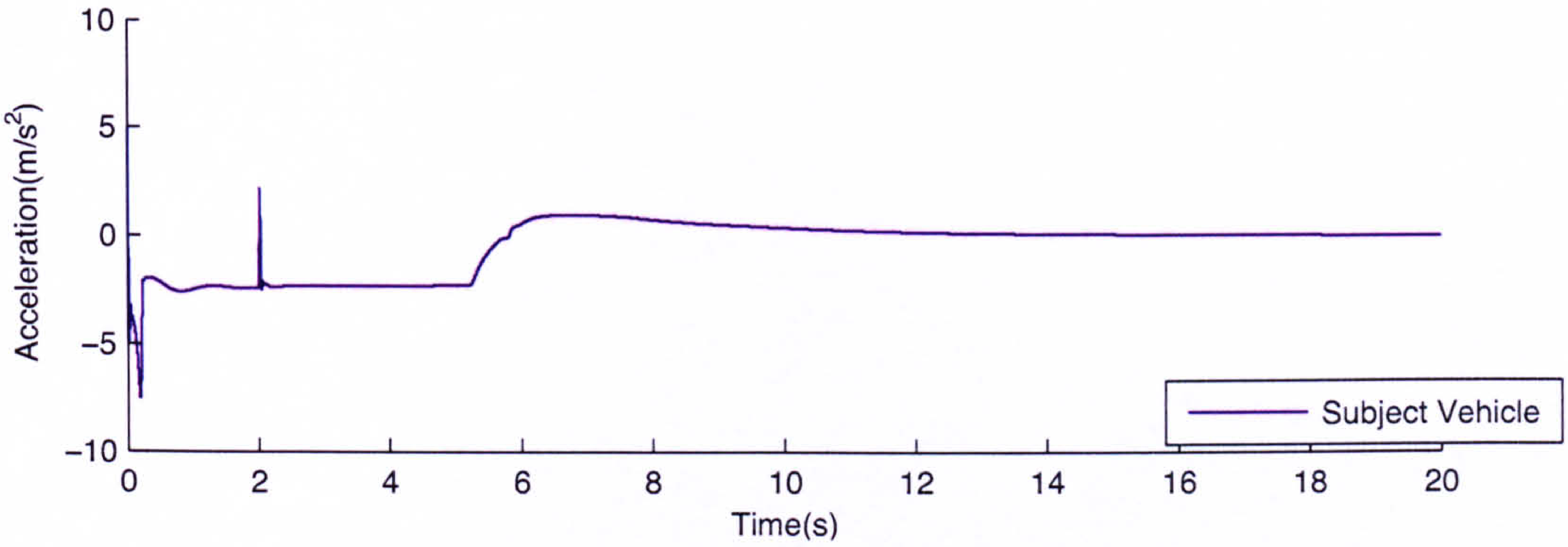


Figure 3.29: Acceleration response of vehicle to CCI event

It is interesting to see that the system could avoid this collision, but it raised the question of driver intervention. Would the driver have had the required trust in the system to let it perform the braking unaided, or would they have intervened with a higher (more uncomfortable) level of braking, to avoid the collision more safely? This event is one of the key events that will be looked at in more detail during the driving simulator experiments discussed in Chapter 6.

3.3 Summary of Results

The following conclusions can be drawn from the tests performed in this section:

- An ACC system has been developed which when integrated with a powertrain system displayed a desirable response to a wide range of lead vehicle behaviours.
- The system remained stable when subjected to out of range accelerations.
- Further investigation is required to measure the driver's trust in the system and the level of feedback that is required to improve this trust.

Chapter 4

Lateral Control

Chapter 4 investigates two types of lateral control system that aim to fully control the lateral motion of the vehicle, rather than provide additional assistance to the driver. An extensive range of scenarios are developed to assess the systems' performances, examining typical motorway manoeuvres including straight, and curved roads, as well as lane changes. These tests are described in detail as a suggested evaluation platform for future lateral control systems. A look down system is initially considered. Its performance and impact on the driver are assessed and discussed. Results from these initial tests were presented at the AVEC '06 international conference (Auckland et al. 2006). A more 'driver-emulating' approach is taken through the development of a look ahead system, where the system has an idea of the future path of the road (much like the human driver). The results of the two systems are compared. For the first time in the field, the impact of environmental factors on the vehicle dynamics of the systems are investigated. The high fidelity vehicle model allows the effects of the system on the comfort levels to be monitored over the full range of vehicle handling.

Lateral control uses road and vehicle position data to control the lateral response of the vehicle to track a desired path. There are many methodologies used to control the lateral motion of the vehicle. This chapter investigates a range of systems and control strategies; their performances are assessed over a range of motorway manoeuvres and conditions. The merits of each strategy are discussed, and their expected impact on the driver and vehicle dynamics is considered.

4.1 Test Scenarios

For any lateral control system to be useful it must inspire confidence in the driver. For this to be the case, the system must perform well for all manoeuvres. Failure or erratic performance during operation may impair drivers trust in the system, and may lead to them disabling the system for all, or some tasks. While the need to disable/enable the system may provide a stimulus to the driver, ensuring that they remain in-the-loop, it may eventually become a nuisance for the driver, and deter them from using the system in the future. Even if the system is sold with warnings detailing when to and when not to use it, the responsibility lies solely with the driver to heed these warnings.

The high speeds experienced in motorway driving can provide some of the most dynamic scenarios for the vehicle. These high speeds can also reduce the time the driver has to react to these situations. These tasks where quick reaction times are required, become the areas where lateral control of the vehicle becomes safety critical. Entry onto and exit from the motorway provide some interesting areas to consider. However the active vehicle's interaction with other traffic is not considered in this research as we are purely concerned with effects of the system on the driver and vehicle itself. From a vehicle performance point of view, it could be assumed that the accelerations experienced in these entry/exit manoeuvres would be similar to that of a standard lane change. All other lateral control tasks during motorway driving can be split up into into the following categories:

Category	Lateral Control Task	Lateral Acceleration	Section
Lane Keeping	Straight Roads	$\approx 0\text{m/s}^2$	4.1.1
	Curved Roads	$\approx 0.4\text{m/s}^2$	4.1.1
Lane Changes	Standard Lane Change	0.5m/s^2	4.1.2
	Evasive Lane Change	1 & 5m/s^2	4.1.2
Disturbances	Banking	$0.05 - 1.5\ \text{m/s}^2$	4.1.3
	Side Winds	$0 - 0.07\text{m/s}^2$	4.1.3
	Low μ Conditions	$0 - 5\text{m/s}^2$	4.1.3
	Split μ Characteristic	5m/s^2	4.1.3

4.1.1 Lane Keeping Scenarios

The most simple motorway manoeuvre is a basic lane keeping task. Motorway roads can be considered to be either straight or curved. Straight roads would seem the simplest case as a balanced car would require no steering input to maintain its course in a flat even straight section. Yet other disturbances such as side winds, mean that the ability to regain a straight course is key to the success of a lateral control system. Any straight road section has an equivalent radius of curvature of infinity, this can be input to the simulation as a desired yaw rate of zero.

Curved road sections provide more of a challenge to the lateral control system. Typically they come in the form of spiral or tangential curves. In a spiral curve, the radius of curvature of the road is initially high, then gradually reduces around the bend, before being increased again in the second half of the bend. This results in a smooth corner with low levels of jerk. Sometimes the underlying land dictates that this design is not possible and tangential corners are required. Here the corner is created using a step change in radius of curvature. The result is a step change in the required level of lateral acceleration of the vehicle. This allows the road to change direction in a shorter space. These tangential corners were investigated in this research, as they will be where the vehicle would experience the highest instantaneous levels of lateral acceleration. Spiral corners, where the radius of curvature is gradually decreased to provide a smoother corner were not considered.

Design guidelines were taken from the UK road design manual (Highways-Agency 1993). For flat roads, a suggested minimum radius of curvature was given for a design speed (Table 4.1). The radius is input into the simulation as a normalised reference yaw rate (ρ_{ref}) for an impulse of 5s.

Table 4.1: Design parameters for flat corners (Highways-Agency 1993)

Speed (m/s)	Speed (mph)	Radius of Curvature (m)	ρ_{ref} (m^{-1})
8.9	20	400	0.0025
13.4	30	520	0.0019
17.9	40	850	0.0012
22.4	50	1300	0.0008
26.8	60	2000	0.0005
31.3	70	2700	0.0004

4.1.2 Lane Changing Scenarios

After lane keeping, the most common manoeuvre in motorway driving is the lane change. Lane changes are used for a variety of reasons; the driver may wish to overtake, return to the inside lane after overtaking, get into the correct lane to exit the motorway, or avoid possible collisions or obstacles. A lane change manoeuvre usually entails the driver checking that it is safe to perform a manoeuvre (using mirrors), signalling that they are about to change lane using the turn indicator, and then applying the necessary steering input to move between lanes. This strategy may change if the manoeuvre is evasive or the driver is unaware of their own situation.

For the purpose of this research lane changing was broken down into two types. Firstly the Standard Lane Change (SLC), which would be used for overtaking and altering lane choice; and secondly the Evasive Lane Change (ELC) which would be used for collision avoidance task.

In the SLC, the time to change lane was less important than the level of comfort transmitted to the driver. For this reason a trapezoidal function of lateral acceleration was prescribed. Figure 4.1 shows the desired lateral acceleration for a SLC, where the gradient of the ramped sections represents the lateral jerk experienced by the vehicle. Equation 4.1 was used to calculate the time of the manoeuvre given the desired level of lateral acceleration and jerk. In this research lateral acceleration of the SLC was set at 0.05g, and lateral jerk was set at 0.1g/s. Table 4.2 details the parameters of the manoeuvre calculated for a wide range of motorway speeds. This manoeuvre is based on work by Chee and Tomizuka (1994), who suggested that the trapezoidal lane change provided a good means of reducing uncomfortable lateral jerk during the manouvre.

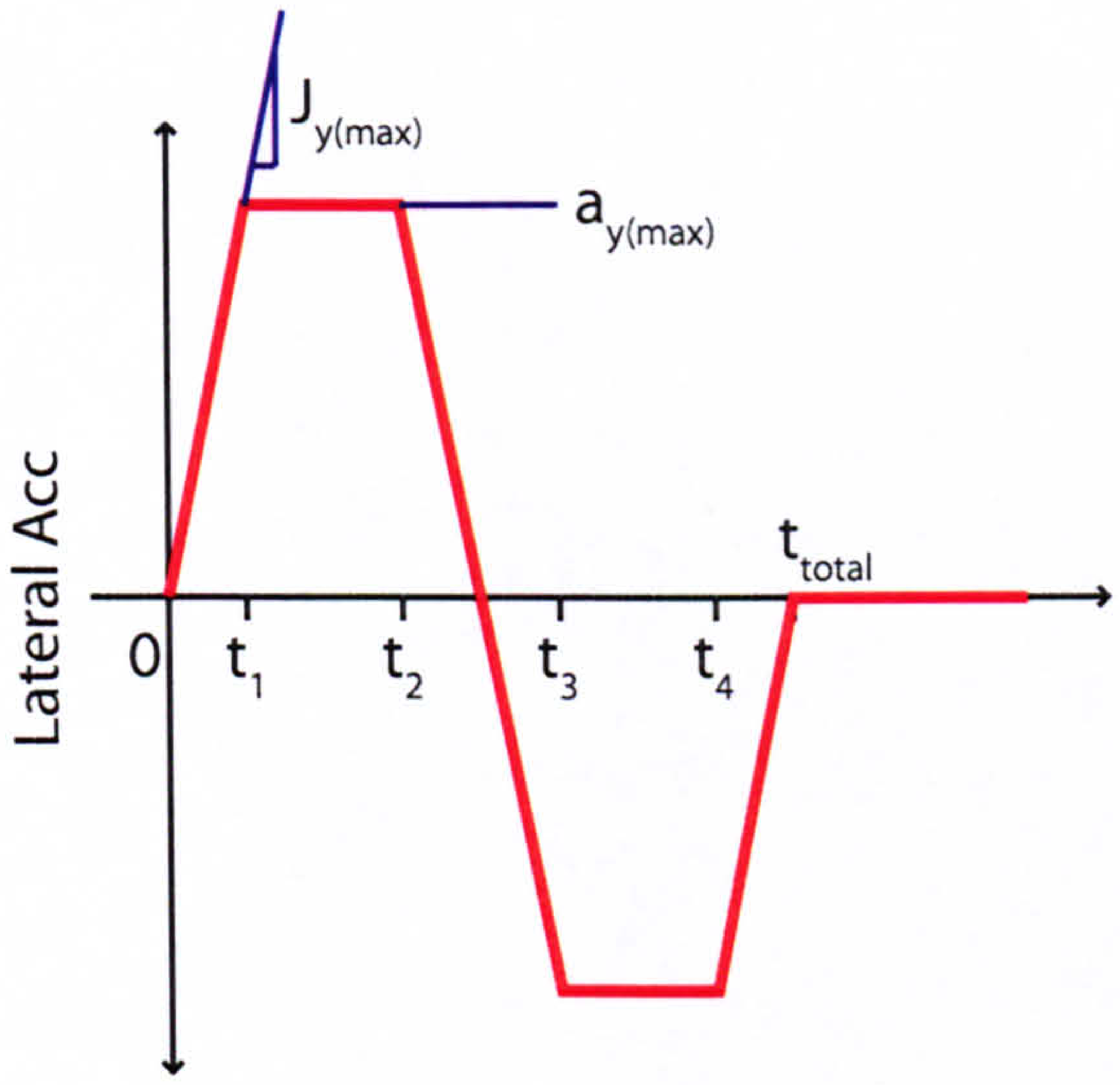


Figure 4.1: Reference lateral acceleration for a SLC

$$\begin{aligned}
t_1 &= \frac{a_{y(max)}}{J_{y(max)}} \\
t_2 &= \frac{-t_1^2 + \sqrt{t_1^4 + 4t_1 \frac{d_{lw}}{J_{y(max)}}}}{2t_1} \\
t_3 &= 2t_1 + t_2 \\
t_4 &= t_1 + 2t_2 \\
t_{total} &= 2t_1 + 2t_2 \qquad (4.1)
\end{aligned}$$

Table 4.2: Trajectory parameters for a SLC

Speed (m/s)	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_{total}(s)	ρ_{ref}
8.9	0.5	2.24	3.24	4.97	5.47	0.0061
13.4	0.5	2.24	3.24	4.97	5.47	0.0027
17.9	0.5	2.24	3.24	4.97	5.47	0.0015
22.4	0.5	2.24	3.24	4.97	5.47	0.0010
26.8	0.5	2.24	3.24	4.97	5.47	0.0007
31.3	0.5	2.24	3.24	4.97	5.47	0.0005

For the ELC, driver comfort levels were not as important as ensuring that the vehicle exited the lane as quickly as possible, whilst remaining stable at all times. With this in mind, the trapezoidal acceleration function was replaced by a square wave generated directly from the desired level of lateral acceleration (Figure 4.2). This resulted in a quicker lane change, with higher levels of both lateral acceleration, and jerk transmitted to the driver. Two trajectories were proposed, one with a lateral acceleration of 0.1g, and one with a lateral acceleration of 0.5g. This would test the controller over a wider range of performance criteria, and simulate driving scenarios of different severity. The parameters of these trajectories are shown in Table 4.3.

4.1.3 Disturbance Scenarios

While motorway roads are generally well constructed and maintained, there are factors of their design and other environmental issues that must be taken into account when considering the performance of any lateral control system. It is common for motorway roads to be designed with some super-elevation or banking. This allows smaller radii of curvature and higher traffic speeds, due to the added component of lateral acceleration

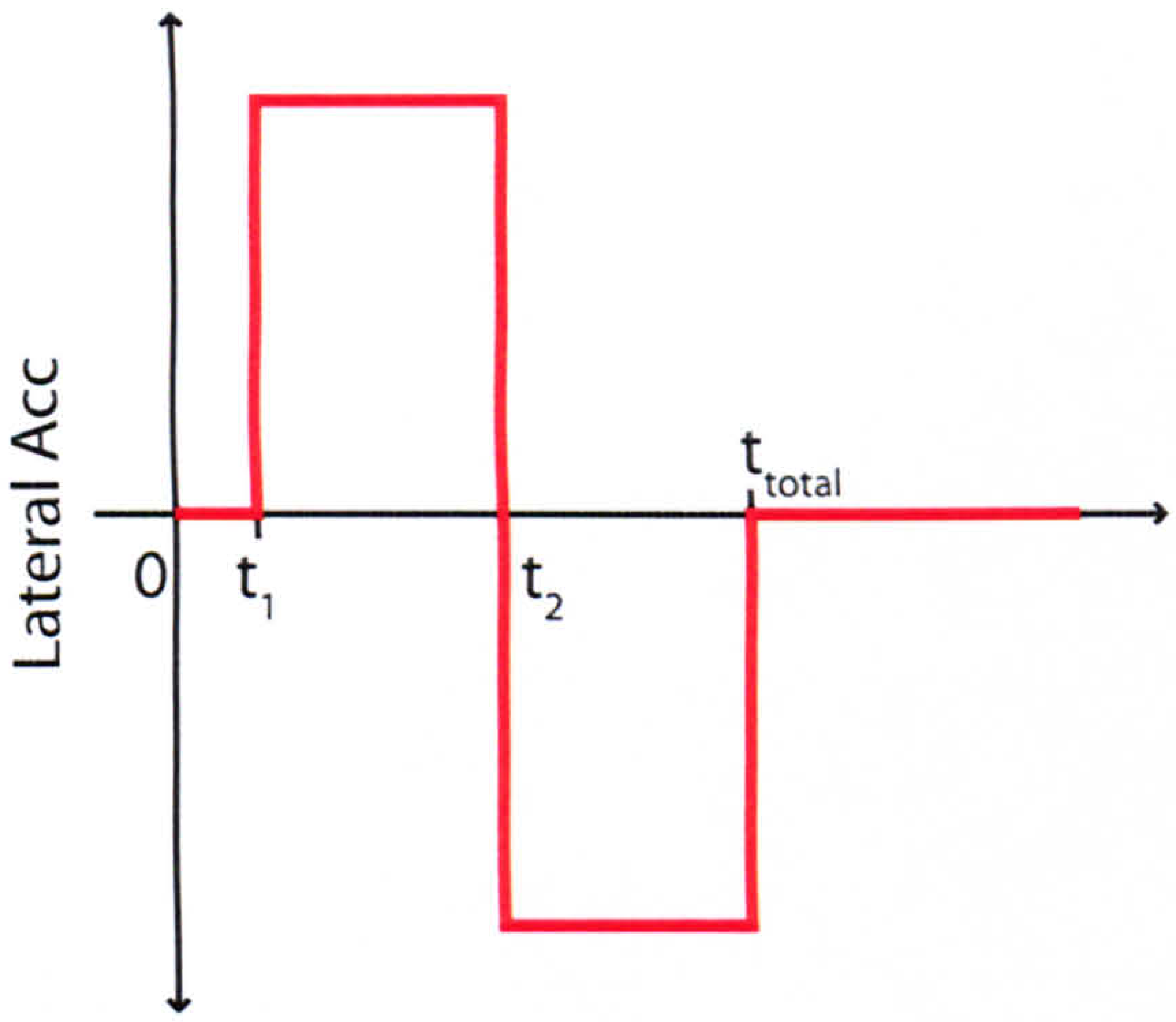


Figure 4.2: Reference lateral acceleration for an ELC

Table 4.3: Trajectory parameters for an ELC

Speed (m/s)	a_{max}(g)	t_1 (s)	t_2 (s)	t_{total}(s)	ρ_{ref}
8.9	0.1	0	1.75	3.50	0.0123
	0.5	0	1.75	3.50	0.0614
13.4	0.1	0	1.75	3.50	0.0055
	0.5	0	1.75	3.50	0.0273
17.9	0.1	0	1.75	3.50	0.0031
	0.5	0	1.75	3.50	0.0153
22.4	0.1	0	1.75	3.50	0.0020
	0.5	0	1.75	3.50	0.0098
26.8	0.1	0	1.75	3.50	0.0014
	0.5	0	1.75	3.50	0.0068
31.3	0.1	0	1.75	3.50	0.0010
	0.5	0	1.75	3.50	0.0050

provided by tilting the vehicle's vertical axis. The UK Highways Agency road design manual (Highways-Agency 1993) suggested that the maximum superelevation on a corner should be 5%, although the maximum allowed is 7%. Table 4.4 shows the modified design parameters for these degrees of superelevation. It can be seen that the radius of curvature was decreased by an average of 29%.

While these tighter radii of curvature would make lateral control a more difficult task, tilting the vehicle generates an additional lateral force due to the inclination of the mass of the vehicle. This increased the level of lateral acceleration that the vehicle could achieve. To run this simulation, additions to the basic vehicle model were required, as discussed

Table 4.4: Road design parameters for superelevation

Speed (m/s)	Radius of Curvature (m)	
	5% Super-Elevation	7% Super-Elevation
13.4	204	146
17.9	364	260
22.4	570	407
26.8	816	583
31.3	1113	795

in Section 2.3.2. The trajectory and level of superelevation could then be input to the simulation.

Environmental factors can also have a large effect on the lateral control of the vehicle. Side winds are often experienced in motorway driving and may cause accidents, especially in high sided vehicles such as trucks and vans. It is important therefore that the vehicle can maintain its lane position when subject to this kind of external disturbance. Again, additions to the vehicle model were required to model these side winds, as described in Section 2.3.1. The wind speed could then be input to the simulation as a vector function of time. For the purpose of this research the maximum side wind was set to 50mph at 90° to the vehicle heading angle, and the desired trajectory was a straight road.

In motorway driving the levels of grip available to the vehicle are always changing. With changing road temperature, rain, and ice, it is sometimes difficult for the driver to judge the level of available grip. It is therefore important that the lateral control systems can function in a wide range of conditions. Three levels of road surface friction were investigated in this research; they were $\mu = 0.85$, $\mu = 0.4$, and $\mu = 0.2$. Each of these frictional coefficients described a different road condition: 0.85 simulated normal driving on a dry tarmac road (Khatun et al. 2002), 0.4 simulated a wet road where grip is reduced, and 0.2 simulated an icy road where very limited grip was available (Sakai and Hori 2000). The full range of simulations (including ELCs), were conducted at these three levels of grip to assess the overall performance of each scheme.

While these parameters were usually constant for a full simulation, a split-μ case was also investigated. Split-μ testing involved one side of the vehicle being subjected to a high level of grip, and the other being subjected to a lower level. This could cause an additional yawing moment as different lateral and longitudinal forces built up at each tyre. This sort of testing has been investigated in the development of ABS systems and was directly relevant to the design of lateral control systems. To explore this condition in this research, during the lane change scenarios, a section of the road was designated as a low μ area; once a tyre entered this, the Pacejka parameters were reduced accordingly.

With all these trajectories and simulations, management of the Simulink® models and parameters became increasingly difficult. Eventually an external Simulink® model was constructed where trajectories and speeds were referenced by the m-file which ran the vehicle model. This meant that trajectories could be modified in one place affecting all vehicle models.

4.1.4 Summary

A range of test scenarios has been developed which fully captures motorway lateral control tasks from a vehicle perspective. Complex road geometry has been considered for lane keeping tasks. Three lane changes of increasing severity have also been covered which capture all styles of driver response. Environmental factors such as side winds and reduced friction have also been incorporated into the scenarios. These tests were used throughout the development of the lateral control systems in this research.

Currently there is no published standard for testing of full lateral control systems. While assessment criteria was not developed in this research, it is hoped that the guidelines and parameters provided may form the basis of test regimes for both off-line simulation development of lateral control systems and even real world testing of the systems.

4.2 Look Down Controller Development

4.2.1 PID Control Overview

Before improvements could be made to any lateral control scheme, it was first necessary to fully investigate the current standard of controllers. Most commonly used schemes are based on a simple lateral position controller developed by Ackermann (1993).

The control strategy involved some basic extensions to the 2dof state-space vehicle model described in Section 2.1. This extended model included not only lateral and yaw motions, but also the relative heading and lateral position of the vehicle with respect to a given path. It was assumed that this position was monitored using a sensor at a fixed distance l_s, along the centreline of the vehicle from its centre of gravity.

The given path was defined by any number of circular arcs. While the path at any transition point was continuous, there was a step change in radius of curvature (R_{ref}) between arcs. During straight sections of road $R_{ref} = \infty$, for this reason the concept of a normalised reference yaw rate was introduced. This was defined as $\rho_{ref} = 1/R_{ref}$, and was defined positive for left hand cornering, negative for right hand cornering and zero for straight sections of road. While it described the curvature of a trajectory, it also described the normalised steady state yaw rate (irrespective of longitudinal velocity) that was required for a vehicle to follow this trajectory. The non-normalised reference yaw rate was defined as $r_{ref} = u\rho_{ref}$, this could be used as the longitudinal velocity of the vehicle was to remain constant. The vehicle motion for this tangential cornering was modelled as follows. Figure 4.3 shows the radial line from the centre, M, passing through the centre of gravity, CG, of the vehicle intersecting the point, z_{ref}, on the given path. The distance from z_{ref} to the vehicle's CG is the deviation y_{CG}. Figure 4.3 also shows the global co-ordinate system x_0, y_0 and the car body fixed co-ordinate system x, y which is rotated by the vehicle yaw angle ψ. The tangent to the path at z_{ref} denoted by $\vec{v}_t$ is rotated by a reference yaw angle ψ_t, with respect to x_0.

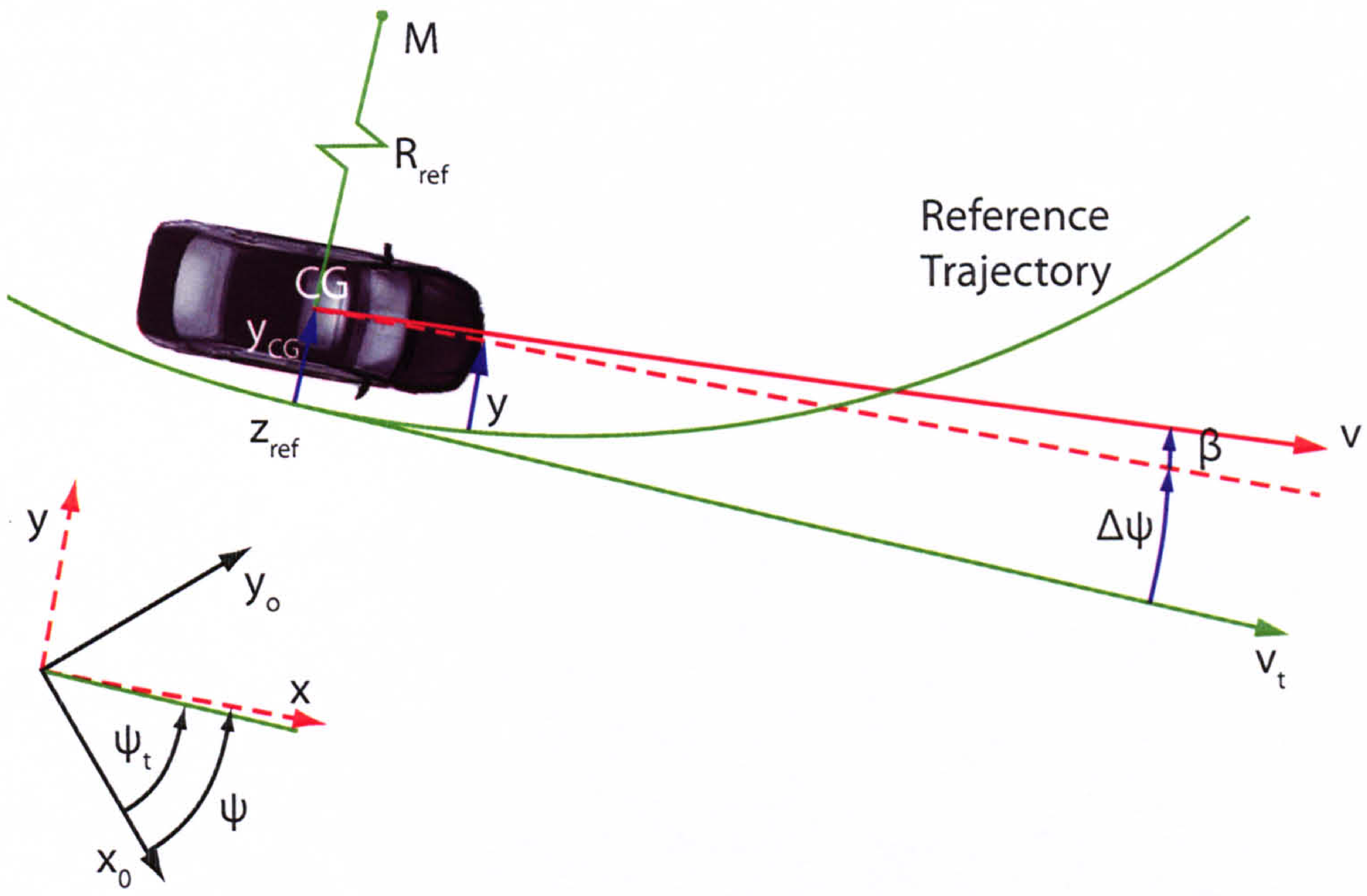


Figure 4.3: Overview of the Ackermann approach to lateral error calculation

As the variable required for lateral control was lateral position error, it was necessary to develop a model for the rate of change of the y_{CG} term. The component of the vehicle velocity that is perpendicular to $\vec{v}_t$ is equal to this rate of change of y_{CG}. This lateral component of the desired vehicle velocity is given by $u \sin\beta + \Delta\psi$, where $\beta = v/u$ is the sideslip of the vehicle, and $\Delta\psi = \psi - \psi_t$ is the angle between the tangent to the path at z_{ref} and the centreline of the vehicle.

It is assumed that this lateral deviation is small and so linearises to:

$$\dot{y}_{CG} = u(\beta + \Delta\psi) \tag{4.2}$$

As the sensor was mounted at the distance, l_s, in front of the centre of gravity, the measured displacement, y, from the given path changed both with $\dot{y}_{CG}$ and the yaw rate of the vehicle. Taking this into account the rate of change of the measured displacement was

$$\dot{y} = u(\beta + \Delta\psi) + l_s r \tag{4.3}$$

Determination of this error term requires knowledge of β, r and $\Delta\psi$. β and r were available from the simple bicycle model. The angle $\Delta\psi$ could be obtained by integrating its derivative

$$\begin{aligned} \Delta\dot{\psi} &= \dot{\psi} - \dot{\psi}_t \\ &= r - r_{ref} \\ &= r - u\rho_{ref} \end{aligned} \tag{4.4}$$

Combining Equations 4.3, 4.4, and the state-space vehicle model (Equation 2.8) yielded the following:

$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \\ \Delta\dot{\psi} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & 0 & 0 \\ k_{21} & k_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ u & l_s & u & 0 \end{bmatrix} \begin{bmatrix} \beta \\ r \\ \Delta\psi \\ y \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ u \\ 0 \end{bmatrix} \rho_{ref} + \begin{bmatrix} n_1 \\ n_2 \\ 0 \\ 0 \end{bmatrix} \delta_f \tag{4.5}$$

where

$$\begin{aligned} k_{11} &= \frac{-(C_r + C_f)}{m_t u} \\ k_{12} &= -1 + \frac{(C_r b + C_f a)}{m_t u^2} \\ k_{21} &= \frac{-(C_r b + C_f a)}{I_{zz}} \\ k_{22} &= \frac{-(C_r b^2 + C_f a^2)}{I_{zz} u} \\ n_1 &= \frac{C_f}{m_t u} \\ n_2 &= \frac{C_f a}{I_{zz}} \end{aligned}$$

Running this state-space model required curvature ρ_{ref} and steer angle δ_f as input variables. The model would then calculate not only the vehicle's lateral and yaw accelerations, but also the lateral position error from the given path which was used as the input to the control system. As automatic steering was required, the steer angle was not available as an input, instead its value was calculated dependent on the position error of the vehicle. The lateral position error output from the extended vehicle model described was used as the feedback signal to the vehicle model.

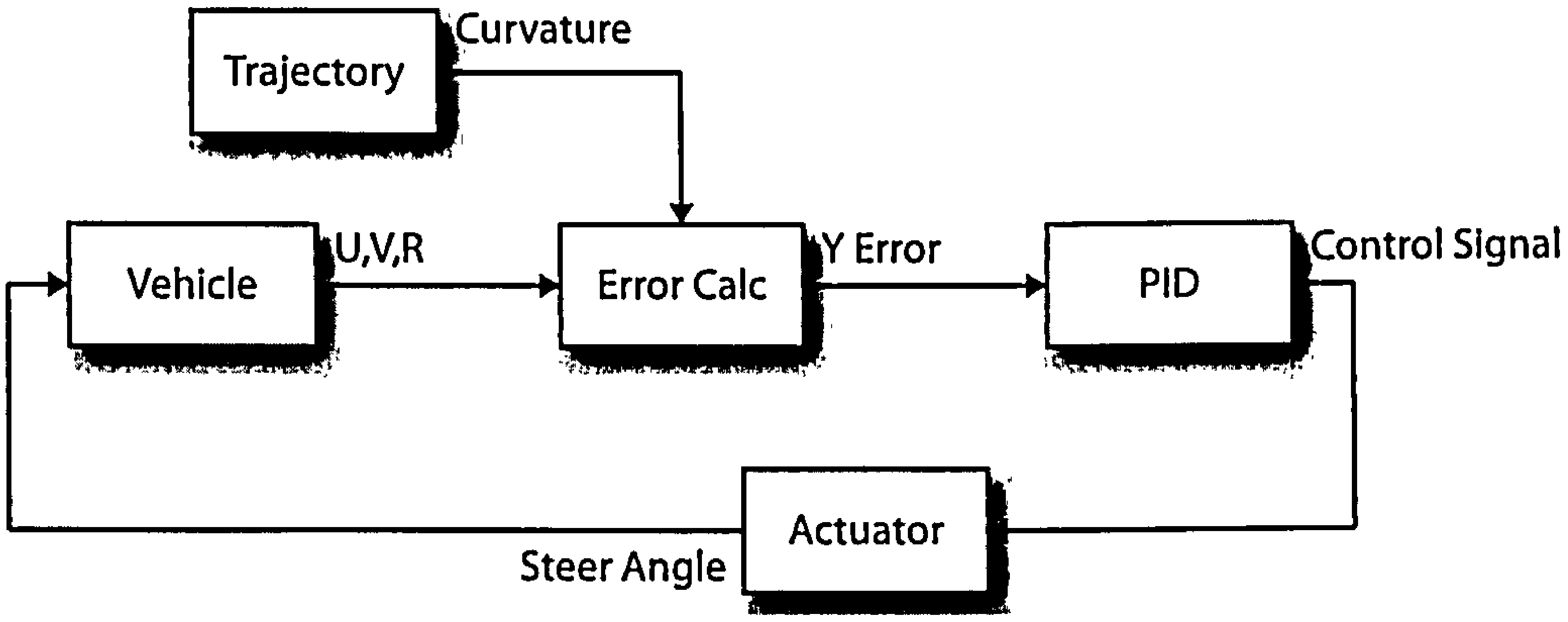


Figure 4.4: Block diagram of PID lateral control strategy

The error was controlled though a PID control system, of which the output was fed back into the vehicle model as the steer angle. The current design of steering actuators was simply modelled with the following parameters: a rate limit of 25°/s, and a steering angle limit of 5°(Sebastian et al. 1997). The block model of the control system is shown in Figure 4.4. This simple control strategy was investigated using an extended state-space 2dof vehicle model. Given u was constant in this model, the only input variable was ρ_{ref}. This was varied to replicate a range of sharp and shallow corners, and tested at different velocities. Initial tuning of the proportional, integral and derivative gains (K_P,K_I,K_D,) was performed manually with little success, given the range of manoeuvres and speed over which the controller was required to perform. It quickly became apparent that a well defined method of tuning was required to generate acceptable performance with this control scheme.

PID Tuning Methodology

One of the main problems with PID control is the need to tune its gains. This was especially the case with this lateral control problem. The wide range of manoeuvres defined in Section 4.1 mean that one set of gains may work well for a certain scenario, but not for another. Standard methods of tuning were investigated, the Cohen-Coon method is used for first order plus time delay systems, and so is not applicable to this 2nd order system. The Ziegler-Nichols method on the other hand, does not require a specific process model. The method involves setting the integral and derivative gains to zero and then increasing the proportional term until the response becomes oscillatory. This 'critical' gain is termed K_C, the period of this oscillation is termed P_C. The integral and derivative terms can then be calculated from Table 4.5.

Table 4.5: Ziegler-Nichols PID tuning method

	P	PI	PID
K_P	$0.5K_C$	$0.45K_C$	$0.6K_C$
K_I		$P_C/1.2$	$P_C/2$
K_D			$P_C/8$

This method was used as the basis for tuning of the PID gains of this look down controller. The tuning scenario inputs for the system are summarised in Table 4.6, (see Section 4.1.2 for a more detailed explanation of each scenario). It was decided to use these manoeuvres alone to tune the PID gains, as they covered a significant proportion of the behaviour of the vehicle in motorway scenarios. The SLC covered low acceleration manoeuvres, where as the ELCs were more concerned with the performance of the system at high accelerations. All manoeuvres were performed at three vehicle speeds (50mph, 60mph, 70mph). The lane change also provided an interesting control input as it created a partly transient response where the vehicle must change direction. Additional manoeuvres such as exterior disturbances could have been added to this list, but it was thought that these scenarios would cover enough of the spectrum of vehicle manoeuvres for tuning purposes.

Table 4.6: Summary of PID tuning scenarios

ID	Manoeuvre	Speed (m/s)
1	Standard Lane Change	22.4
2	Standard Lane Change	26.8
3	Standard Lane Change	31.3
4	Evasive Lane Change 0.1g	22.4
5	Evasive Lane Change 0.1g	26.8
6	Evasive Lane Change 0.1g	31.3
7	Evasive Lane Change 0.5g	22.4
8	Evasive Lane Change 0.5g	26.8
9	Evasive Lane Change 0.5g	31.3

To tune the controller, the control strategy was first coded in Simulink® and added to the 2dof vehicle model. A Matlab® m-file was constructed with the vehicle data-set and additional parameters, including vehicle velocity and the gains for the PID controller.

This m-file also ran the simulation and plotted the lane position error and yaw rate response results. This worked well, but tuning still required the manual changing of the gains, which was a laborious process, especially when it is considered that there were nine scenarios to tune for. It was decided to create a loop that would repeatedly run the simulation varying the gains as requested by the user, allowing the 'critical' gain to be found a lot quicker. Results from multiple runs could also be displayed on the same axis so their performance could be instantly compared. Once K_C (the value of proportional gain where the steady state yaw rate response became oscillatory) was found, K_P and K_D were set as suggested by the Ziegler-Nichols method. As there was little or no steady state error, K_I was always set to zero. The derivative term K_D was then fine tuned over a range of 10%, again using the simulation loop, to achieve near critical damping.

The controller was initially tuned for the ELC 0.1g manoeuvres and its performance validated in both the SLC and ELC 0.5g manoeuvres.

After extensive gain tuning it was obvious that this control strategy would fail at high lateral acceleration (0.5g) lane change manoeuvres, even at the lower speeds of 50mph and 60mph. The controller was instead tuned to provide the best response over the remaining range of manoeuvres. Work then moved on to integrating the same PID controller with the 9dof vehicle model. While high lateral acceleration manoeuvres were not possible, this scheme still provided a base line against which other strategies could be compared.

PID Control on the Full Vehicle Model

While the 2dof vehicle model provided an ideal foundation on which to develop the control logic and test scenarios, it was not sufficient to investigate the dynamic performance of the vehicle at the level of detail required for this research. In Section 2.3 a 9dof vehicle model was developed which was capable of capturing the performance of the vehicle in a range of conditions, including at the limit of linear handling, and with variable frictional coefficients.

While the 2dof vehicle model uses linear cornering stiffness values, the 9dof model has a non-linear tyre model. This added complexity may cause problems with this control methodology due to the linear nature of the PID controller. It was hoped to investigate these complexities and implement any improvements if required. As the Simulink® model calculated the accelerations for all 9dof, it was possible to use the same lateral position error calculation as for the 2dof model.

This version of the 9dof vehicle model had the following features to reduce simulation time and ensure that high fidelity testing was repeatable and accurate:

No Powertrain or brake model Instead a simple speed control system provided an evenly distributed torque to all four wheels ensuring the test was carried out at a constant speed, similar to the 2dof model.

No Steering System As the actuator was to directly control the desired steer angle, no model of the power steering system was required.

Standard Slip Calculations None of the test scenarios began at zero or low speed, so additional modelling of low speed slip behaviour was not required.

Pacejka tyre model A vectorised version of the full Pacejka Tyre model described in Section 2.4 was used.

The gains from the 2dof simulations were initially used in these full model simulations. The system was then fine tuned again using a 10% margin for both the proportional and derivative term. Figure 4.5 shows the effect of increasing the proportional term for the SLC manoeuvre. Again the controller failed for the high lateral acceleration manoeuvres (Figure 4.6) and so the gains were tuned to provide a smooth quick response for the rest of the range of manoeuvres.

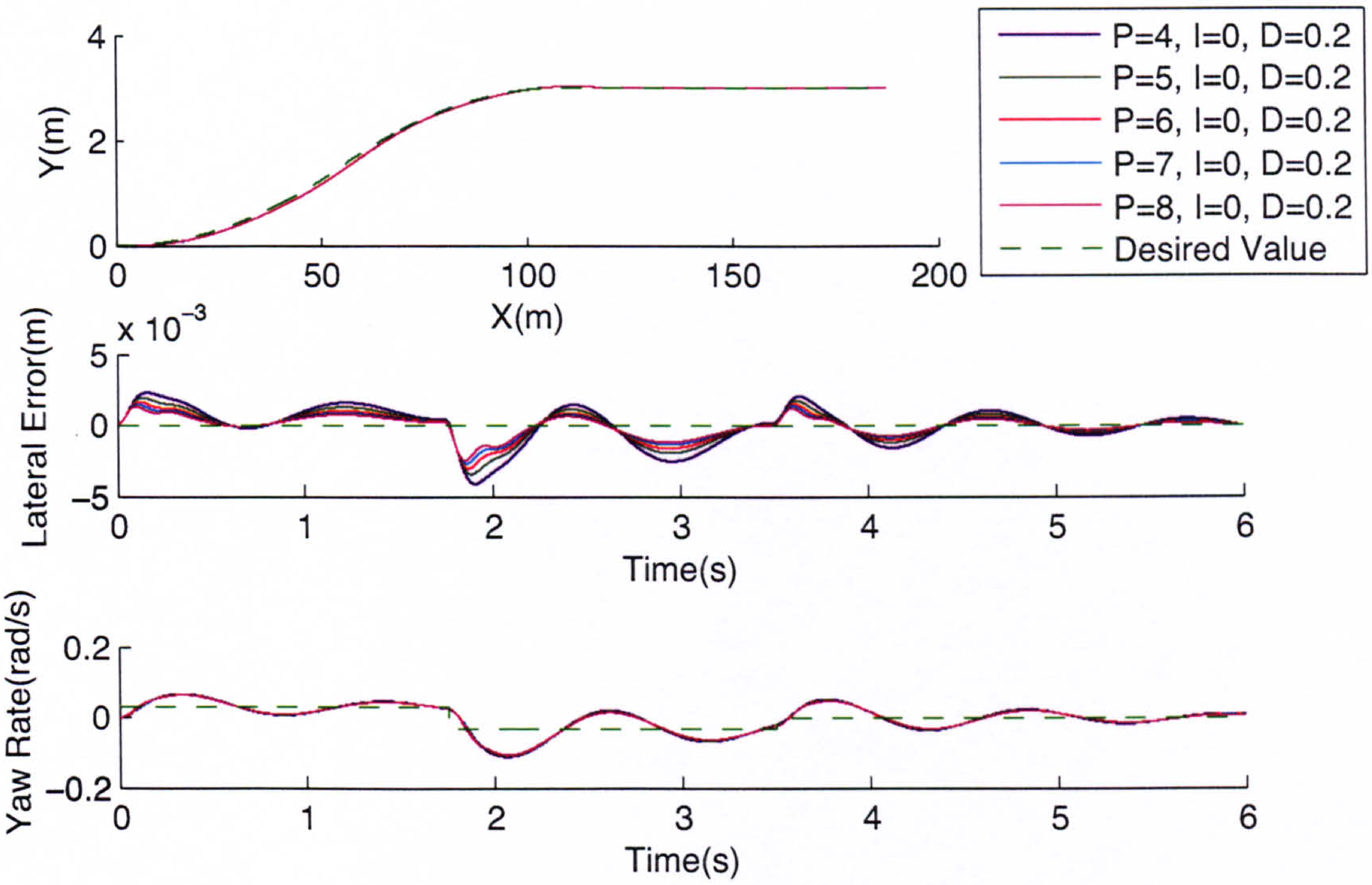


Figure 4.5: Tuning output of 9dof PID lateral control system for a SLC at 60mph

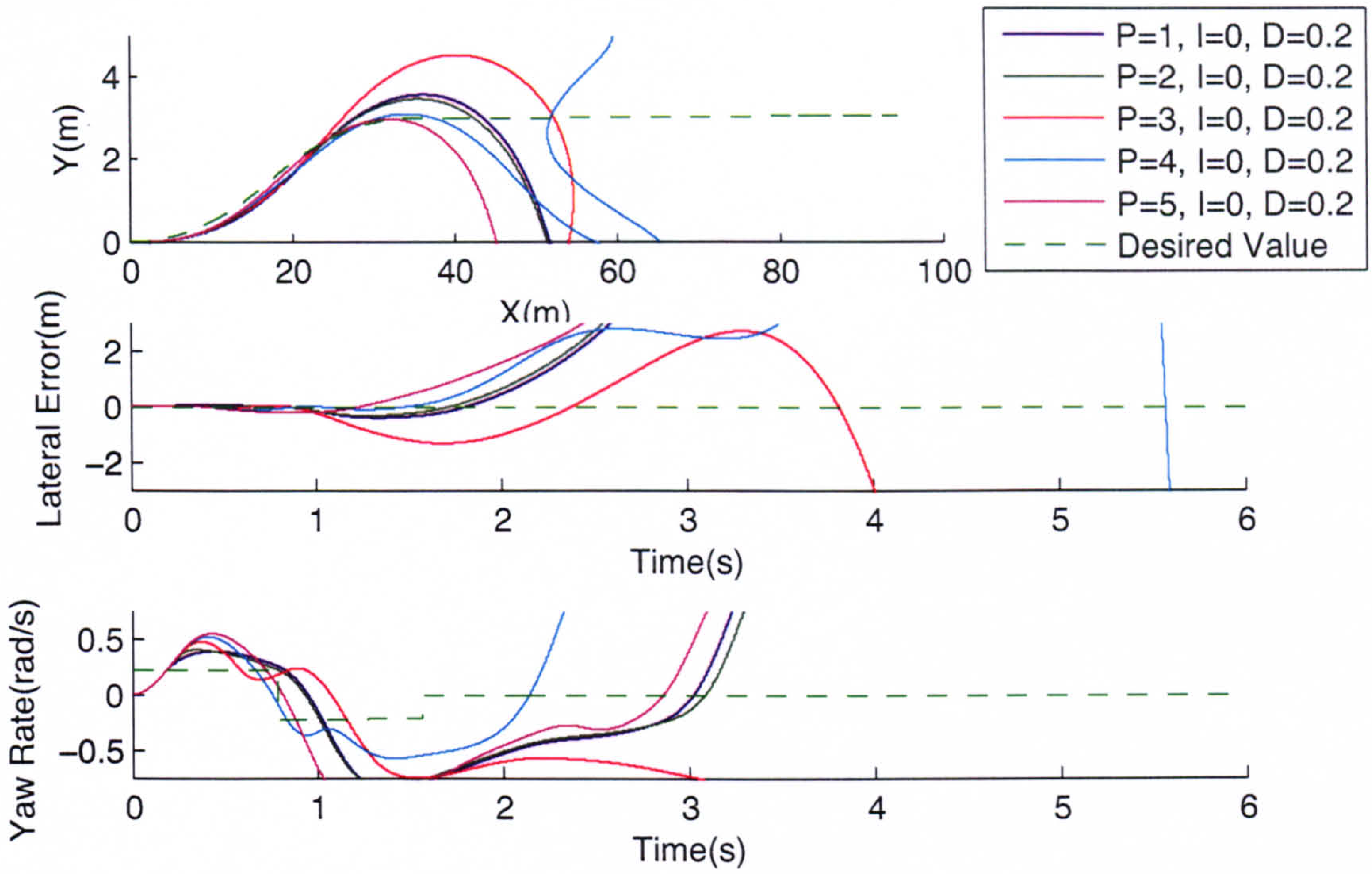


Figure 4.6: Tuning output of 9dof PID lateral control system of a 0.5g ELC at 60mph

The PID strategy was then tested over the full range of manoeuvres discussed in Section 4.1. The results from these tests are presented in Section 4.3, where the merits of this system are compared to other strategies.

4.2.2 Combined Internal Model and PID Control

While the simple PID controller provided good results for low speed non-severe manoeuvres, it relied solely on the lateral position of the vehicle. It provided no direct control over the yaw rate or heading direction of the vehicle. This could lead to complications during severe manoeuvres. To overcome this problem a more sophisticated Internal Model Control (IMC) scheme was developed to ensure minimal yaw rate errors.

Another problem with the PID scheme was the need to tune the controller to make its performance acceptable over a range of conditions. Internal Model Control (IMC) was suggested as a alternative strategy. The internal model principle states that:

> "A structurally stable synthesis must utilise feedback of the regulated variable, and incorporate in the feedback path a suitably reduplicated model of the dynamic structure of the disturbance and reference signals."(Francis and Wonham 1976)

If the control scheme developed is based on an exact model of the process, then perfect control is theoretically achievable. Figure 4.7 shows a simple control system.

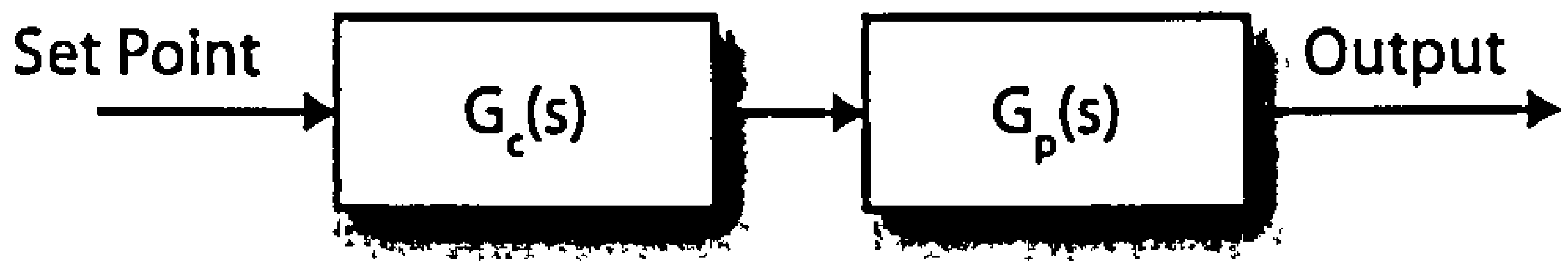


Figure 4.7: Simple Internal Model Control (IMC)

A controller G_c is used to control the process G_p. An accurate model of the process $\tilde{G}_p$could be created, by setting G_c to be the inverse of the process model:

$$G_c = \tilde{G}_p^{-1}$$

And if $G_p = \tilde{G}_p$, then it is clear that the output will always be equal to the input, perfect controller performance is achievable without feedback. As with all controllers, problems can be created in the accuracy of the model used. Chapter 2 considered the accuracy of the vehicle models used throughout this research, the simplest of which was the 2dof state space model. While this did not provide the most accurate representation of the vehicle's behaviour, it was the most simple to use to test out this IMC principle.

The first requirement was to invert the state space vehicle model. Given the vehicle model in matrix form:

$$\begin{bmatrix} m_t & 0 \\ 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} \frac{C_f+C_r}{u} & m_t u + \frac{aC_f-bC_r}{u} \\ \frac{aC_f-bC_r}{u} & \frac{a^2C_f+b^2C_r}{u} \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} = \begin{bmatrix} C_f \\ aC_f \end{bmatrix} [\delta_f] \quad (4.6)$$

the state space of this is in the form

$$P\dot{\mathrm{x}} + Q\mathrm{x} = R\mathrm{u}$$

in which x is the state vector and u is the input vector

$$\mathrm{x} = \begin{bmatrix} v \\ r \end{bmatrix} \qquad \mathrm{u} = [\delta_f]$$

the state space notation then takes the general form

$$\begin{aligned} \dot{\mathrm{x}} &= A\mathrm{x} + B\mathrm{u} \\ \mathrm{y} &= C\mathrm{x} + D\mathrm{u} \end{aligned}$$

Where:

$$A = -P^{-1}Q \quad \text{and} \quad B = P^{-1}R$$

It was then possible to convert this state-space model into two transfer functions describing the system, one for the $\dot{v}_y$ term and one for the $\dot{r}$ term. This was done using the *ss2tf* function in Matlab® at the start of each simulation, as the velocity u was only variable between runs. The process is shown here for reference.

Taking the Laplace transform of:

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}$$

yielded:

$$s\mathbf{X}(s) = A\mathbf{X}(s) + B\mathbf{U}(s)$$

Next, simplifying for $\mathbf{X}(s)$, gave

$$(s\mathbf{I} - A)\mathbf{X}(s) = B\mathbf{U}(s)$$

$$\mathbf{X}(s) = (s\mathbf{I} - A)^{-1}B\mathbf{U}(s)$$

taking the lapace transform of the output vector:

$$\mathbf{y} = C\mathbf{x} + D\mathbf{u}$$

gave the following:

$$\mathbf{Y}(s) = C\mathbf{X}(s) + D\mathbf{U}(s)$$

substituting for $\mathbf{X}(s)$ in this equation, gave:

$$\mathbf{Y}(s) = C((s\mathbf{I} - A)^{-1}B\mathbf{U}(s)) + D\mathbf{U}(s)$$

Since the transfer function $\mathbf{G}(s)$ is defined as the ratio of the output to the input,

$$\mathbf{G}(s) = \frac{\mathbf{Y}(s)}{\mathbf{U}(s)}$$

substituting in the previous expression for $\mathbf{Y}(s)$, gave

$$\mathbf{G}(s) = C(s\mathbf{I} - A)^{-1}B + D$$

As the state space model was made up of two equations of motion, there were two transfer functions. The PID control strategy demonstrated low lane position error for its capable range of manoeuvres (Section 4.3). This method used lateral position error as the only input to the system, and so had no means of directly controlling yaw rate. It was hoped that it could be achieved using the IMC and so the second of these two transfer functions was used as it modelled the yaw rate behaviour of the vehicle.

The next step in the inversion process was to add a first order delay into the system to ensure that the denominator is of equal order to the numerator.

$$Y'(s) = Y(s) \times (\tau(s) + 1)$$

This time period τ, was the time taken for the yaw rate to reach 66% of its input. It was initially set to 0.05s, but could be tuned to provide a quicker response if required.

The transfer function was inverted so that an input of yaw rate would give the required steer angle.

$$G^{-1}(s) = \frac{U(s)}{Y'(s)}$$

This transfer function was converted back to a state space model using the Matlab® function *tf2ss*. This state-space model could then be used as the controller. Figure 4.8 shows this simple 2dof state space model, notice its similarity to the example in Figure 4.7.

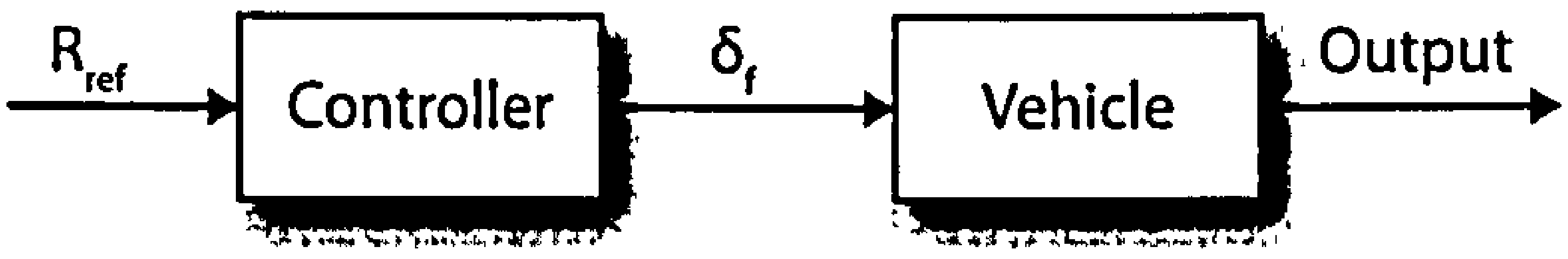


Figure 4.8: Block diagram of yaw rate IMC of the 2dof vehicle model

Initial results from this were positive (Figure 4.9). Yaw rate tracking was excellent, and as expected the system behaved like a first order delay. As there was no control over lateral position the error was high. Had the control action been perfect, this would not be the case, but due to the first order delay perfection is not possible. This error could be minimised by reducing the τ term, but it is not practical given the simulation step size. To control the lateral position successfully, additional control action was required, this could be provided by the PID control explored in the previous section. An initial idea was to combine the two control methods adjusting the influence of the PID control scheme through an additional gain. This would ensure low lateral error, while the IMC ensured a stable yaw rate response.

Figure 4.10 shows the responses of the three control strategies to an ELC at 0.1g using the 2dof vehicle model. The combined effect of both control strategies is immediately

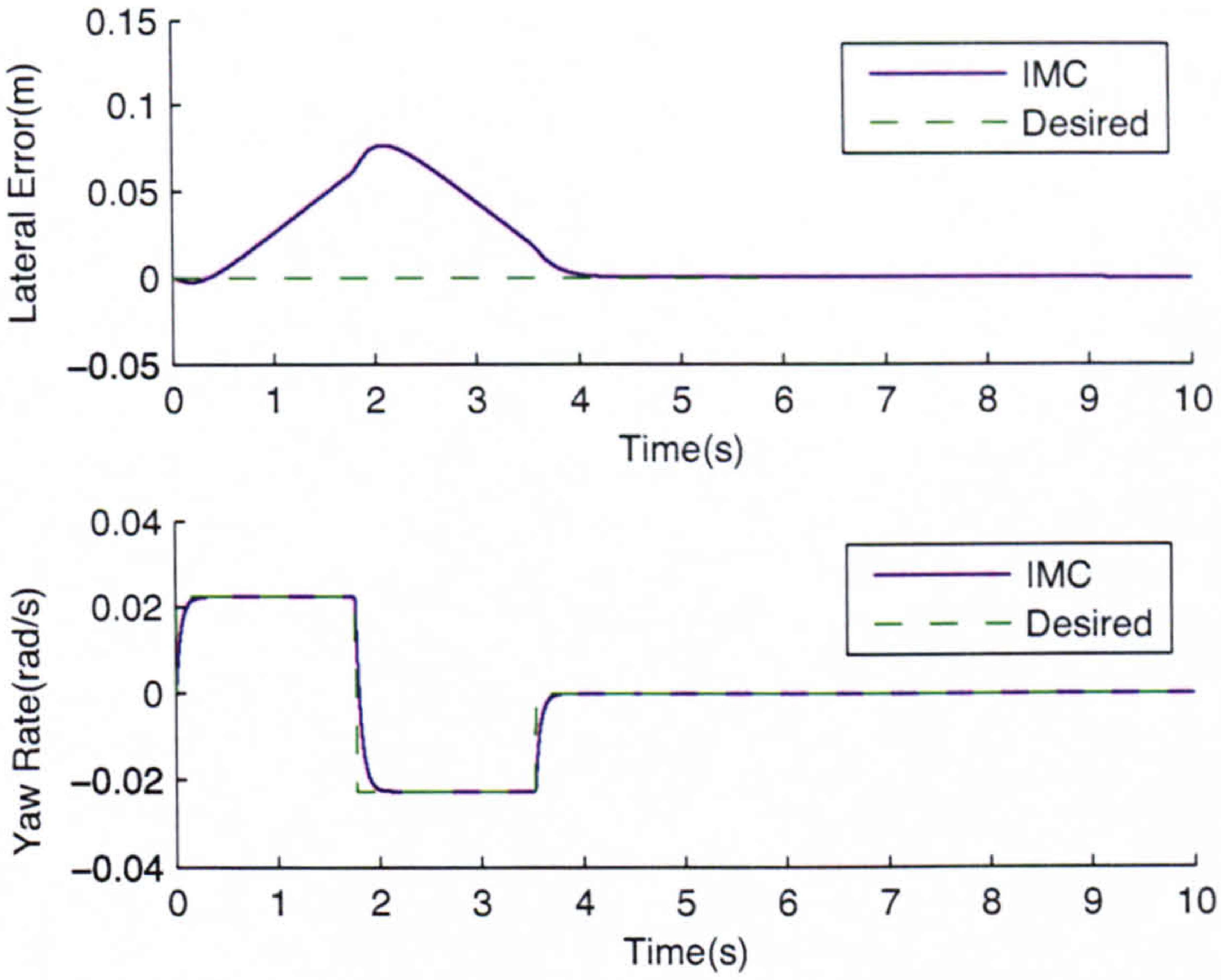


Figure 4.9: Yaw rate and lateral error plots from yaw rate IMC

apparent, even before tuning the influence of each method. While the lateral error was increased from the pure PID case, the yaw rate was less oscillatory, and while there was still some overshoot, it was less than in the pure PID case. It was hoped that this increased stability of yaw rate would in turn increase the stability of the vehicle through the full range of manoeuvres.

To employ the IMC on the full 9dof vehicle model, it was first necessary to extend the control scheme. The inverse model of the 2dof was relatively simple to formulate due to its linear nature and small number of equations. Due to the complexity of the 9dof model it was not possible to invert it. The inverse 2dof model was used instead, but due to the differences between the vehicle and inverse model, and possible unknown disturbances, a feed-forward control scheme was proposed based on the inverse model discussed above. A block diagram of the model is shown in Figure 4.11.

In this model, the inverse model output was the input to both the vehicle and a reference or internal model. The difference between the outputs of these models was then fed back as the error term for the inverse model. This closed loop control meant that differences between the inverse and vehicle model were taken into account and their effects mitigated.

Again this control scheme was concerned with only the yaw rate response of the vehicle, and so the PID strategy was added to the model to provide the required lateral position control. Figure 4.12 shows this control strategy in block diagram form.

One of the advantages of IMC control was the lack of tuning required. This benefit

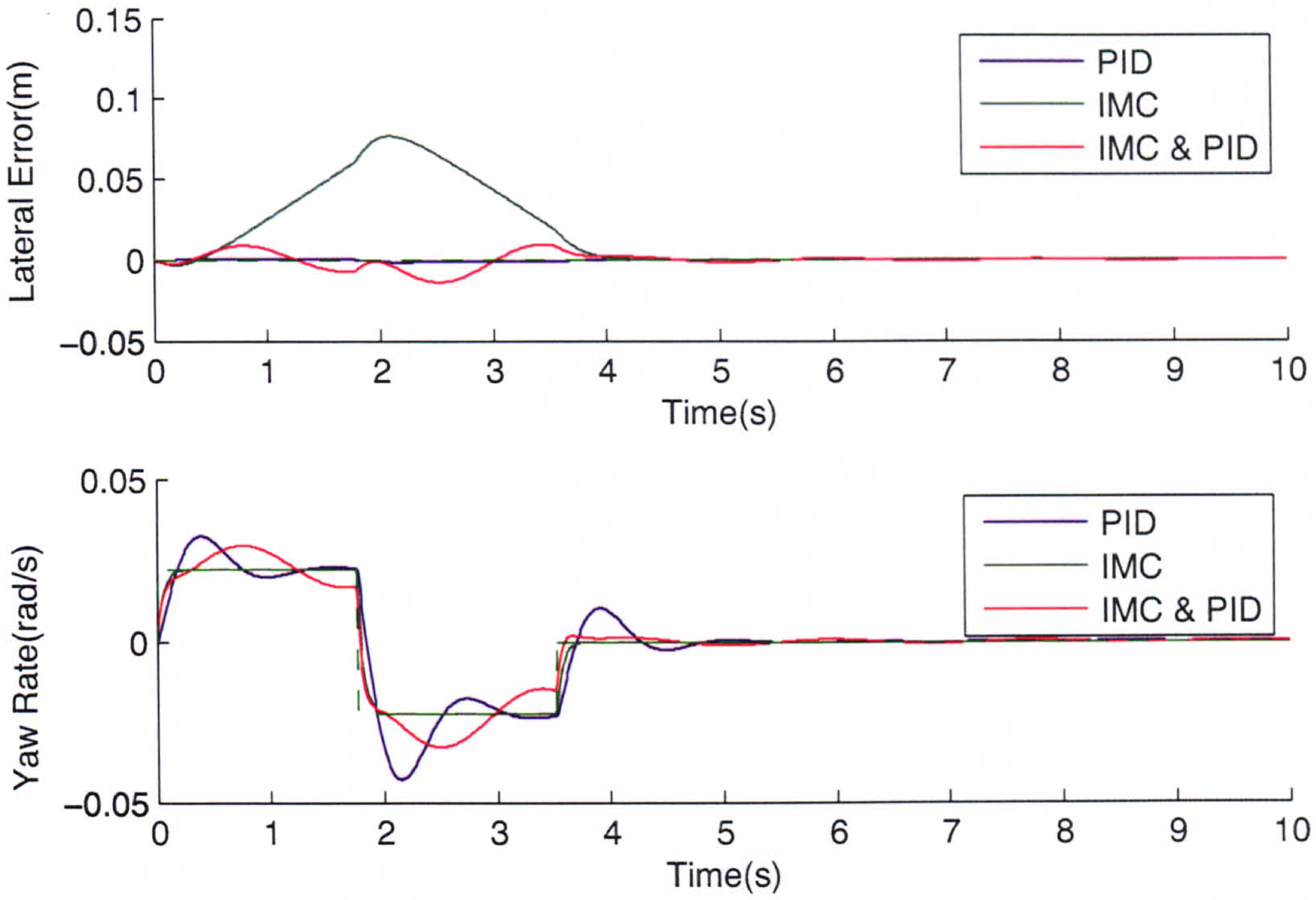


Figure 4.10: Comparison of IMC and PID control schemes for ELC 0.1g manoeuvre at 70mph

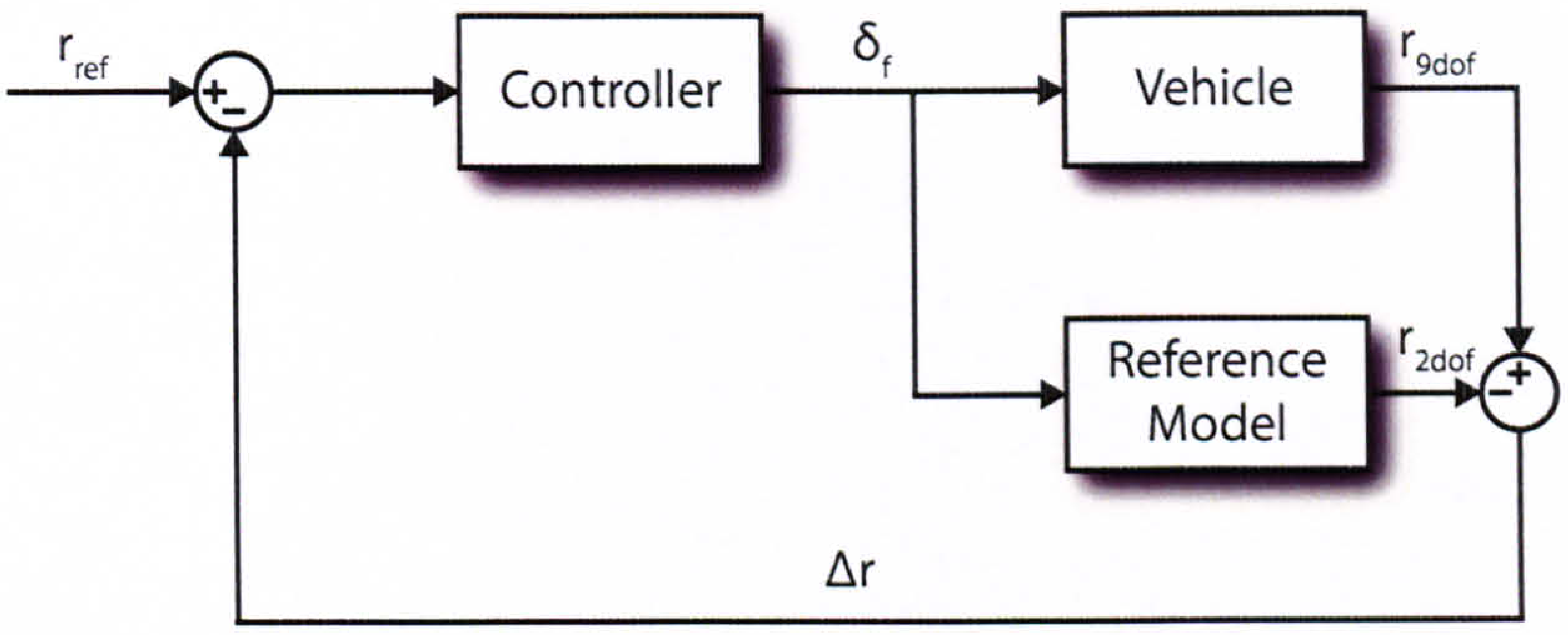


Figure 4.11: Block diagram of 9dof IMC model

was obviously negated when the IMC was used in conjunction with the PID strategy. Once again the proportional, derivative and integral gains required tuning. This time to increase or decrease the effect of the lateral position control. Increasing the influence of the PID controller would reduce the lateral position error of a manoeuvre, but make the yaw rate response more oscillatory, eventually resulting in an unstable manoeuvre. Results were positive with the controller capable of the full range of manoeuvres. With this in mind the PID gains were tuned to ensure a stable performance on the evasive 0.5g manoeuvres with the minimum lateral position error possible.

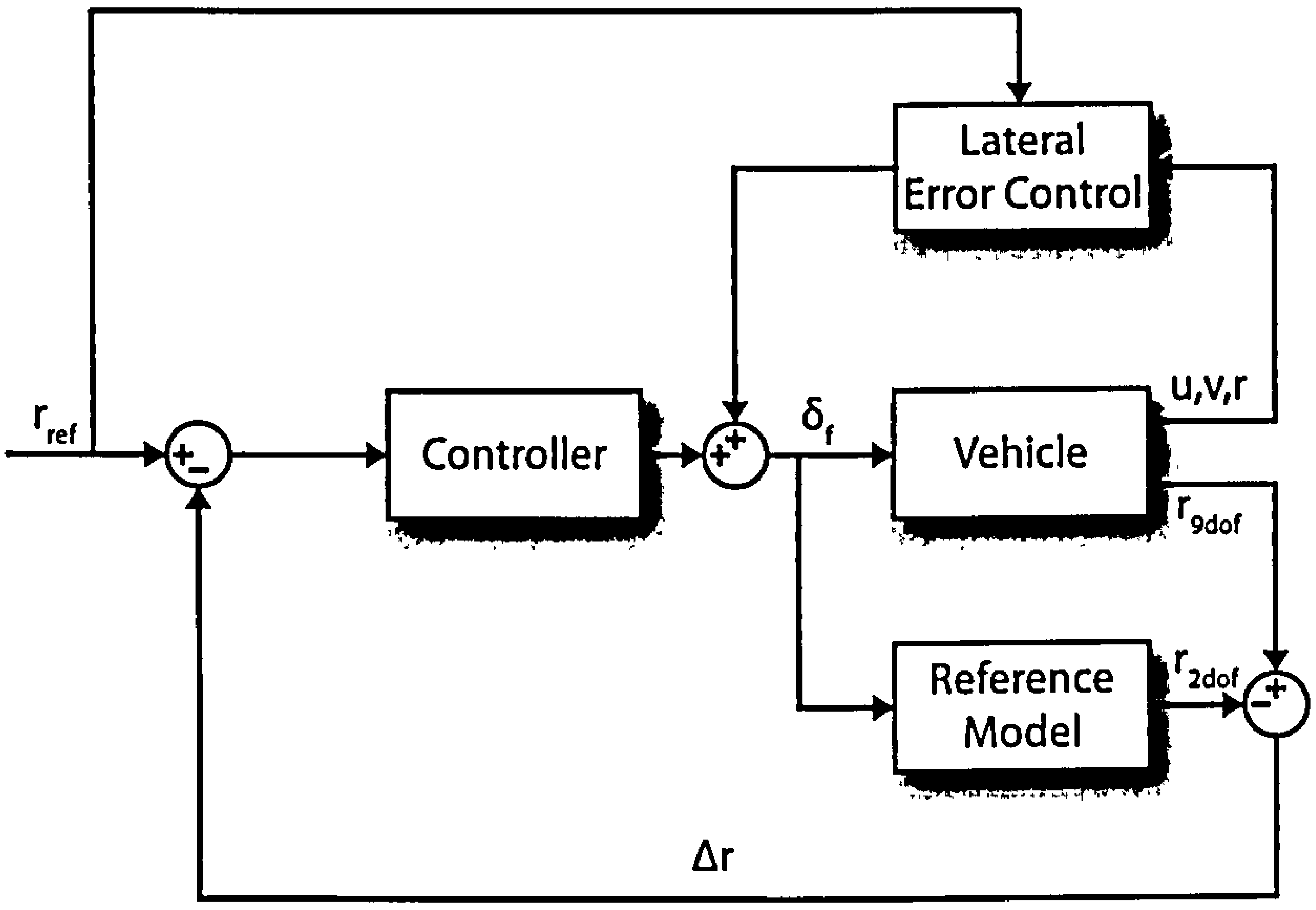


Figure 4.12: Block diagram of 9dof IMC & PID model

4.3 Look Down Analysis

The look down schemes developed in the previous sections were tested using the test scenarios suggested in Section 4.1. The results of these tests are presented in this section, and the merits of the standard PID system, and combined IMC and PID system are discussed.

4.3.1 Lane Keeping Results

Straight Roads

While straight flat roads may seem the simplest lateral control task, they are also one of the most common. Good performance in these tasks is key to successful control in other more complex manoeuvres, for this reason this was always the first simulation run.

Both control systems performed excellently for this scenario, the controllers tracked the straight road with no noticeable error. Any lateral error was caused by the residuals of the simulation. This lateral error was, at worst cases in the magnitude of 10^{-24} after a 10s simulation. The error was fairly consistent over the full range of speeds, 20mph - 70mph. These results were as expected, and provided the foundations for other more complex tests.

Curved Roads

With the success of both systems on the straight flat roads, the first complexity was added to the scenario. Flat corners may again seem like a simple lateral control task but due to the irregular nature of UK motorways these curved sections of road are maybe more prevalent than straight sections found in other less densely populated countries. The tests were carried out for the full range of design speeds with positive results. Three of the six speed sets of results are discussed below. They fully demonstrate the behaviour of each controller over the full speed range. At a time of 1s there was a step change in reference yaw rate from 0 (straight road), to a yaw rate which replicated an ideally designed corner (Section 4.1) for 5s, there was then a step change back to zero for the rest of the simulation.

Figure 4.13 shows the response of the controllers on a flat corner at 13.4 m/s (30mph). The first set of axes shows the desired trajectory and that taken when the vehicle is equipped with either control system. The plot shows that both controllers are near identical, which signifies a successful tracking task. More can be gained by considering the second graph which shows the lateral error generated by each system.

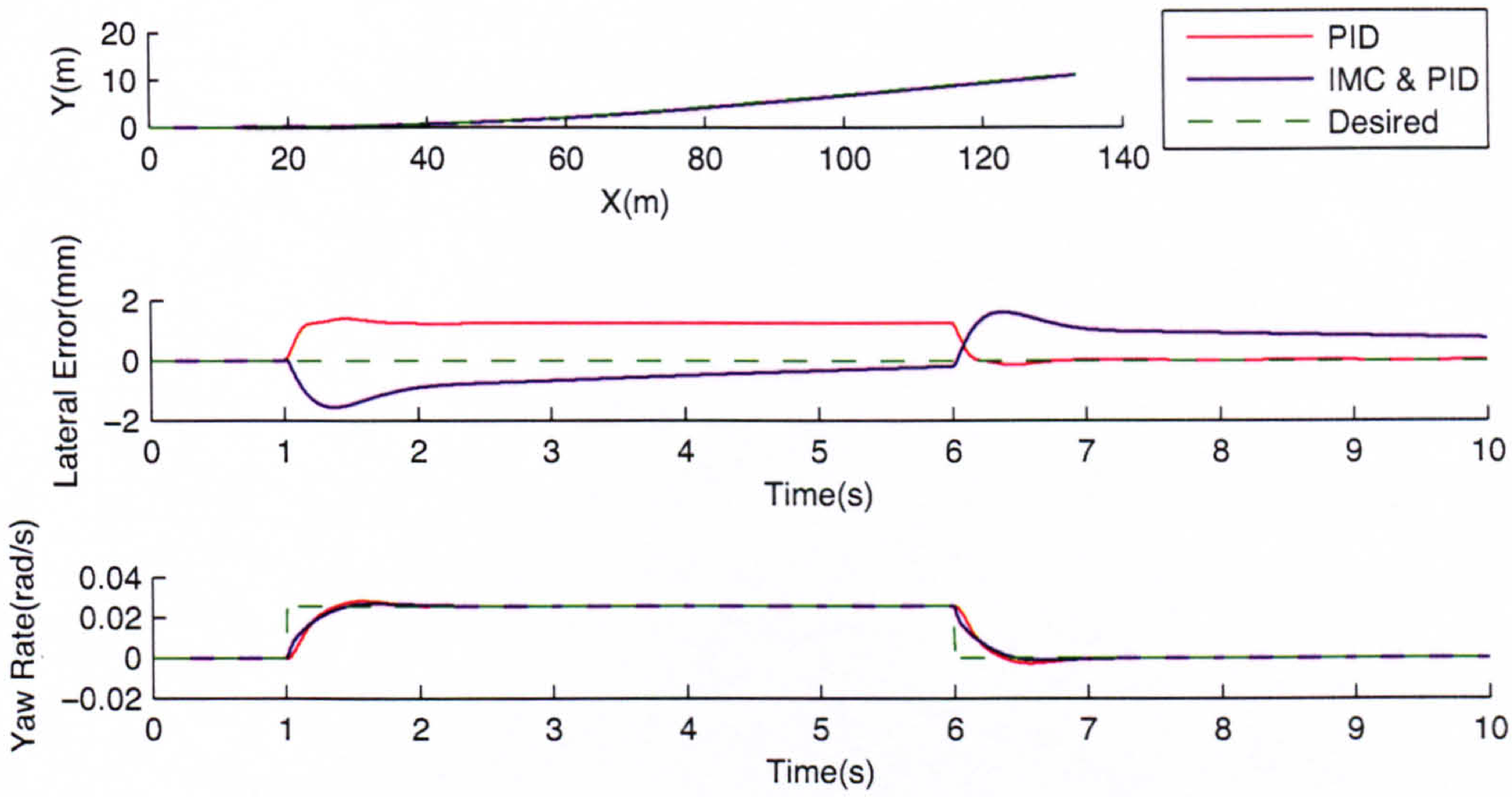


Figure 4.13: Response of look down systems during a flat corner at 30mph

Before commenting on the trends shown in the graph, it is important to notice the scale on the y-axis. The maximum error is of the order of 2×10^{-3}m (2 mm), this explains why the first set of plots look identical. The error with both systems is very low, and therefore acceptable; but it is important to consider any trends in this low speed response that may affect the response at higher speeds. Firstly, the errors from each system are of a similar magnitude, although they are in opposite directions. As the IMC-PID scheme is trying to reduce yaw rate error, it immediately processes the step change in desired yaw rate error and so turns into the corner early, hence the negative error. The PID scheme on the other hand does not directly receive this step change in desired yaw rate. Instead it monitors only lateral error, and so is not able to react as quickly as the IMC-PID scheme.

This can be seen in the third plot which shows the yaw rate of both systems, the IMC-PID scheme reacts more quickly to the change in yaw rate. It is also noticeable that the yaw rate of both systems is stable and non-oscillatory. At 6s where the yaw rate is again reduced to zero, the PID system quickly reduces the lateral error to zero with a slight overshoot. The IMC-PID again responds to the step change in desired yaw rate and as a result generates a positive lateral error. This error will eventually decay to zero, but it is one of the disadvantages of the IMC scheme. Again it is important to consider that the magnitude of this error is $\approx$ 1mm.

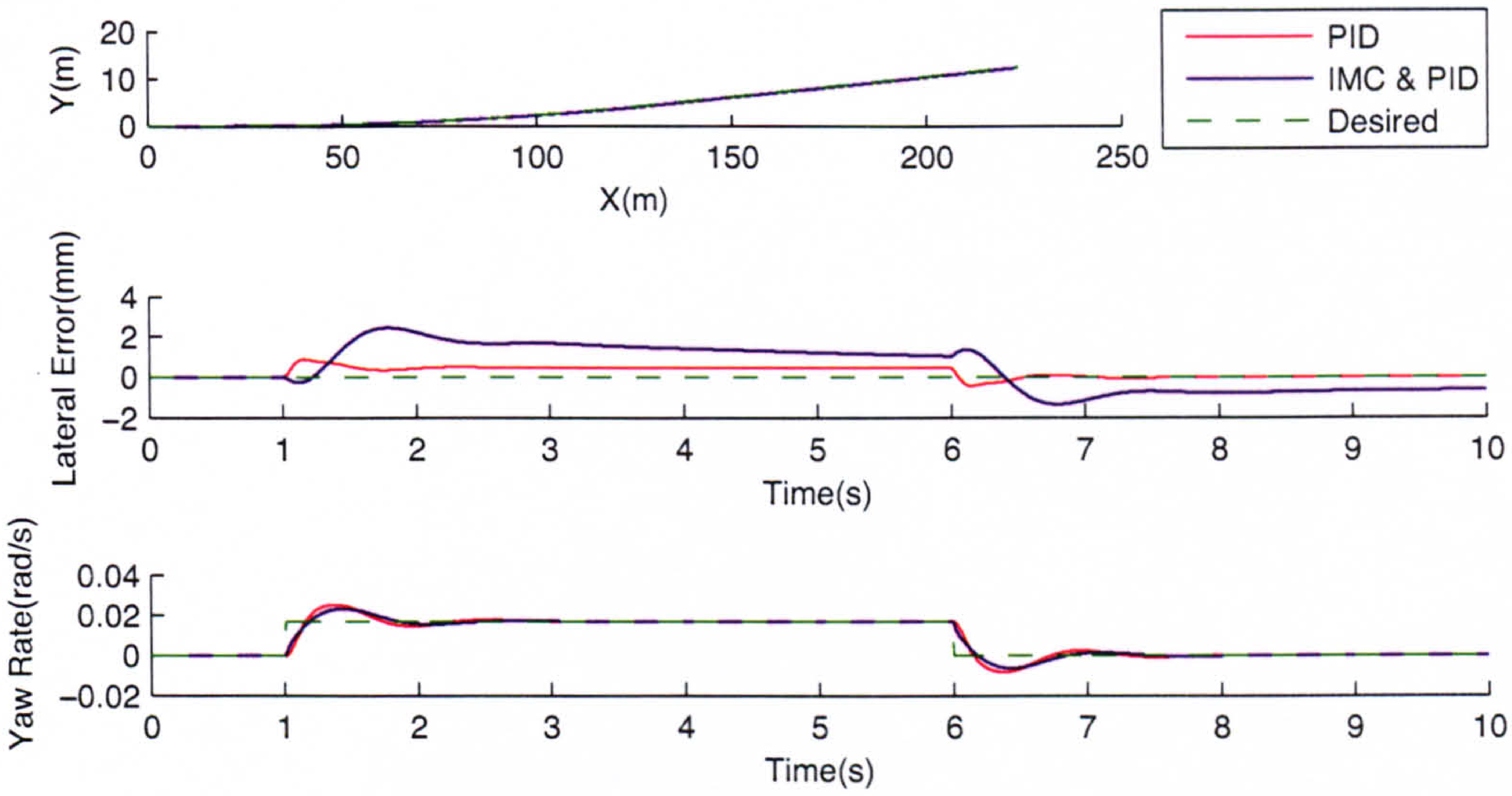


Figure 4.14: Response of look down systems during a flat corner at 50mph

The response was similar for flat corners undertaken at the mid range speed of 50mph. Figure 4.14 shows these same plots for the higher speed. Again the trajectory plot showed no discernible change, which suggested that both control schemes were successful. The lateral error plot is slightly different, again the error was of a small magnitude for both schemes; but this time the direction of the error appeared to be the same for both systems. Closer inspection shows that initially the error for the IMC-PID system was negative, although this was short lived. Due to the higher level of lateral acceleration at this increased speed, the quick response of the IMC-PID scheme was not enough to prevent the system from slightly overshooting the desired trajectory. This controller actually ended up with a larger error than the PID scheme, as by this time the yaw rate was being tracked accurately, its influence on the controller prevented the lateral error being reduced to the level of the PID scheme. Looking at the yaw rate response, it was possible to see some overshoot at this higher speed, although both systems still provided a stable and non-oscillatory response.

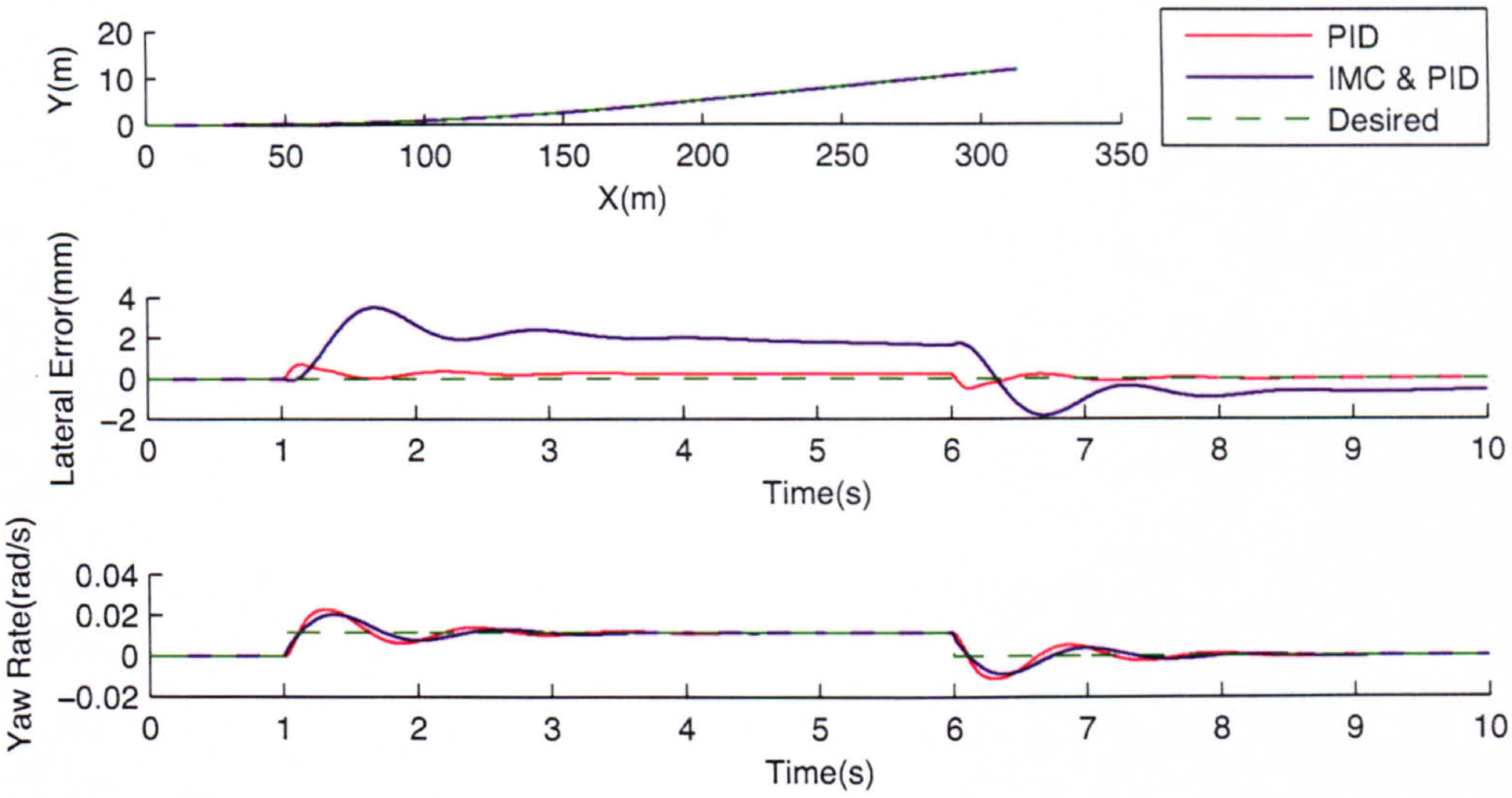


Figure 4.15: Response of look down systems during a flat corner at 70mph

The high speed (70mph) response of both systems on the flat corners is shown in Figure 4.15. This was very similar to the mid range speed response. Again both systems were successful, there is no noticeable deviation in the trajectory plot. As expected the lateral error is slightly larger and the yaw rate response has greater overshoot than at lower speed. This is caused by the increased accelerations experienced in this manoeuvre. These are only minor variations with little impact on the driver or vehicle response.

4.3.2 Lane Changing Results

Standard Lane Changes

The SLC is a transient manoeuvre conducted at a low level of lateral acceleration (0.05g). It provided an effective means of changing lane with reduced jerk and acceleration levels to ensure comfort for the driver. These lower levels of acceleration meant that the manoeuvre took longer to complete ($\approx$ 5.5s) than other lane changes and so is unsuitable for evasive operation. It was hoped that both systems would be able to complete the manoeuvre successfully, over the full range of speeds, as the accelerations experienced were comparable to those experienced in the flat corner scenario.

Figure 4.16 shows the low speed response of both systems to the SLC. As expected the response was similar to that of the flat corner. While there is no step change in yaw rate, the ramp increase still yields similar results. The magnitude of the error was similar between both scenarios, and control schemes ($\approx$ 2mm). Again the error's directions oppose each other, due to improved yaw rate tracking at low speeds allowing the IMC-PID scheme to respond quickly to the change in desired yaw rate. There was little or no overshoot in the yaw rate response of both systems, which led to the low lateral error at the end of the simulation for the IMC-PID system.

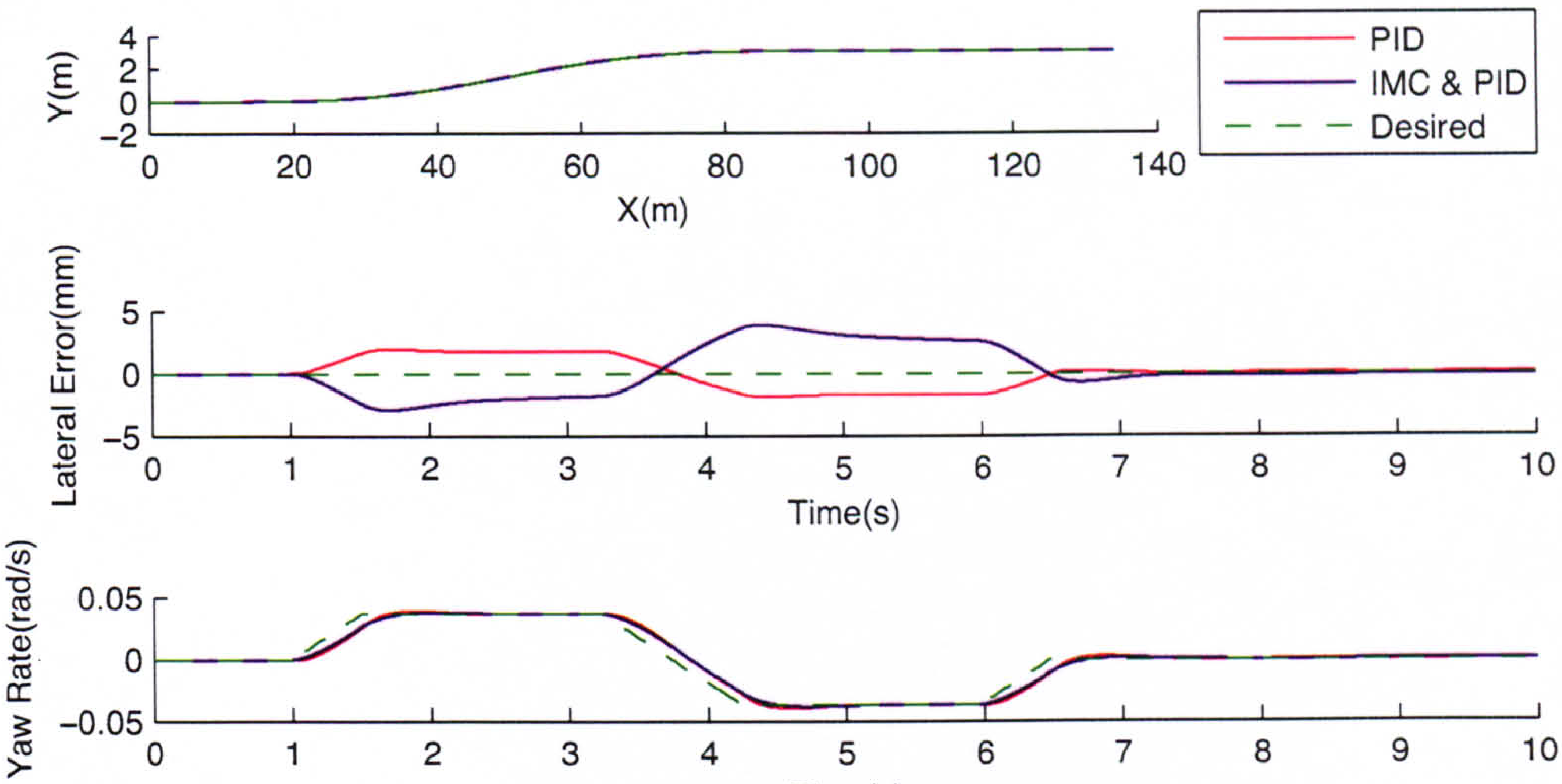


Figure 4.16: Response of look down systems during a SLC at 30mph

The mid range and high speed simulations show similar trends to that of the flat corner, so only the high speed results are shown here (Figure 4.17). Both control schemes performed well over all speeds. The trajectory plot shows no noticeable error; this is confirmed by looking at the lateral error plot which indicates maximum errors were in the range of 2mm. As in the flat corner, the direction of these errors was the same, due to the fact that the quick response of the IMC-PID was not enough to prevent the vehicle from slightly overshooting the trajectory. The yaw rate response of the vehicle was stable, but slightly more oscillatory at this higher speed.

These results have demonstrated the success of both control systems on SLC manoeuvres for the full range of motorway speeds. The low levels of jerk and stable yaw rate responses suggest that the manoeuvre will be comfortable for the driver.

Evasive Lane Changes

It was during the ELC manoeuvres that the major performance differences between the two control schemes became apparent. It was decided to investigate two levels of severity, a 0.1g manoeuvre and a 0.5g manoeuvre. The 0.1g manoeuvre moved the vehicle between lanes in approximately 3.5s where as the 0.5 g manoeuvre took only 1.5s. This event was designed to be used in safety critical scenarios where the level of comfort is not so important, only the rapid exit of the lane.

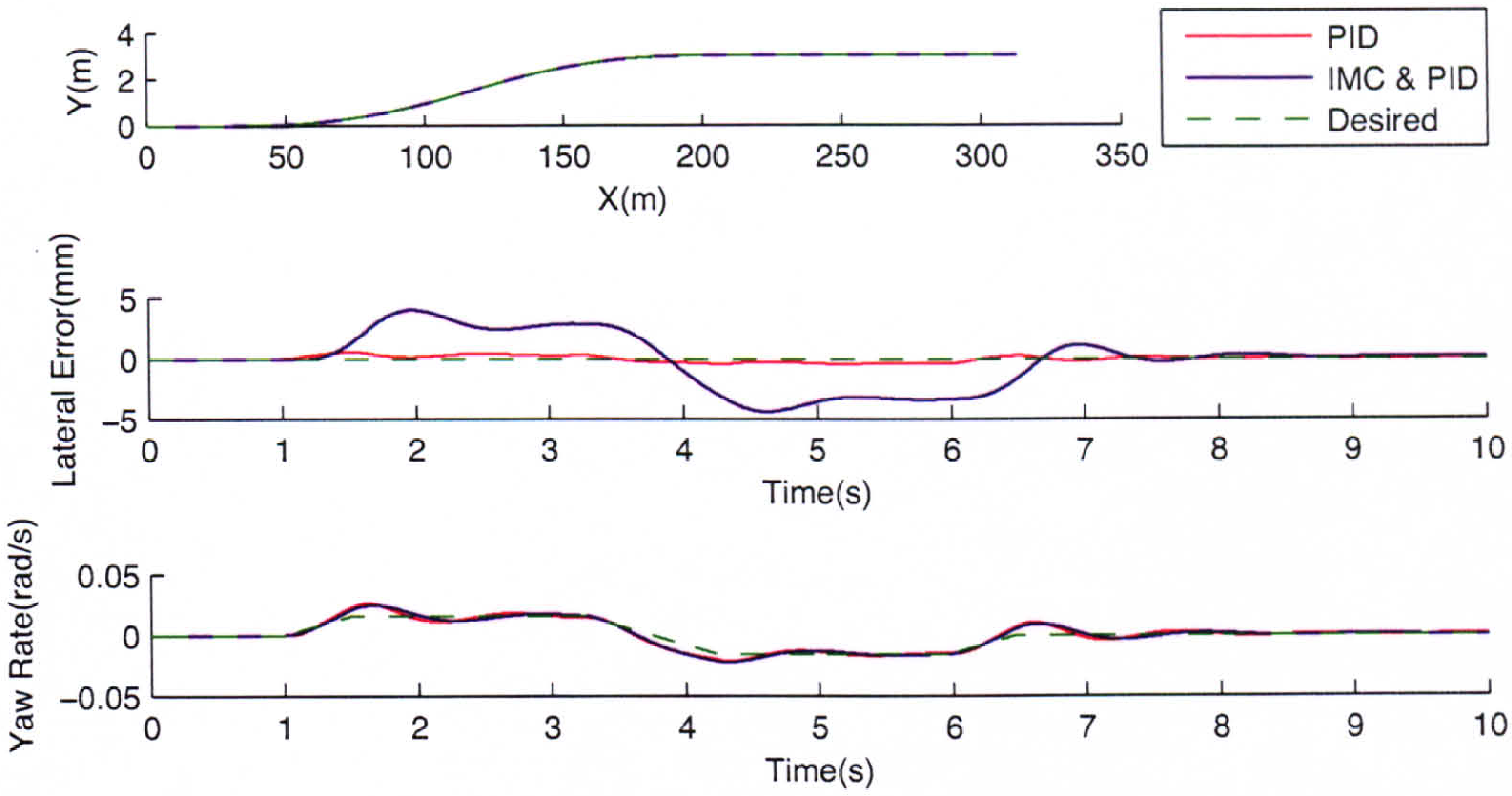


Figure 4.17: Response of look down systems during a SLC at 70mph

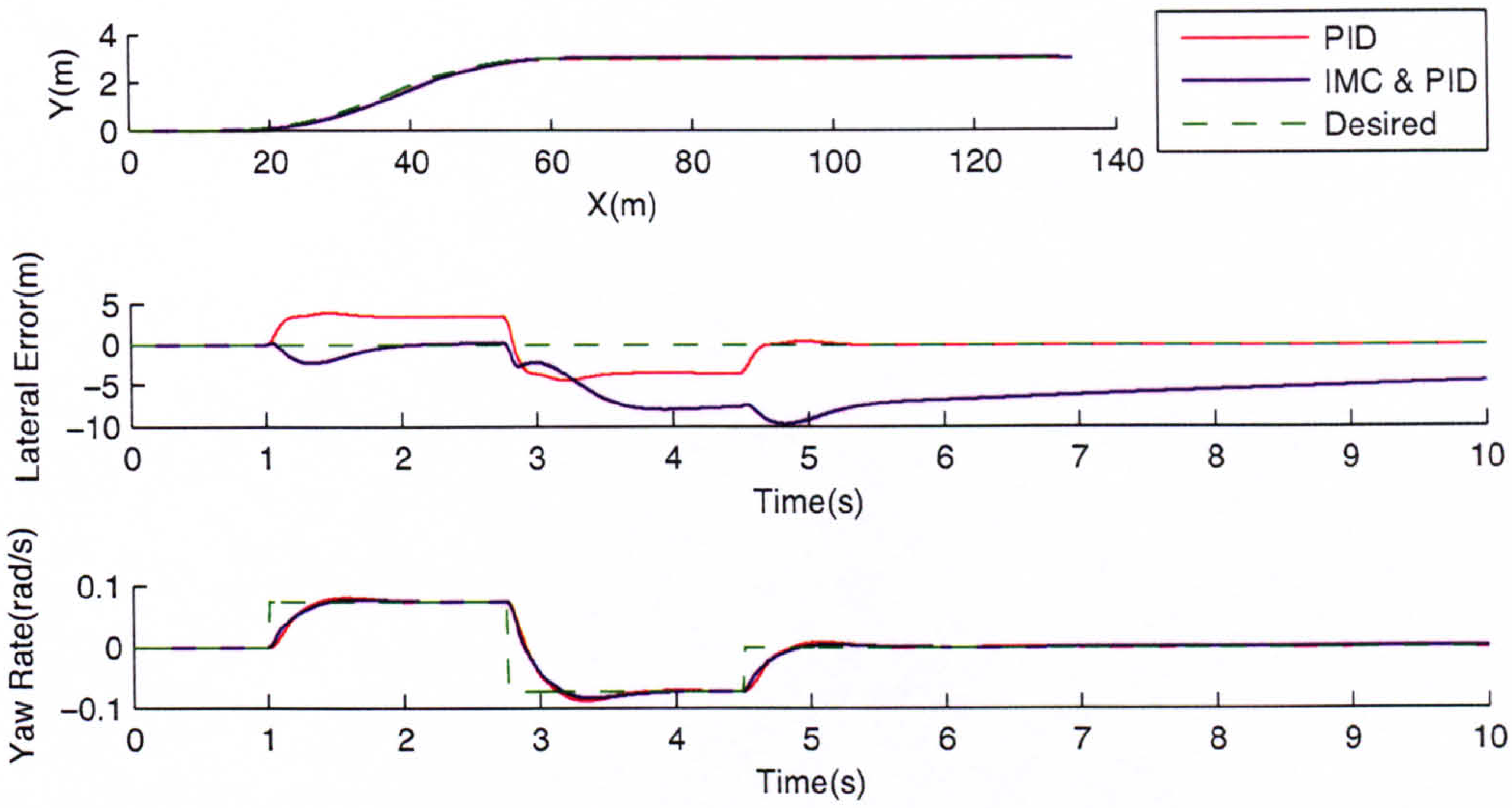


Figure 4.18: Response of look down systems during a 0.1g ELC at 30mph

Figure 4.18 shows the low speed behaviour of the control systems to this 0.1g ELC. Considering the trajectory plot, both systems look to have been successful, only minor deviation was noticeable and the vehicle remained stable. While this plot may look similar to that from the SLC manoeuvre, it is important to notice the scale of the x-axis. This ELC was completed within 60m where as the SLC took about 80m. These 20m could be the difference between collision with the lead vehicle and a safe lane change.

While the manoeuvre was stable, there was a larger lateral error experienced when compared to previous tests. This was initially more noticeable with the PID scheme, but in the second half of the manoeuvre the performance of the IMC-PID scheme generated the largest lateral error, caused by the overshoot in the yaw rate plot. The overshoot caused the IMC-PID scheme to steer away from the desired trajectory to reduce the vehicle's yaw rate. The maximum value of this error was still only 10mm, which is relatively small considering the width of the lane (3000 mm). The yaw rate plot demonstrates the stability of the manoeuvre, and shows the overshoot caused by the double step change in desired yaw rate.

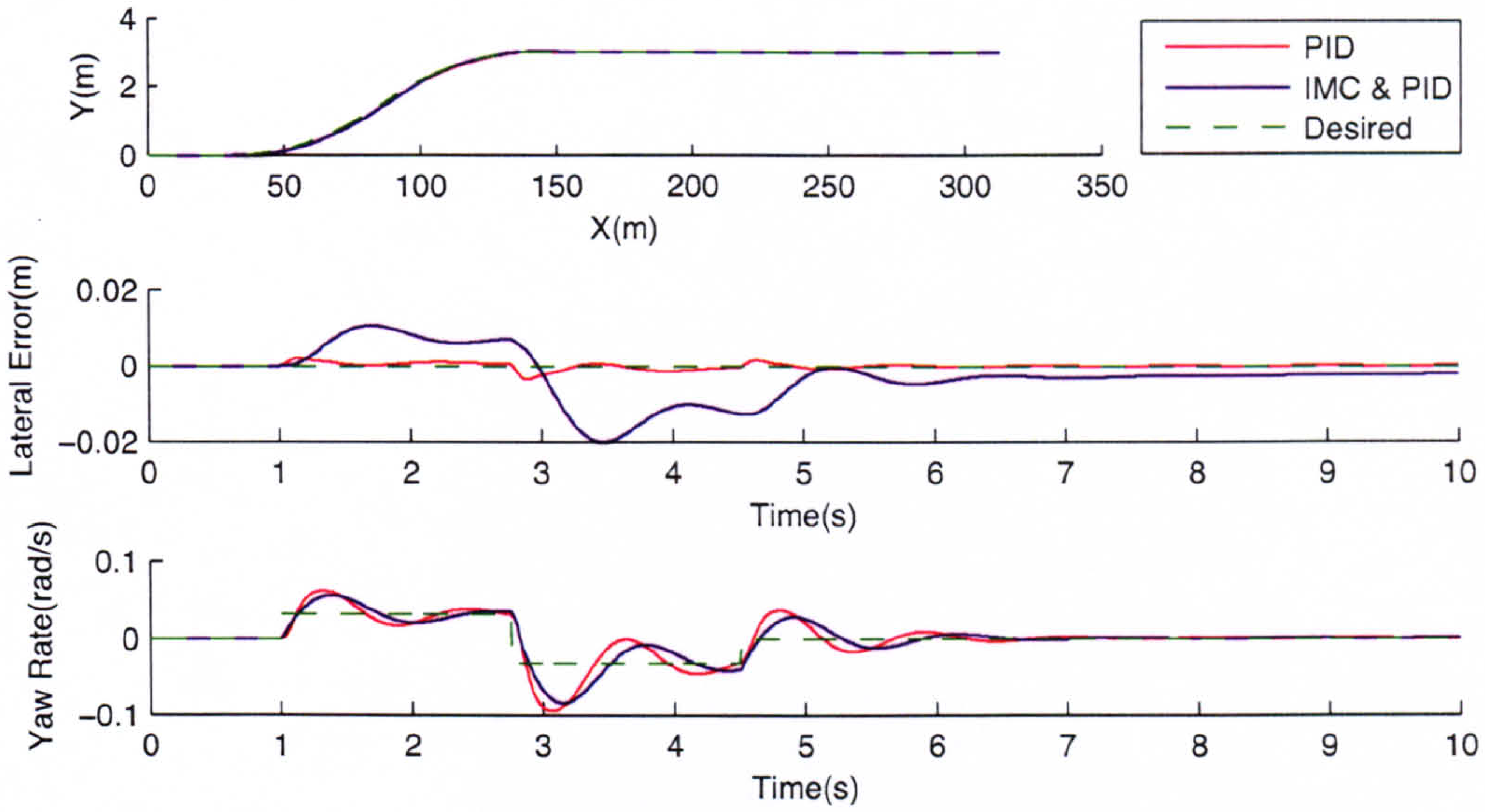


Figure 4.19: Response of look down systems during a 0.1g ELC at 70mph

The performance was similar over the full range of test speeds. Both controllers successfully complete the manoeuvre at all speeds. As the speed was increased, the yaw rate response became more oscillatory and the lateral error became larger, Figure 4.19 demonstrates this at the highest speed (70mph). While the trajectory plot shows little deviation, the lateral error was increased to 20 mm for the IMC-PID case. This was still less than 1% of the lane width and is therefore acceptable. More worrying is the increased oscillation in the yaw rate response of the vehicle, especially in the second half of the manoeuvre. It is important to note that the amplitude of this oscillation was large in the PID scheme, as it makes no attempt to reduce the error, unlike the IMC-PID controller. This oscillation of yaw rate leads to increased yaw accelerations, which may be uncomfortable for the driver. But given the evasive nature of the test, this is of secondary importance. Overall both systems are capable of conducting the ELC at 0.1g for the full range of test speeds.

The 0.5g ELC is the most severe manoeuvre that is considered in this research. While the previous manoeuvres have examined the common motorway behaviour of the vehicle, the 0.5g ELC is suggested as a test for the controllers to investigate the limits of their performance and also to propose a system that if successful could ensure the vehicle exits its lane as quickly as possible.

Figure 4.20 shows the performance of both control schemes for low speeds. Looking at the trajectory plot it is immediately obvious that the PID scheme failed. The system overshot the desired lane by nearly 3m (one whole lane) and when trying to reduce this error, the vehicle again overshot before becoming unstable. This instability was caused by the inability of the PID system to track the desired yaw rate. Initially the vehicle performance was limited by the steering actuator, which only allowed the road wheel angle to increase by 25°/s, this deficiency caused the initial positive lateral error apparent with both systems. As the yaw rate reached its desired level, the IMC-PID control action levelled off, but as there was still a positive lateral error, the control action of the PID scheme increased to reduce this. The levelling off of the yaw response of the IMC-PID scheme is key to the increase in stability of the vehicle (compared to the PID scheme). While the initial lateral error of the PID scheme was reduced, the yaw angle was increased, such that the vehicle was heading away from the desired trajectory. This quickly resulted in a high negative lateral error ($\approx$ 3m), from which point it became impossible to regain control of the heading of the vehicle.

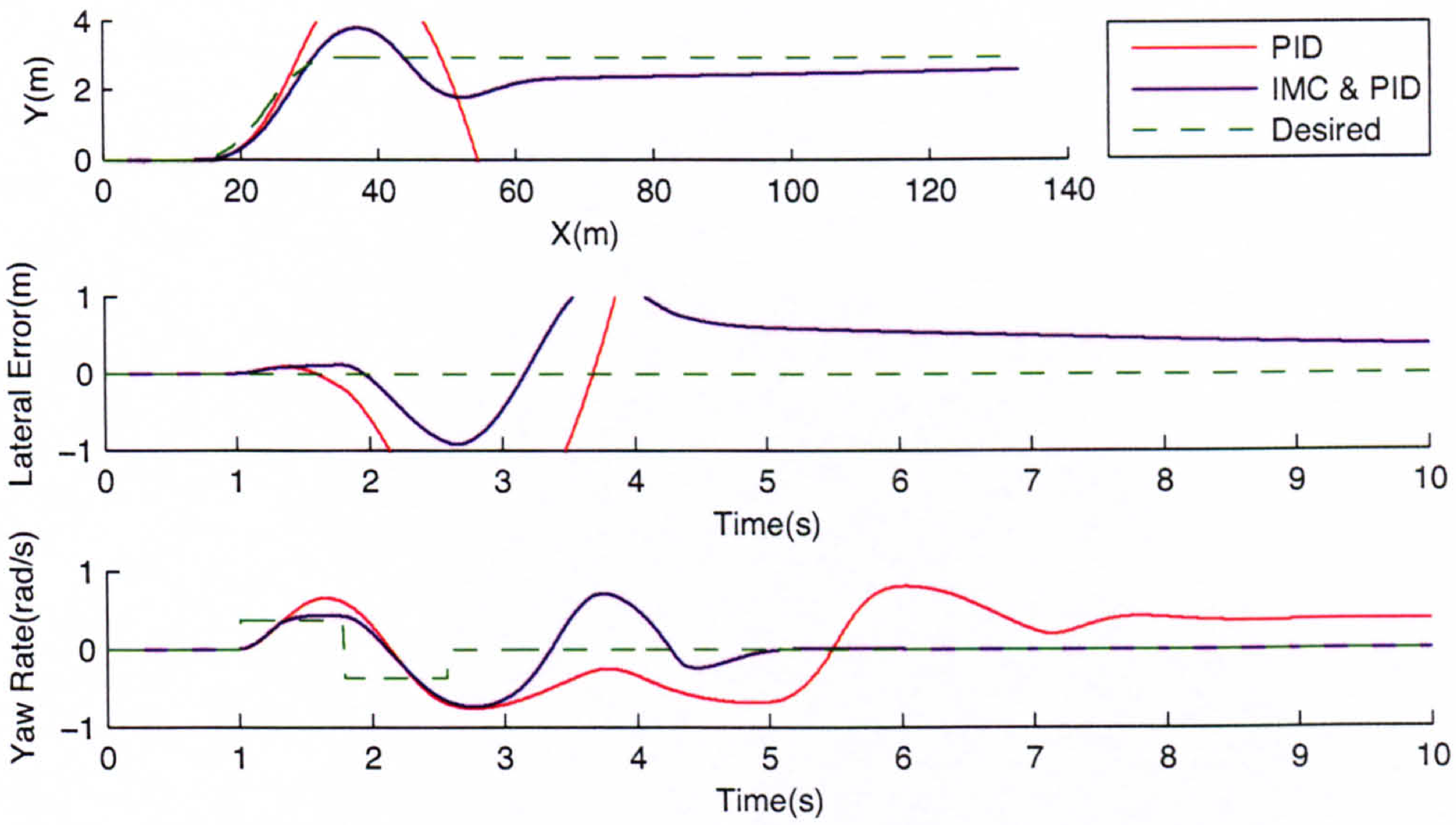


Figure 4.20: Response of look down systems during a 0.5g ELC at 30mph

The IMC-PID scheme performed as adequately as can be expected in this extreme manoeuvre. The yaw rate response was oscillatory but stable, and control of the vehicle heading was regained within 3s. The lateral error was much higher than has previously been experienced ($\approx$ 1m, or 33% of the lane width). This was unacceptable for this manoeuvre as it could easily result in side impact with vehicles in adjacent lanes. Again the IMC-PID scheme failed to quickly reduce the lateral error, due to the increased influence of the yaw rate error. While reducing the influence of the IMC part of the controller may have allowed quicker reduction in this error, it would have compromised the stability of the vehicle in this, and future simulations.

Figure 4.21 shows the mid range speed response to the 0.5g ELC, again the PID system failed. This was expected as higher speed only increased the severity of the manoeuvre. The performance of the IMC-PID scheme on the other hand is slightly improved. The higher speed reduced the ability of the system to adequately track the desired yaw rate. This can be seen by looking at the overshoot in the yaw rate response at 1.5s, in which increased overshoot actually allowed the vehicle to reduce the lateral error. The same was the case in the second half of the manoeuvre, leading to a reduced maximum lateral error of 0.5m, compared with 1m at lower speeds. The yaw rate response was no more oscillatory and appeared to settle in a similar period of time.

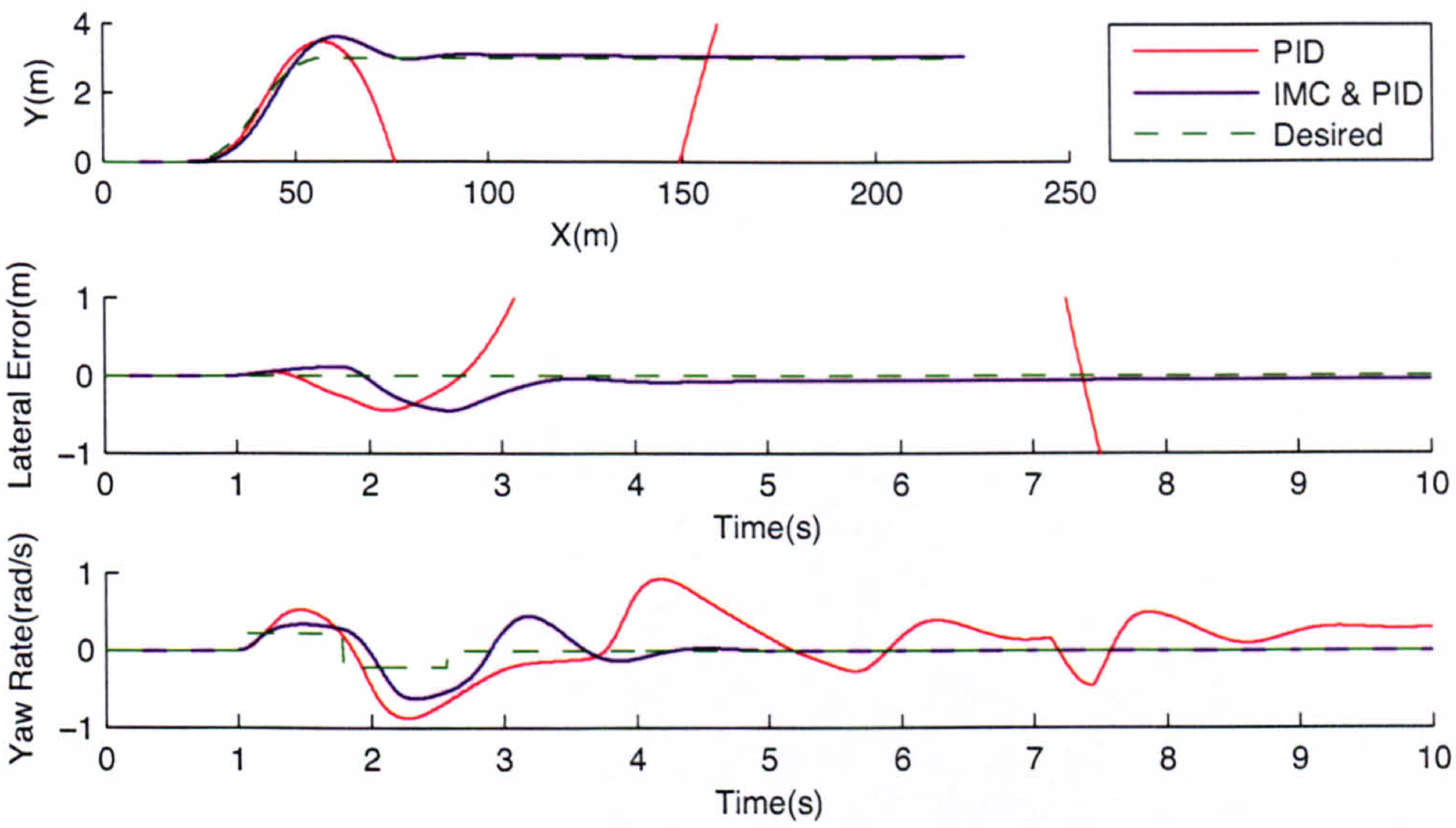


Figure 4.21: Response of look down systems during a 0.5g ELC at 50mph

Figure 4.22 illustrates the performance of the PID-IMC scheme at the highest modelled speed of 70mph. The response of the PID scheme is not shown as it again failed to maintain stability of the vehicle. While the IMC-PID scheme was successful for the other range of speeds (20 - 60), it failed at 70mph. The failure of the IMC-PID scheme was caused by the increased influence of the PID control as the overshoot in lane position generated a lateral error which the PID part of the controller tried to counteract. At this higher speed it was not possible to change the position and heading attitude of the vehicle

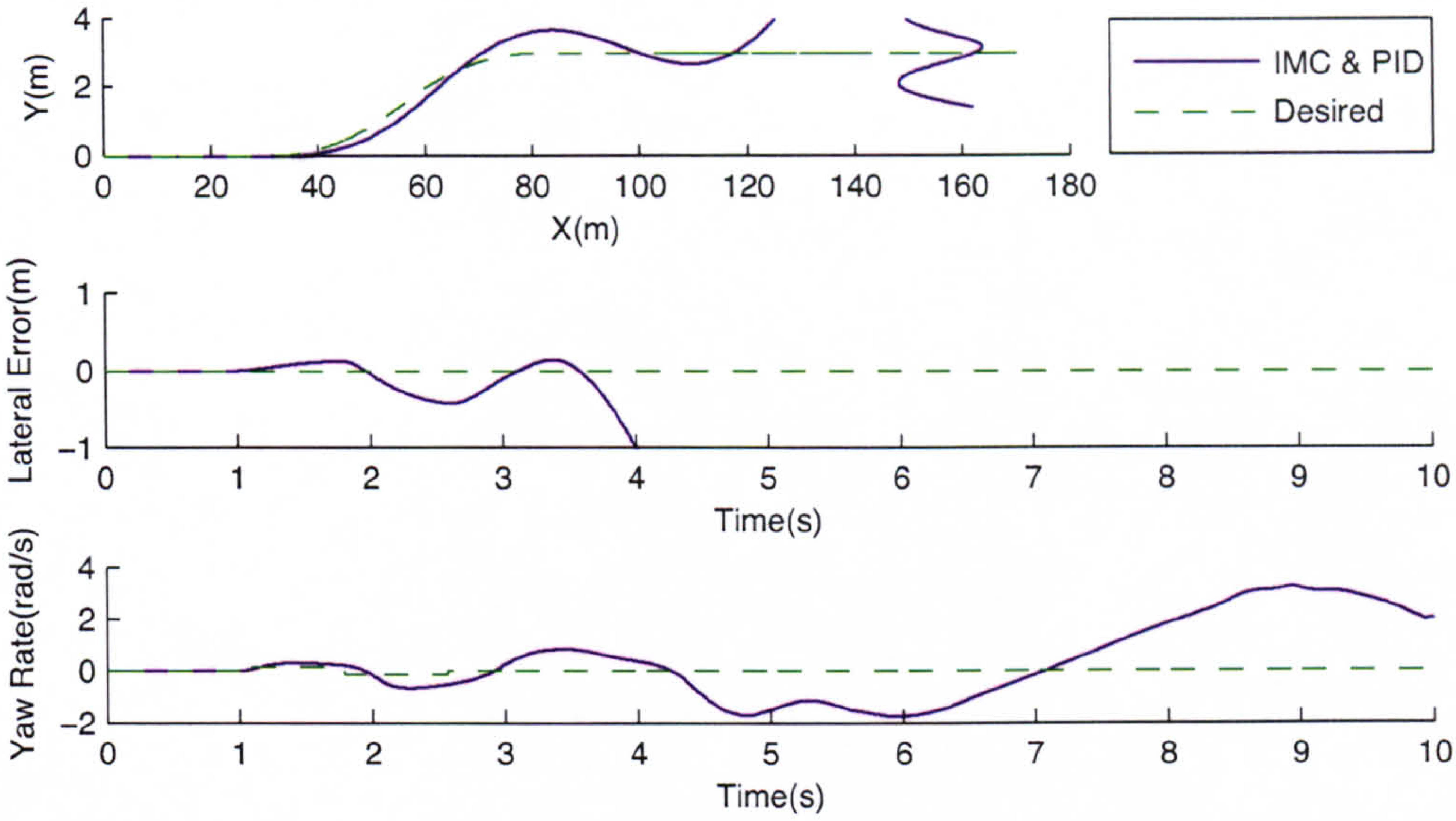


Figure 4.22: Response of look down systems during a 0.5g ELC at 70mph

as quickly, and so the result was that the yaw rate response started to become divergent, from which point there was no way back.

4.3.3 Summary

The two look down control systems developed in this section have shown promising results. Excellent path tracking response was possible for non-evasive manoeuvres, with both the basic PID system, and the IMC-PID system. The PID system showed improved path tracking results with lower lateral errors than the IMC-PID system. The PID scheme's lack of yaw rate control compromised the stability of the vehicle, when performing the 0.5g ELC. The IMC-PID on the other hand was capable of the the 0.5g ELC, up to speeds of 50mph, as the yaw rate controller prevented the large trajectory overshoots seen in the PID scheme. Throughout all simulations the IMC-PID scheme's path tracking was slightly less accurate than that of the PID scheme, again due to the system trying to track yaw rate. Neither control system was capable of the high speed 0.5g ELC, as lateral forces could not be generated quickly enough to maintain the desired path and heading.

Disturbance tests such as low friction results, side winds, and banking were performed with these two control schemes. The findings from these tests are not presented in this body of work, as their results demonstrate similar trends to those shown in other manouvres. More interesting results from these disturbance tests can be seen in the following section, for another type of lateral control system.

Throughout this look down analysis, we have been concerned primarily with the path tracking and stability of the vehicle. Little attention has been paid to the comfort levels of the driver, and their approach to the lateral control task. The following section follows on from this initial exploration by considering a control methodology more in tune with that of a human driver.

4.4 Look Ahead Controller Development

Until now, we have only considered look down forms of lateral control system. Such systems have shown promising results over a range of driving scenarios. These types of lateral control system are becoming more commonplace in automated traffic systems such as CalTrans Guided Buses (Chee and Tomizuka 1994). Systems of this kind cause the vehicle to track a path as accurately as possible, with little knowledge of the desired trajectory. Certain additions to look down systems can improve vehicle stability during operation, for example the inclusion of IMC to reduce yaw rate error. Look down systems lack the ability to control the vehicle in a predictive method, similar to that of a human driver. By solely considering the vehicle's current position and heading, it is not possible to prepare for upcoming changes in road geometry and/or required manoeuvres. Human drivers on the other hand, have only a limited knowledge of their current position, but are continuously updating their view of the upcoming road and obstacles. This allows them to adjust the vehicle's position in advance.

There has been much research into driver modelling to provide an accurate interpretation of the driver's behaviour. There are many different ideas as to how best to do this (Section 1.4.2). Apparent in most driver models is some kind of preview of the road in front. In order for lateral control systems to be a commercial success, it is important that drivers are able to accept them and utilise them in everyday driving. To this end, every effort should be made to ensure that systems replicate human driver's behaviour while improving the stability of the vehicle, safety of all road users, and maintaining or improving the level of comfort experienced by the driver and passengers.

With these ideas in mind, it was decided to utilise a more 'driver-emulative' approach to lateral control of the vehicle. Many driver models were investigated, before it was decided to base a control scheme on the methods investigated in Sharp et al. (2000). This paper presented a control algorithm which projected a virtual lever from the front of the vehicle and then calculated the error normal to the optical lever from the desired trajectory at a number of points along its length. The influence of these points was tuned by a range of gains, and the result was fed back to the vehicle as a desired steer angle. Sharp et al.

(2000) proposed this method for use in lap time simulation to estimate the racing line around a given circuit. It was chosen for our application as the range and simplicity of parameters (lever length, number of error points and individual error gain), meant that the performance of the system could be easily adapted to a vehicle of this type. Also its performance could be adjusted to better approximate the driver's behaviour, while ensuring a safe and stable response of the system.

4.4.1 Control Methodology

Some driver models have suggested that drivers estimate lateral errors at a range of points in front of them, rather than one fixed point. This control scheme attempts to replicate this, by calculating the error at a range of preview points, assuming the vehicle continues in its current heading direction. The vehicle's instantaneous lateral position and heading angle are also taken into account. These error signals are then processed using a range of gains before they are fed back into the vehicle as a desired steer angle. Sharp et al. (2000) finally opted for an exponentially decaying series of gains along the length of lever, i.e. the influence of error terms is exponentially reduced further away from the vehicle. It was decided to implement this scheme in this research, although the initial gain and rate of decay would require tuning to provide optimum performance. Figure 4.23 shows the virtual lever, and other features of the system.

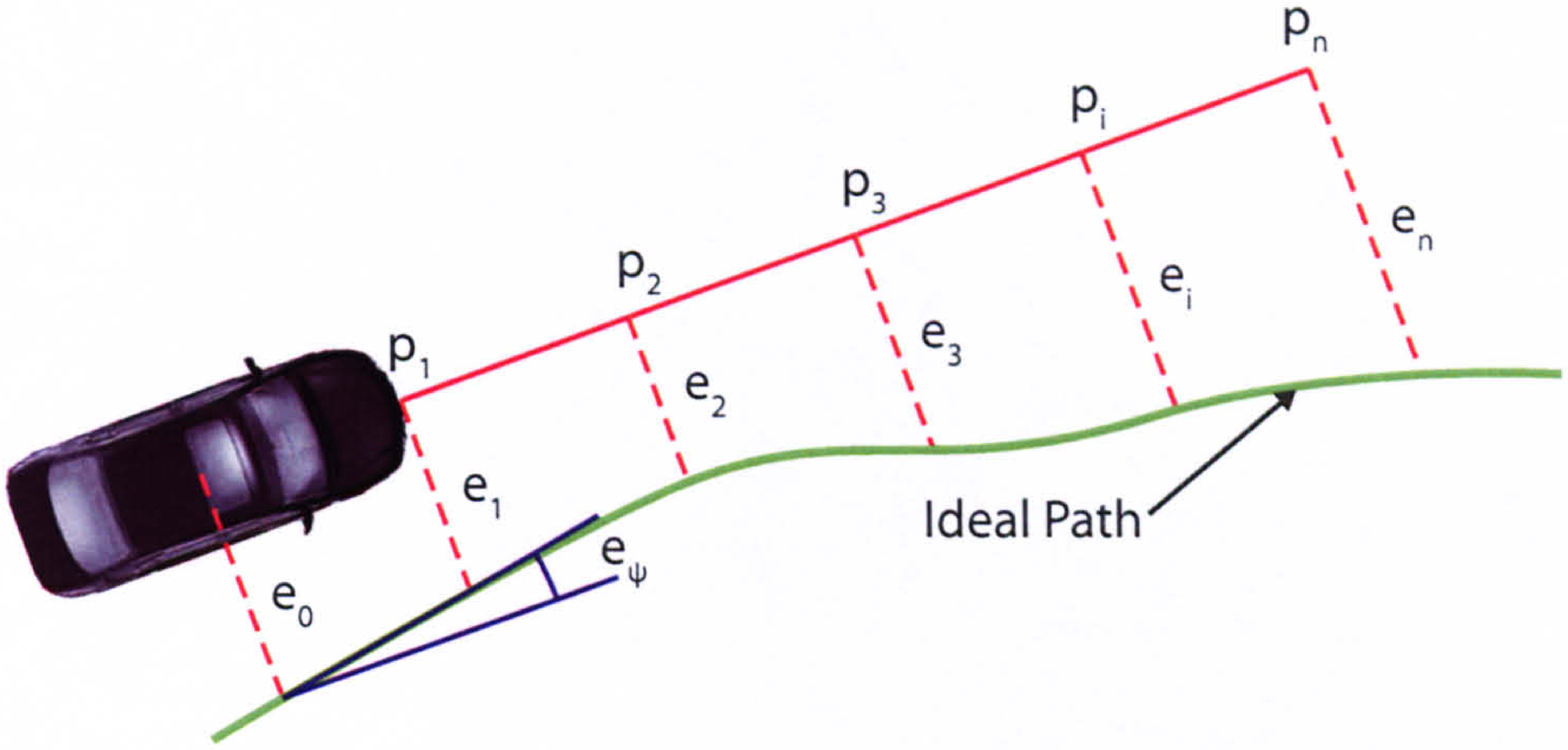


Figure 4.23: Overview of look ahead lateral control scheme

Assuming we know the projected road trajectory it was possible to calculate the projected error at a given distance along this line. The previously described trajectories required certain modifications, which are discussed in the following section. Control then became relatively straight forward. Equation 4.7 was used to calculate the desired steer angle dependent on state feedback (e_ψ and e_0), and trajectory preview (e_i), which were scaled by gains $K\psi$, K_0...Kn.

$$\delta_f = K_\psi.e_\psi + K_0.e_0 + \sum_{i=2}^{n} K_i.e_i \tag{4.7}$$

4.4.2 Processing Road Data

Through previous sections of this research, trajectories have been input to the model as time histories of desired yaw rate. This has worked well for constant speed manoeuvres that generally occurred within the linear limits of the vehicle. But as constant speed cannot always be guaranteed, and as we wanted to investigate the issues of the high acceleration manoeuvres in more detail, another approach was required. Sharp et al. (2000) suggested that road profile data is obtained in the following form:

$$Trajectory = [\ s_i \quad R_{ref(i)} \quad \psi_i \quad x_i \quad y_i\ ] \tag{4.8}$$

Where s is the distance of a point along a specified path, R_{ref} is the path radius of curvature at that point, ψ is the heading angle of the path at that point, and x and y are the global co-ordinates of the point. In order to convert the previously defined trajectories, a Matlab® routine was written and employed to ensure consistency and accurate results. The routine calculated the (x,y) co-ordinates of each trajectory point using the following logic:

1. Time history yaw rate data is converted into (x,y) data at constant speed.
2. The linear distance between each (x,y) point is calculated.
3. Starting at (0,0) the distances are added until greater than the desired s.
4. Actual s x, y are worked out by linear interpolation. The remainder is carried over into the next s.
5. This continues until total path is split up into s length components.

To find the radius of curvature at each of these s points the equation of a circle given three coplanar points was used. To implement this the (x,y) co-ordinates of the current trajectory point, those of the preceeding and following points were used to generate an instantaneous circle. The centre of the circle and respective radius of curvature could then be found (Figure 4.24). This worked well unless the three points lay on a straight line. In this case the instantaneous radius of curvature was infinite, an exception was introduced for points of this type.

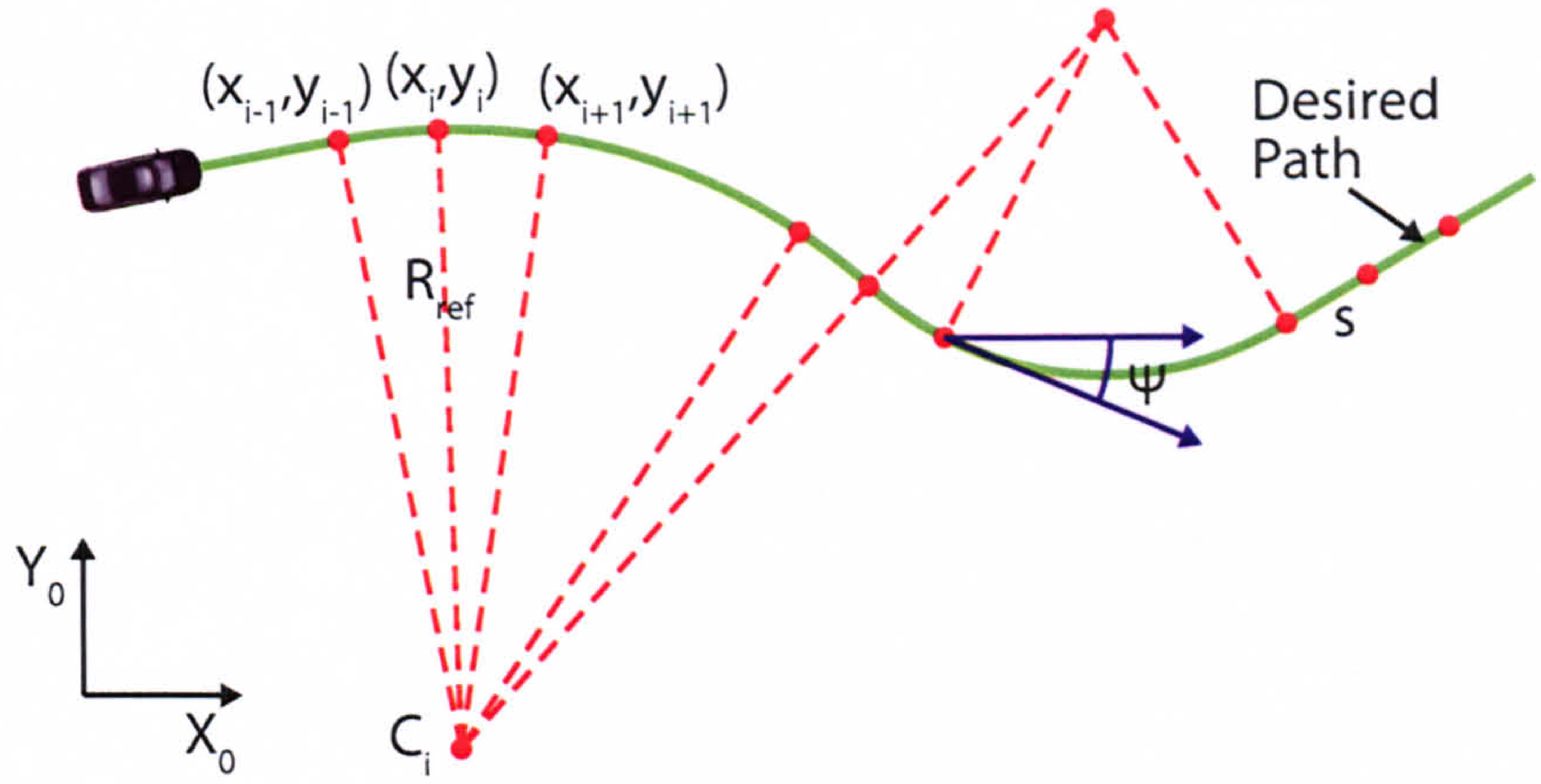


Figure 4.24: Method of calculating path radius of curvature and heading angle

Given the centre of the instantaneous circle C_i, the desired heading angle was the tangent at the trajectory point. This could be found by calculating the normal to the line, which defined the radius *r*, therefore giving the trajectory in the required form.

4.4.3 Error Estimation Techniques

With this trajectory in place, the next task was to develop a methodology for calculating the lateral and heading errors at the vehicle's current position, and at points projected along the virtual lever. We knew the vehicle's global position and heading (x,y,ψ), and therefore the positions of the points on a lever projected forward. We could invert the equation of the lever at each preview point to project a perpendicular line from each. However, we did not know the point at which these error lines intersected the trajectory. Once this was discovered, we could calculate the distance between this intersection point, and the point on the lever, to generate an error value. If the trajectory was a straight line we could set the equations of both lines equal to each other and find their intersection. But, as the trajectory could be a complex combination of curves, with varying gradients this was not possible. It was decided to use the Newton-Raphson method (Kelley 2003) to solve this problem. This is a root-finding algorithm that applies a Taylor series to an initial guess in the vicinity of the required root. Lets consider only the error at the current vehicle position (errors at other points are calculated in the same way) and run through how the problem is solved at this point.

1. Given the global location and heading of the vehicle (x,y,ψ), a line normal to this vector is derived.
2. An initial guess is made as to the location of the intercept. This is taken as the intercept in the previous time step or (0,0) at the first time step.
3. The tangent at this initial guess is calculated.
4. The intercept of this tangent and the normal from the vehicle is calculated.
5. For the guess to be acceptable as the intercept of the trajectory and the normal, the X value of the guess intercept should be within a tolerance of the X value of the guess point.
6. If this is not the case the X value of the returned intercept is input as the updated guess in the second iteration of the method.
7. This continues until the error between X intercept and X guess is within an acceptable level.

This method was applied at each point along the virtual lever with a revised normal line and initial guess as shown in Figure 4.25. Although the calculations involved in this iterative method were uncomplicated, their number could become high, depending on the accuracy of the initial guess and complexity of the trajectory. It was also necessary to complete the method at each time step of the full simulation. Therefore we decided to code the algorithm as a C-Mex S-Function. This would increase the speed of the calculations, and ensure that the time step of the overall simulation was not affected by repeated iterations. With the control methodology in place, the next step was to tune the various parameters, to ensure accurate path tracking, a stable vehicle and a 'human feel'.

4.4.4 Controller Tuning

Many aspects of the control system could be tuned to provide the desired response of the system, in this section each of these parameters are looked at in turn. Their influence is assessed in isolation while the other gains and parameters are maintained at their final tuned levels. these parameters are listed in Appendix A.2.

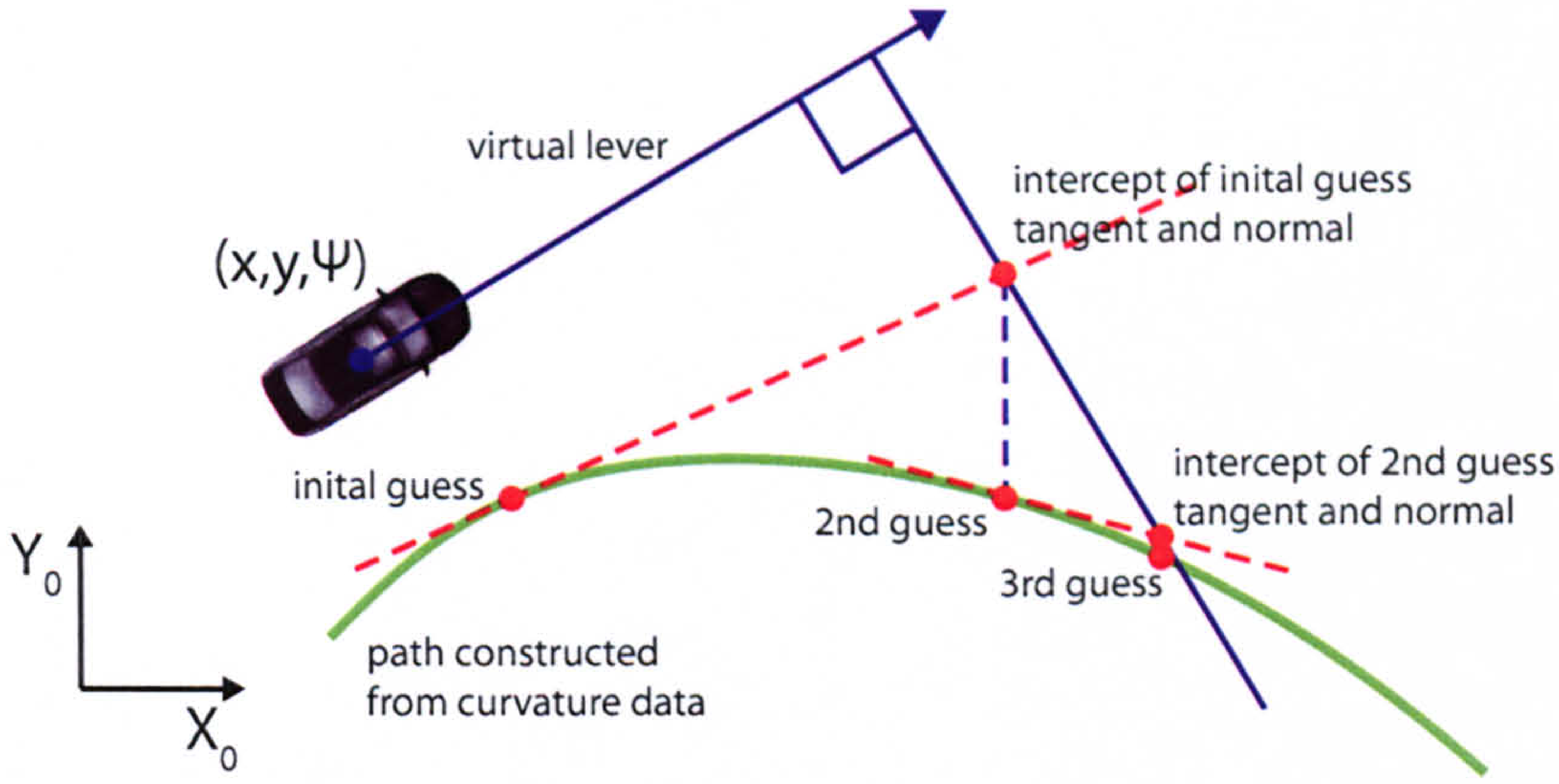


Figure 4.25: Method of calculating look ahead lateral errors

Look Ahead Distance

This control methodology has the ability to preview the upcoming trajectory, but until now this preview distance has not been investigated. There are a few key factors to consider when deciding upon this.

- Should the distance be variable depending on the speed and type of manoeuvre?
- How far ahead can vision systems accurately predict lateral position error?
- What preview distances do human drivers use?
- What preview distance is best for vehicle stability?
- Is there a trade off between vehicle stability/lateral deviation and human feel of the system, and if so what do we define as acceptable?

It was initially decided to use a fixed preview distance for all speeds and manoeuvres. While this may slightly limit the capabilities of the system, it would be one less parameter to tune. While certain driver models suggest that drivers vary their preview distance with speed, it was that thought that the relative high speed of the manoeuvres considered, and the motorway based scenarios mean that this is an acceptable assumption. There is potential for investigating variable preview distance dependent on vehicle speed, but that is beyond the scope of this work.

Current state of the art vision systems are capable of previewing distances of up to 80m (Bosch 2004). It is assumed that these measures are taken in perfect road and environmental conditions (straight flat road and good visibility). As we are only considering motorway driving, it is reasonable to assume that the road will be fairly straight and that road markings will be of a high quality. Therefore the maximum previewing distance may be possible. It was decided to test the system with a maximum preview distance of 50m, as this would hopefully increase the reliability of the visual system. But, depending on the gain tuning, this may cause excessive corner cutting.

The driver models discussed in earlier sections propose a range of suitable preview distances to replicate human driving. Ungoren and Peng (2005) suggest most driver models fall within the range of 15-60m for motorway speeds. For the purpose of this research it was decided to test the system with preview distances of 10m to 50m to assess the suitability of these distances, and fully investigate their effects on corner cutting, and comfort levels (through lateral accelerations and jerk levels experienced). This is where the subtlety of the tuning will occur. It was expected that increasing the preview distance would reduce the desired yaw rate and lateral acceleration required throughout the manoeuvre; increasing the stability of the vehicle and comfort levels experienced. But this in turn would increase the degree of corner cutting, although corner cutting may not always take the vehicle into the adjacent lane. Depending on the width of vehicle and lane, there could be a large degree of corner cutting without compromising the safety of the controlled and surrounding vehicles. Somewhere between the extremes of zero and maximum corner cutting exists both the human driver's strategy, and the safest outcome in terms of stability and risk of collision.

Results from a full set of lane change tests with varying preview distance are presented below. Figures 4.26, 4.27 and 4.28 show the performance of the controller during a 60mph ELC at 0.5g. Tables 4.7 and 4.8 summarise the effects of varying preview distance over the whole range of lane changes.

Figure 4.26 shows the trajectory taken by the vehicle when a control with a given preview distance was used. The desired path, or proposed trajectory is shown as a dotted black line. With a preview distance of 10m, the system failed to control the vehicle, becoming unstable. This occurred as the short preview distance caused overshoot in the left hand steer part of the manoeuvre. Whilst trying to recover this lateral error the vehicle's heading error increased, meaning increased steering input was required to counteract this in the latter, right-hand part of the manoeuvre. This additional steering input, again combined with a short preview of the upcoming trajectory, caused increasing overshoot and eventually instability. For this reason the results of the 10m preview controller are not shown in other figures. The larger preview distances gave more promising results, all remained stable, with much reduced overshoot. As expected an increase in preview distance resulted in reduced lane overshoot, although this effect appeared to lessen with distances above 30m.

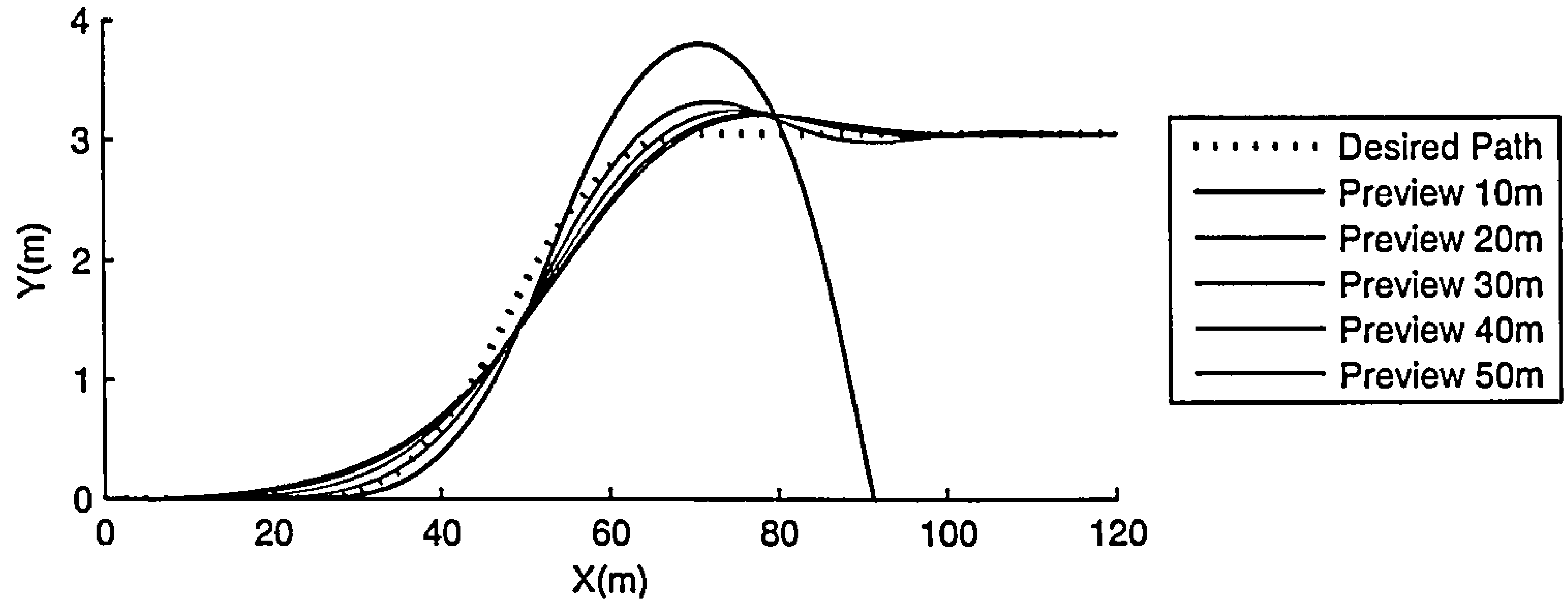


Figure 4.26: Trajectory of vehicle for ELC with varying preview distance

Figure 4.27 illustates the lateral error at the vehicle's CG. This is a measure of how closely the trajectory is being followed at any given time. It appears that the 20m preview distance gave the lowest peak values, but it is important to note that the second trough is larger in the 20m case. The initial performance of the larger preview distances appeared poor, as they caused the vehicle to deviate from the straight section of road, pre-empting the corner. In this manoeuvre, the initial error was compensated for later in the manoeuvre, when the lateral error of the higher preview distances was reduced, while the lower preview distances caused the vehicle to oscillate. The error levels were generally acceptable. Although 0.4m was close to the limit, given an overall vehicle width of 2m and a lane width of 3m. However it should be remembered that this test was for a severe lane crossing manoeuvre.

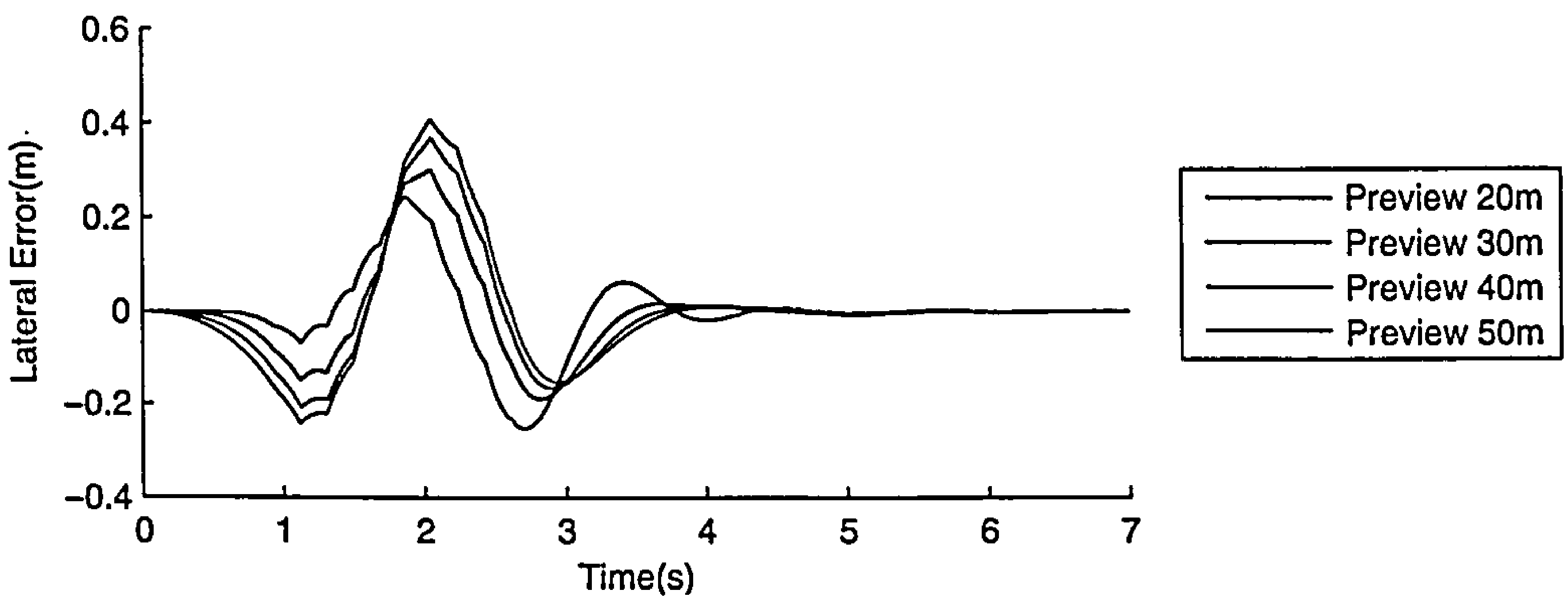


Figure 4.27: Lateral position error of vehicle for ELC with varying preview distance

While Figure 4.27 gives a good indication of the controller's performance at any given time during the manoeuvre, it was difficult to judge which performed better overall. To assess this, a cumulative measure of the time and distance out of lane was taken (Equation 4.9), termed Cumulative Lateral Error (CLE). Table 4.7 gives results for this measure for the full range of lane change manoeuvres. As expected the shorter preview distance yields less CLE for the low speed, low lateral acceleration tests, but as these increased the 30m look ahead distance gave the lowest CLE. This metric is a good way of demonstrating the safety of the vehicle during the test (i.e. The lower the number the more time spent in the centre of the lane). Maximum Lateral Error (MLE) can also be used to see if the vehicle departed from the desired lane at all, but for these tuning scenarios that was not of prime importance. Both of these measures failed to capture the levels of comfort experienced by the driver. An improved comfort level for the driver is thought to be one of the main benefits of the look ahead methodology over the look down systems; it is hoped that the look ahead system will be more in tune with the lateral control method of human drivers.

$$\text{Cumulative Lateral Error} = \int |e_0| dt \qquad (4.9)$$

Table 4.7: Cumulative lateral position error (ms) for lane change manoeuvres with varying preview distance

Preview Distance	**20m**	**30m**	**40m**	**50m**
SLC 50mph	0.027	0.092	0.153	0.199
SLC 60mph	0.049	0.038	0.071	0.102
SLC 70mph	0.070	0.058	0.054	0.057
ELC 0.1g 50mph	0.058	0.150	0.235	0.295
ELC 0.1g 60mph	0.087	0.083	0.129	0.173
ELC 0.1g 70mph	0.122	0.106	0.111	0.124
ELC 0.5g 50mph	0.275	0.419	0.533	0.603
ELC 0.5g 60mph	0.317	0.361	0.447	0.507
ELC 0.5g 70mph	0.433	0.379	0.433	0.479

In this research lateral acceleration is the main means of assessing the controller's impact on the comfort levels experienced by the driver. Figure 4.28 and Table 4.8 displays these results for the full range of lane changes. Both show that an increase in preview distance, caused a reduction in the lateral acceleration experienced by the driver. The figure shows lateral acceleration was reduced as preview distance increased. From the table the effect of the increased preview distance appeared to be negligible at low speeds, but is increased with speed.

Given the results of the above tests and metrics it was decided to use the 30m preview distance for the remainder of the look ahead simulations.

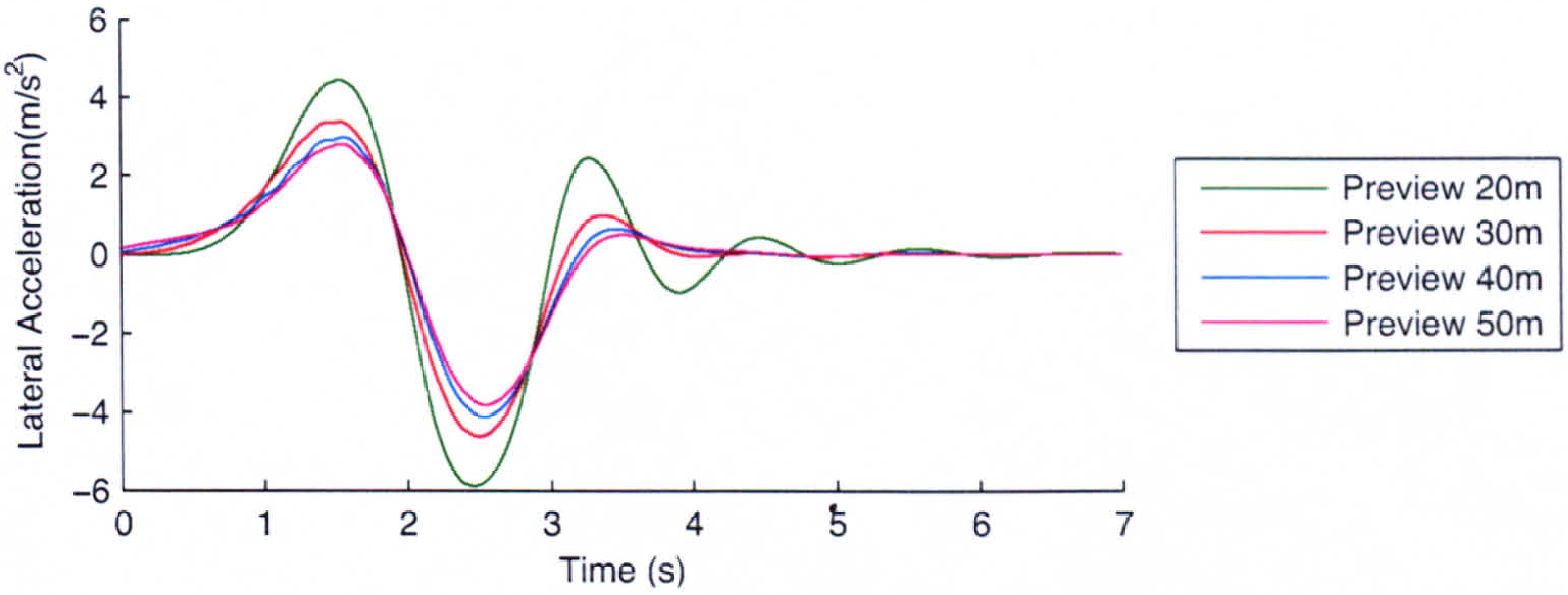


Figure 4.28: Lateral acceleration of vehicle for ELC with varying preview distance

Table 4.8: Maximum lateral acceleration (m/s^2) for lane change manoeuvres with varying preview distance

Preview Distance	**20m**	**30m**	**40m**	**50m**
SLC 50mph	0.546	0.526	0.510	0.495
SLC 60mph	0.574	0.546	0.536	0.525
SLC 70mph	0.607	0.573	0.562	0.554
ELC 0.1g 50mph	1.113	1.026	0.956	0.907
ELC 0.1g 60mph	1.186	1.113	1.051	1.008
ELC 0.1g 70mph	1.273	1.176	1.140	1.102
ELC 0.5g 50mph	3.700	2.749	2.443	2.234
ELC 0.5g 60mph	4.444	3.374	2.970	2.807
ELC 0.5g 70mph	5.079	4.052	3.559	3.321

Number of Look Ahead Points

Increasing the number of look ahead points should result in a better picture of the upcoming trajectory. Errors caused by anomalies in the landscape or its interpretation would be smoothed out. It was thought that this technique would yield a smoother response from the vehicle as the number of points were increased. However, there will come a point where increasing the number of preview points will yield diminishing returns. Tests were carried out to determine this ceiling.

A full range of simulations were conducted using a preview distance of 30m but varying the number of points at which errors were calculated. The influence of these errors was scaled using an exponential decay function along the length of the virtual lever extended from the front of the vehicle. The results of these tests for a 60mph 0.5g ELC are shown in Figures 4.29, 4.30, and 4.31 and are summarised for the full set of manoeuvres in Tables 4.9 and 4.10.

Considering the trajectory taken by the vehicle shown in Figure 4.29, it can be seen that as the number of points used increases, the trajectory is tracked more accurately. This was because with fewer points along the virtual lever the desired trajectory was not captured with as high resolution. With one preview point the controller only knows the desired path locally and at 30m ahead, and therefore cannot adjust the vehicle's path to account for any subtleties in the trajectory between these points.

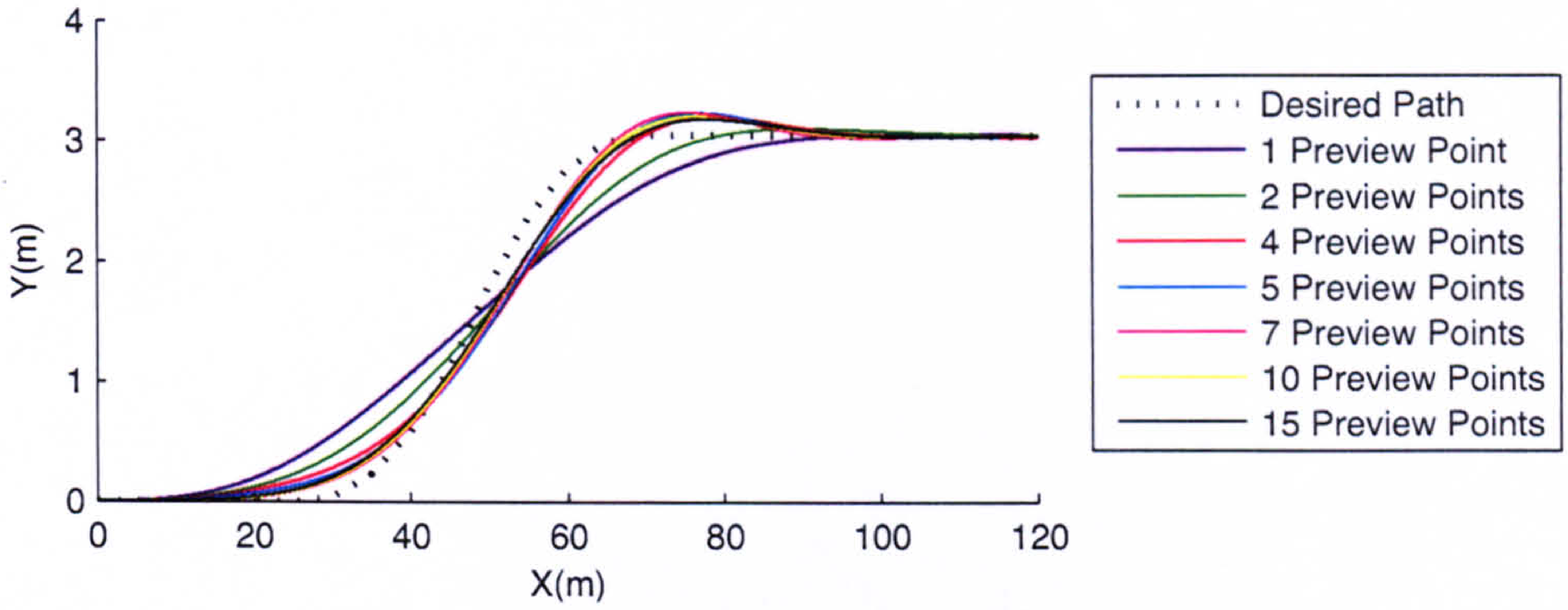


Figure 4.29: Trajectory of vehicle for ELC with varying preview points

As expected, fewer preview points yielded higher lateral errors. Moreover, looking at Figure 4.30 it is evident that increasing the number of preview points beyond seven did not reduce the lateral error significantly. The segmented nature of these errors was caused by the trajectory estimation technique. This could have been reduced if more trajectory points were used, but as can be seen from the other figures, these non-smooth errors do not affect the performance or comfort of the vehicle. These effects would be reduced as the trajectory point spacing (s) is reduced, or as a vision based system is employed on real road data.

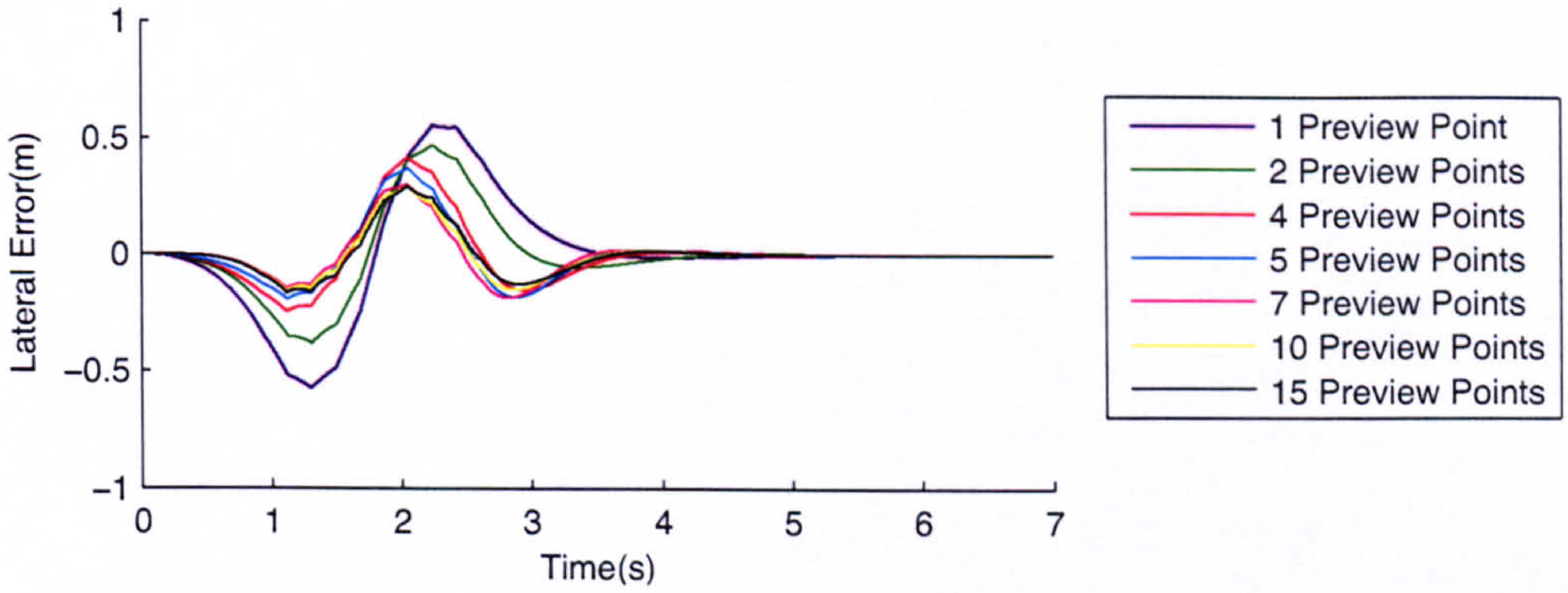


Figure 4.30: Lateral position error of vehicle for ELC with varying preview points

Table 4.9 shows the CLE for the full range of simulations. Again diminishing returns in lateral error reduction were noticed as the number of preview points was increased above seven. For the less severe manoeuvres additional preview points actually slightly increased the CLE. This may have been due to the increased influence given to the future path, detracting from the current positional influence.

Table 4.9: Cumulative lateral error (*ms*) with varying preview points

No. Of Preview Points	1	2	4	5	7	10	15
Flat Corner 50mph	0.324	0.185	0.097	0.070	0.044	0.050	0.057
Flat Corner 60mph	0.168	0.091	0.044	0.029	0.015	0.017	0.022
Flat Corner 70mph	0.106	0.053	0.026	0.028	0.029	0.024	0.021
SLC 50mph	0.628	0.379	0.203	0.147	0.092	0.105	0.121
SLC 60mph	0.384	0.213	0.105	0.070	0.038	0.042	0.052
SLC 70mph	0.226	0.112	0.058	0.058	0.058	0.051	0.044
ELC 0.1g 50mph	0.849	0.527	0.301	0.224	0.150	0.166	0.186
ELC 0.1g 60mph	0.543	0.326	0.177	0.126	0.083	0.083	0.095
ELC 0.1g 70mph	0.354	0.203	0.126	0.118	0.106	0.095	0.087
ELC 0.5g 50mph	1.296	0.876	0.616	0.519	0.419	0.414	0.425
ELC 0.5g 60mph	0.936	0.661	0.519	0.450	0.361	0.348	0.349
ELC 0.5g 70mph	0.723	0.553	0.490	0.451	0.379	0.360	0.354

While low lateral errors are key to the success of any lateral control scheme, the comfort levels experienced must also be considered. This is assessed by the levels of lateral acceleration experienced by the driver throughout the manoeuvre. Figure 4.31 shows the effect of the number of preview points on the measure for the same ELC event discussed in previous tests. Fewer preview points seemed to generate a more gentle acceleration profile, although these accelerations occurred over a longer period of time. While accelerations were increased with more preview points, the levels were still much lower than with look down lateral control systems. To follow the trajectory exactly the vehicle would need to produce 0.5g, and the highest value generated in these tests was 0.33g. The objective of the event is to change lane as quickly as possible, this is not compromised by additional corner cutting instead the stability of the vehicle throughout the event is increased (compared with a look down system). It could be argued that the system is just being asked to follow a smoother trajectory but the influence of the number of preview points and gains used add additional benefits to this method.

The lateral acceleration experienced in the full range of test scenarios is summarised in Table 4.10. As before, seven preview points seemed to be the value at which maximum lateral acceleration was experienced. Although it should again be noted that the levels experienced with seven preview points were much lower than those of a vehicle follow-

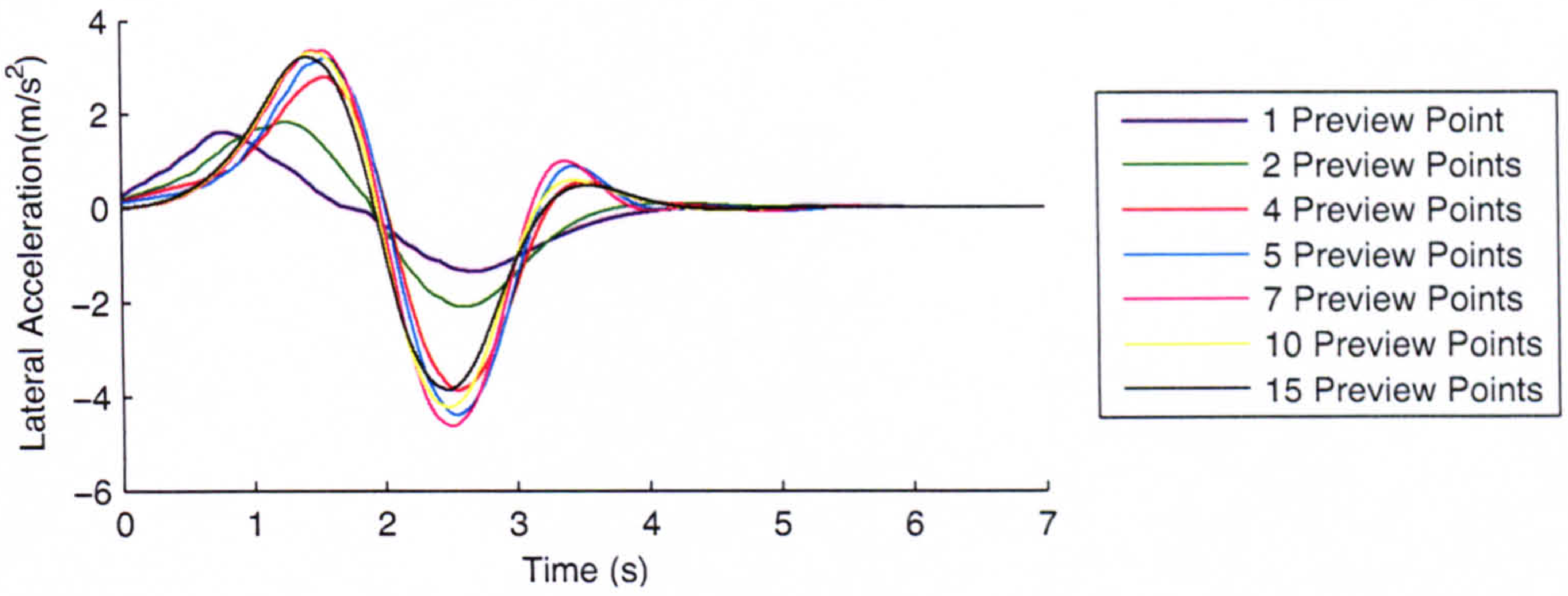


Figure 4.31: Lateral acceleration of vehicle for ELC with varying preview points

Table 4.10: Maximum lateral acceleration (m/s^2) with varying preview points

No. Of Preview Points	**1**	**2**	**4**	**5**	**7**	**10**	**15**
Flat Corner 50mph	0.365	0.388	0.416	0.427	0.435	0.422	0.416
Flat Corner 60mph	0.353	0.367	0.396	0.406	0.410	0.396	0.388
Flat Corner 70mph	0.401	0.416	0.455	0.469	0.470	0.452	0.441
SLC 50mph	0.415	0.456	0.496	0.511	0.526	0.513	0.506
SLC 60mph	0.458	0.489	0.527	0.540	0.546	0.531	0.523
SLC 70mph	0.490	0.514	0.555	0.569	0.573	0.554	0.544
ELC 0.1g 50mph	0.669	0.756	0.902	0.979	1.026	0.995	0.970
ELC 0.1g 60mph	0.789	0.878	1.009	1.061	1.113	1.074	1.044
ELC 0.1g 70mph	0.895	0.975	1.105	1.151	1.176	1.132	1.104
ELC 0.5g 50mph	1.353	1.324	2.227	2.581	2.749	2.699	2.631
ELC 0.5g 60mph	1.623	1.842	2.798	3.198	3.374	3.318	3.206
ELC 0.5g 70mph	1.906	2.342	3.293	3.768	4.052	3.924	3.741

ing the trajectory exactly, or without any preview. It was decided to use seven preview points for all future simulations, yet the possibility of using a variable number of points depending on the style of the driver and type of driving (urban, rural, motorway) should not be discounted from future studies.

Gain Tuning

There were two important factors influencing the selection of gains for the control algorithm; firstly the relative importance of the lateral error at each preview point, and secondly the importance of the current vehicle position and heading errors relative to the preview errors. It was decided to use an exponential decay function for the preview gains. This would increase the influence of errors local to the vehicle, and would also work for any number of preview points. As for the current errors, their influences were tuned using an iterative process with the look down gains as a starting point. Measures of yaw rate and lateral error were then used to assess the success of this tuning.

To test the effects of scaling these gains a fixed decay constant of $\frac{1}{\ln(1000d_p)} = 0.097$ was used, but the initial gain K_0 was varied. The other gains were calculated using the following functions.

$$K_i = K_0 \times e_i^{\left(\frac{-p_i}{\ln(1000d_p)}\right)} \tag{4.10}$$

$$K_\psi = \frac{K_0}{4} \tag{4.11}$$

Where K_i is the gain to be applied to a lateral error e_i, calculated at a distance p_im, along the virtual lever of length d_pm, and K_ψ is the gain applied to the heading error of the vehicle. Figures 4.32, 4.33, and 4.34 show the effects of varying the first gain (and therefore all others) for the ELC manoeuvre, and Tables 4.11, and 4.12 summarise the trends for the whole range of lateral scenarios.

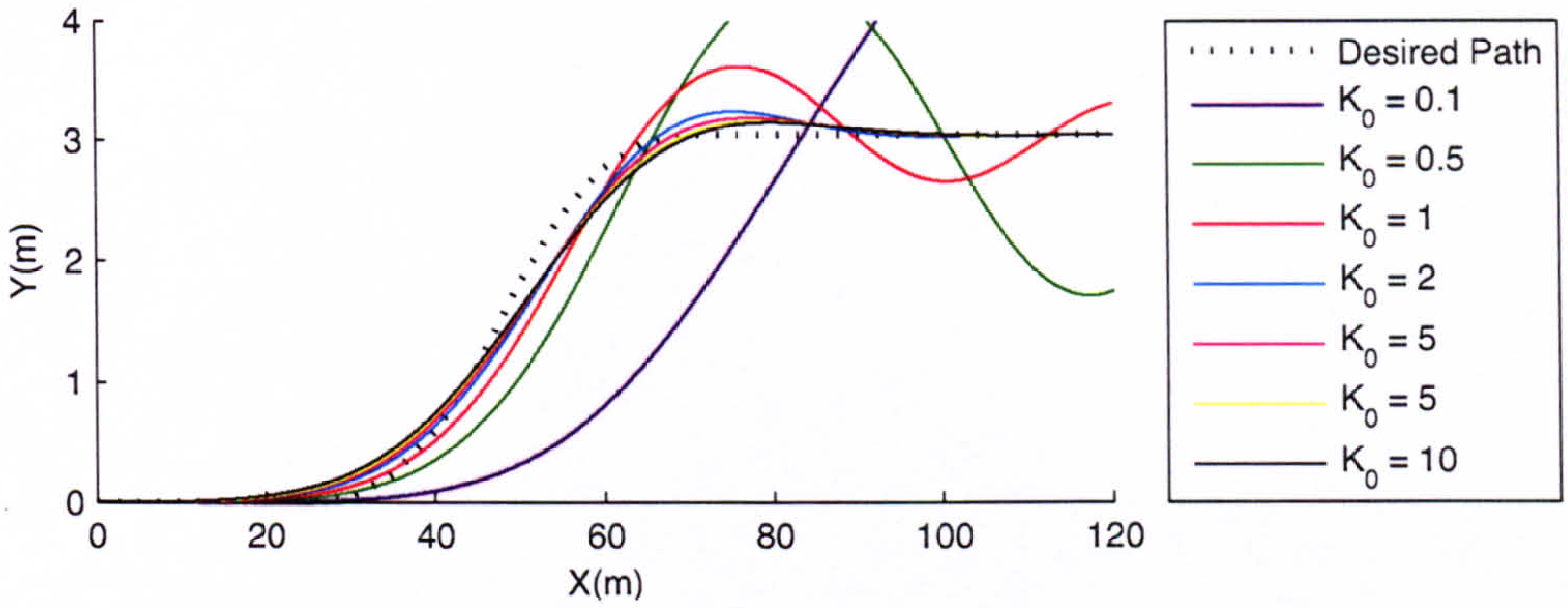


Figure 4.32: Trajectory of vehicle for ELC with varying gain magnitude

The trajectory taken by the vehicle is shown in Figure 4.32. It can immediately be seen that with low gains ($K_0 = 0.1, 0.5$) the system was not capable of completing this manoeuvre. This is because the low gains prevented the system applying enough steering angle quickly enough to remain on course. This resulted in the vehicle diverging from the desired path early on, it was then constantly fighting to get back on course, but because it was slow to react to changes in trajectory (both locally and previewed), it could never regain its desired path. With $K_0 = 1$ results were more promising: the initial corner was cut, albeit only slightly, but the ideal path was crossed quickly, because the controller was slow to react to changes in the upcoming path. Large overshoots were then generated and although oscillation was noticed, the system was able to retain stability. Higher gains increased the speed of response, and hence stability of the vehicle.

The lateral error displayed in Figure 4.33 validated the results shown in Figure 4.32. The instability created by lower gains is visible, and the direction of the inital error demonstrates whether the first turn was cut. It should also be noticed that the level of lateral error experienced was not significantly reduced when K_0 was increased above 2.

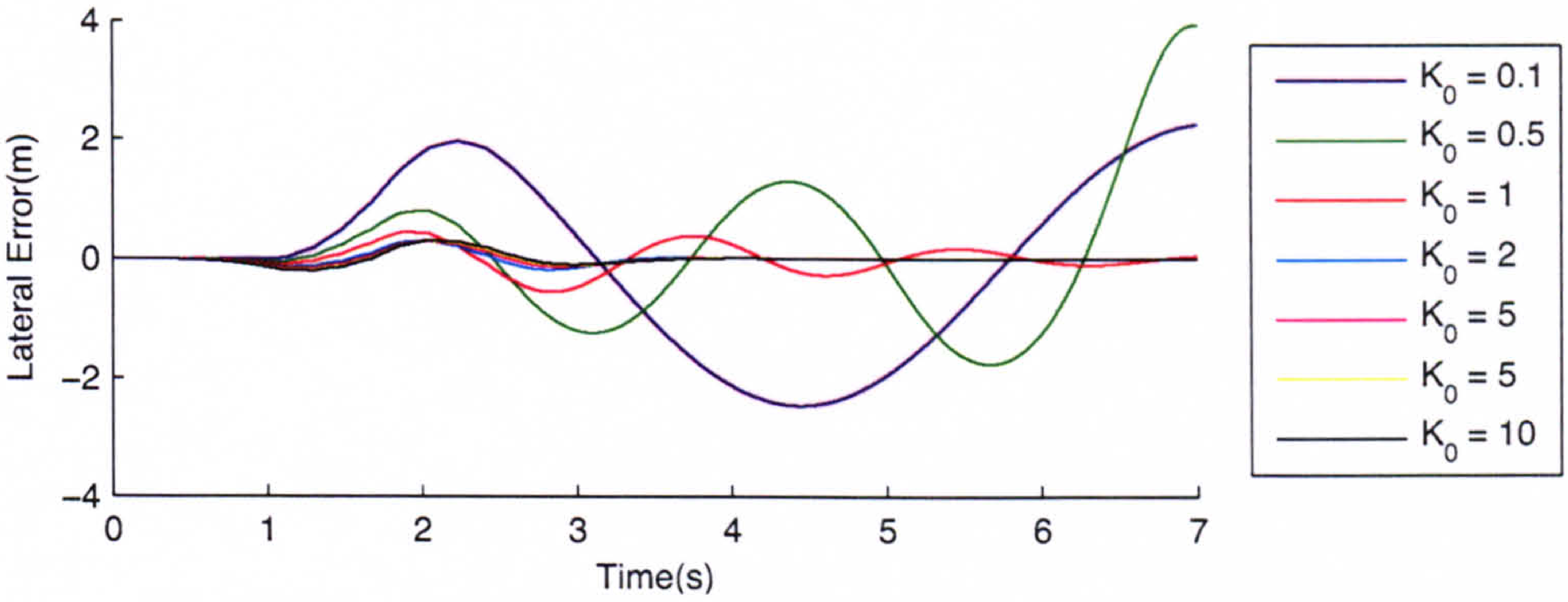


Figure 4.33: Lateral error of vehicle for ELC with varying gain magnitude

Looking at Table 4.11 it can be seen that when $K_0 = 0.1$ the system was incapable of any of the scenarios. This is deduced through the relatively high lateral error compared to other gains. With K_0 = 0.5 and 1, the vehicle was capable of all but the 0.5g ELC's. With K_0 = 2, all manoeuvres were possible, and this gain in fact gave the lowest level of lateral error for most scenarios. Higher gains may have resulted in the vehicle responding slightly quicker, but as the vehicle was not responding to the exact trajectory (merely a self determined path) this did not greatly improve the lateral error experienced.

Table 4.11: Cumulative lateral error (ms) with varying gain magnitude

K_0	**0.1**	**0.5**	**1**	**2**	**3**	**5**	**10**
Flat Corner 50mph	1.960	0.160	0.041	0.044	0.058	0.069	0.078
Flat Corner 60mph	1.612	0.119	0.050	0.015	0.022	0.029	0.034
Flat Corner 70mph	1.508	0.151	0.074	0.029	0.022	0.018	0.017
SLC 50mph	2.988	0.307	0.080	0.092	0.121	0.144	0.162
SLC 60mph	2.902	0.261	0.100	0.038	0.052	0.068	0.081
SLC 70mph	2.652	0.231	0.125	0.058	0.058	0.037	0.036
ELC 0.1g 50mph	5.187	0.761	0.167	0.150	0.186	0.217	0.241
ELC 0.1g 60mph	4.719	0.716	0.171	0.083	0.095	0.117	0.134
ELC 0.1g 70mph	4.703	0.619	0.189	0.106	0.088	0.081	0.079
ELC 0.5g 50mph	7.053	2.378	0.797	0.419	0.433	0.462	0.488
ELC 0.5g 60mph	7.995	5.836	1.154	0.361	0.356	0.370	0.387
ELC 0.5g 70mph	9.512	31.548	49.948	0.379	0.358	0.358	0.365

The comfort levels experienced by the vehicle are noted in Figure 4.34 for the 0.5 60mph ELC, and summarised in Table 4.12 for the full range of manoeuvres. Looking at Figure 4.34 it can be seen that the lower gains resulted in lower initial levels of lateral acceleration, but due to the slow speed of response they became unstable and were not suitable in this instance. At $K_0 = 10$ there was some second order oscillation in the acceleration response of the system. This was caused by the trajectory points and their spacing, but it was not amplified with lower values of K_0. These oscillations would increase the lateral jerk experienced by the vehicle, and may result in an uncomfortable feel to certain manoeuvres. Although the effects of this phenomenon would be reduced in real vehicles with vision based systems as more trajectory points could be used.

With these issues in mind it was decided to use a K_0 value of 2 for the rest of the simulations in this research. This would result in a system capable of the full range of manoeuvres, with low lateral error (low safety risk), and good comfort performance (lateral acceleration reduced from look down system).

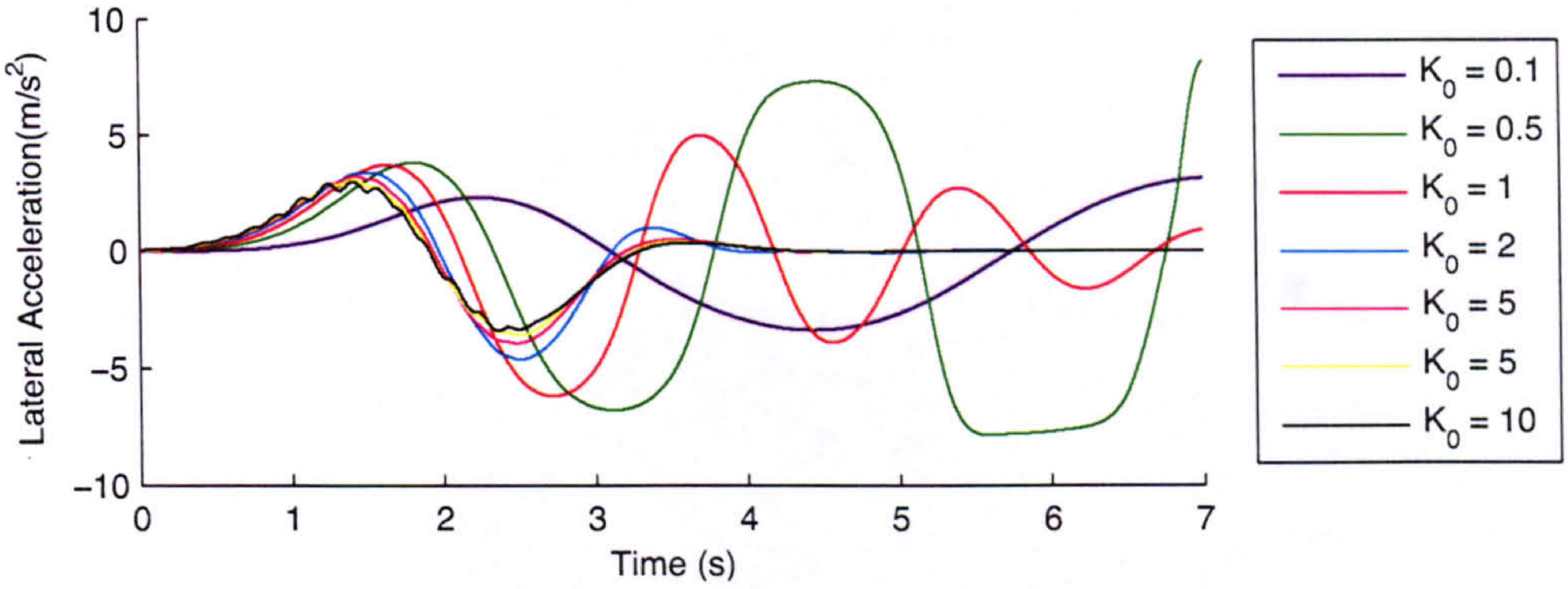


Figure 4.34: Lateral acceleration of vehicle for ELC with varying gain magnitude

For the above simulations the influence of the heading error was kept constant. With K_0 fixed at 2, it was decided to investigate the influence of K_ψ. Results from these tests are shown in Figure 4.35. It can be seen that changes made to this yaw gain ratio had little effect on the response of the system. Similar trends to this were noticed through the range of metrics and scenarios investigated in previous tests, and so their results are not shown here. It was thought that these high speed manoeuvres would be more limited by the lateral errors, rather than the relatively small heading errors. The yaw error gain(K_ψ) may have more influence at slower speeds. Sharp et al. (2000) suggested a value of 0.5 but for the purpose of these tests the obvious choice was to set the K_ψ at 0. As some of the initial simulations were conducted before the investigation into the effects of this gain it was decided to maintain the same gain of 0.5 throughout all future experiments.

Table 4.12: Maximum lateral acceleration (m/s^2) with varying gain magnitude

K_0	**0.1**	**0.5**	**1**	**2**	**3**	**5**	**10**
Flat Corner 50mph	0.646	0.566	0.489	0.435	0.420	0.419	0.426
Flat Corner 60mph	0.645	0.552	0.474	0.410	0.390	0.387	0.393
Flat Corner 70mph	0.762	0.658	0.558	0.470	0.444	0.442	0.440
SLC 50mph	0.727	0.680	0.589	0.526	0.510	0.508	0.518
SLC 60mph	0.830	0.735	0.627	0.546	0.528	0.524	0.527
SLC 70mph	0.921	0.798	0.672	0.573	0.547	0.543	0.544
ELC 0.1g 50mph	1.106	1.286	1.158	1.026	0.980	0.961	0.973
ELC 0.1g 60mph	1.348	1.466	1.279	1.113	1.056	1.041	1.029
ELC 0.1g 70mph	2.505	1.635	1.394	1.176	1.110	1.103	1.097
ELC 0.5g 50mph	1.756	3.480	2.904	2.749	2.649	2.524	2.680
ELC 0.5g 60mph	3.127	8.120	4.981	3.374	3.236	3.077	2.991
ELC 0.5g 70mph	4.924	8.383	7.777	4.052	3.778	3.508	3.400

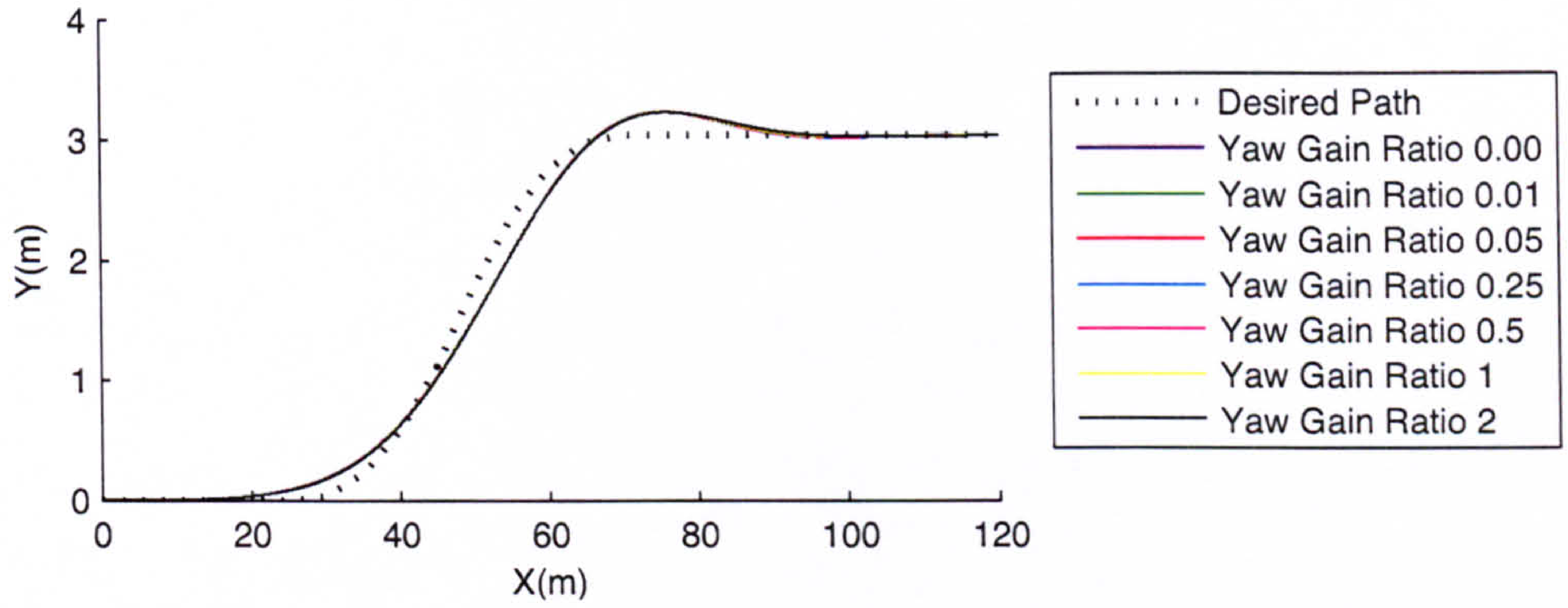


Figure 4.35: Trajectory of vehicle for ELC with varying yaw and displacement gains

4.5 Look Ahead Analysis

The controlled vehicle was tested through the full range of manoeuvres described in Section 4.1. Some of the issues found in these simulations have been noted in the previous sections, but certain interesting aspects of the controller's performance are considered in more detail in this section. Some additional disturbance scenarios were performed, including a split-μ lane change, again their results are discussed in detail. The results of the look ahead and look down systems are not compared directly throughout this chapter, instead the two types of system are compared in Section 4.5.4.

4.5.1 Lane Keeping Results

Straight Roads

Straight sections of road are commonplace in urban, rural and motorway driving. Successful control of the vehicle's straight line heading is imperative to the successful operation of the system in more complex manoeuvres.

The controller performed well for a given straight section of road over the full range of speeds. Any lateral errors measured were well below perceivable levels ($\approx 1e^{-10}$). Any changes in the comfort of the vehicle, lateral, roll and pitch accelerations were again undetectable.

Curved Roads

During the curved roads simulations, we were especially concerned with the lateral errors experienced by the vehicle, as it is vitally important that the vehicle remains within the defined lane, throughout the whole manoeuvre. Deviation from this path could cause collision with other traffic or obstacles. Driver comfort levels were also of importance as curved road scenarios make up a large proportion of typical driving.

Results for the full range of simulations are shown using the trajectory plots in Figure 4.36, and overall results for the comfort and error levels of the systems are presented in Table 4.13. The results for all speeds are shown together to validate the success of the controller over the full range.

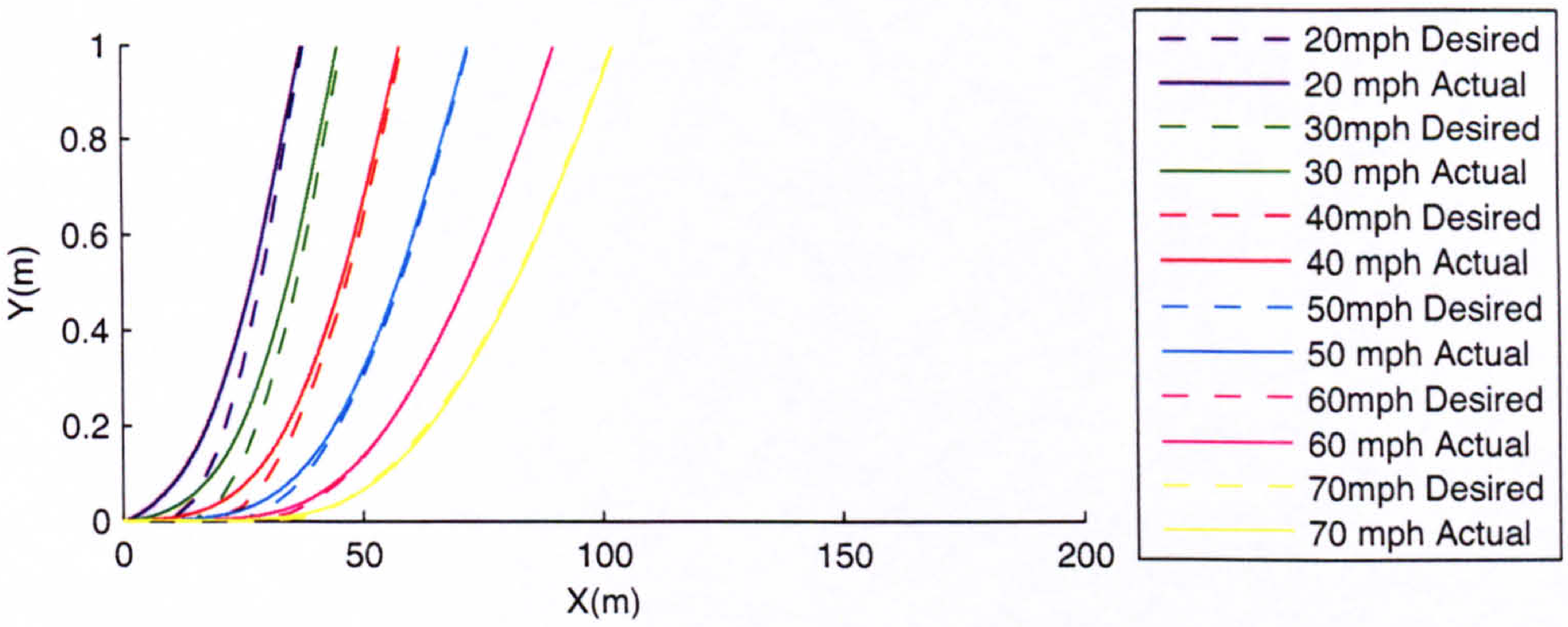


Figure 4.36: Trajectory of vehicle for flat corners

Considering the trajectory plot, it is possible to see the corner cutting evident in the lower and medium speed range. The degree of corner cutting decreased, as the speed increased. From Table 4.13 we can see that at the lowest speed the maximum lateral error was 0.104m, meaning the corner was cut by $\approx 10cm$. Given an average lane width of 3m, and a vehicle width of 2m, this was still within acceptable limits. It should also be noted that this was for low speeds, uncommon in flowing motorway traffic. The level of corner cutting was increased at lower speeds due to the ability of the vehicle to adjust its desired heading relatively quickly. When a preview lateral error was picked up by the control system, the vehicle was able to respond to changes in the desired trajectory. At higher speeds the changes in the desired trajectory were smaller (as prescribed by the motorway design manual) and the vehicle was not able to react to these changes as quickly as at lower speeds. This was mainly due to the relatively slow build up of slip angles, and the corner was therefore cut to a lesser extent ($\approx 1cm$ at 70mph).

Table 4.13: Flat corner results for look down system

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
Flat Corner 20mph	0.104	0.133	0.010
Flat Corner 30mph	0.080	0.323	0.013
Flat Corner 40mph	0.042	0.395	0.010
Flat Corner 50mph	0.023	0.435	0.015
Flat Corner 60mph	0.011	0.410	0.016
Flat Corner 70mph	0.014	0.470	0.012

Considering comfort at low speeds, corner cutting reduces the lateral acceleration experienced by the vehicle. The level of lateral acceleration increased with speed as the lack of corner cutting meant that additional lateral acceleration was required throughout the manoeuvre to maintain the desired trajectory. Both lateral and roll accelerations were well within acceptable levels for a manoeuvre of this type.

4.5.2 Lane Changing Results

Standard Lane Changes

The SLC event is one which is common in motorway driving. During the event the driver wishes to change lane, safely and comfortably. Trajectories for this event are shown in Figure 4.37, and the results are summarised in Table 4.14. Similar trends to those in the flat corner events were noticed. At low speeds the degree of corner cutting was increased. Again, this is due to the improved ability of the vehicle to change heading quickly and the sharper desired trajectory. At these low speeds this still resulted in relatively low lateral accelerations. As speed was increased corner cutting was reduced, due to the smoother desired trajectory (less preview error) and the longer response time of the vehicle.

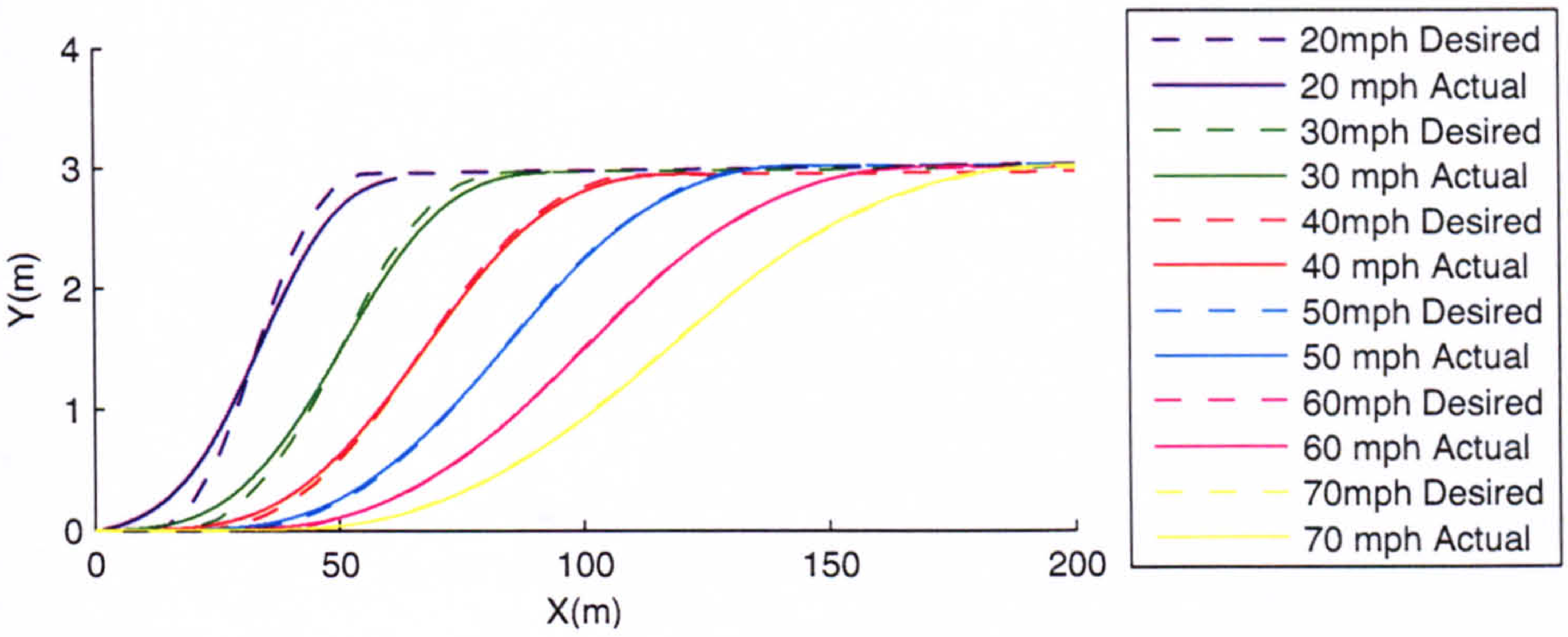


Figure 4.37: Trajectory of vehicle for SLC

Lateral acceleration increased with vehicle speed, as additional cornering was required to maintain the trajectory (less corner cutting). Roll accelerations displayed interesting results, as the change of direction in the middle part of the trajectory is more sudden at lower speeds, increased roll acceleration was perceived. At higher speeds the smoother change of direction yields a lower roll acceleration. From a roll motion point of view it should mean that the higher speed manoeuvres are more comfortable, yet it should be noted that all roll accelerations were well within the desirable limits.

Table 4.14: Standard lane change results for look down system

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
SLC 20mph	0.228	0.283	0.028
SLC 30mph	0.111	0.437	0.021
SLC 40mph	0.053	0.488	0.013
SLC 50mph	0.030	0.535	0.012
SLC 60mph	0.018	0.557	0.012
SLC 70mph	0.017	0.583	0.013

Evasive Lane Changes

The ELC represents the more severe events used when the driver is trying to avoid an obstacle, or maybe a driver with a more aggressive style changing lane. The manoeuvres were conducted at two levels of lateral acceleration 0.1g, and 0.5g. While comfort was of secondary importance in these events, it was still interesting to consider the impact of these events on the driver.

Figure 4.38 shows the trajectory followed by the vehicle during the 0.1g ELC. The results of this event are summarised in Table 4.15. While the desired lateral acceleration

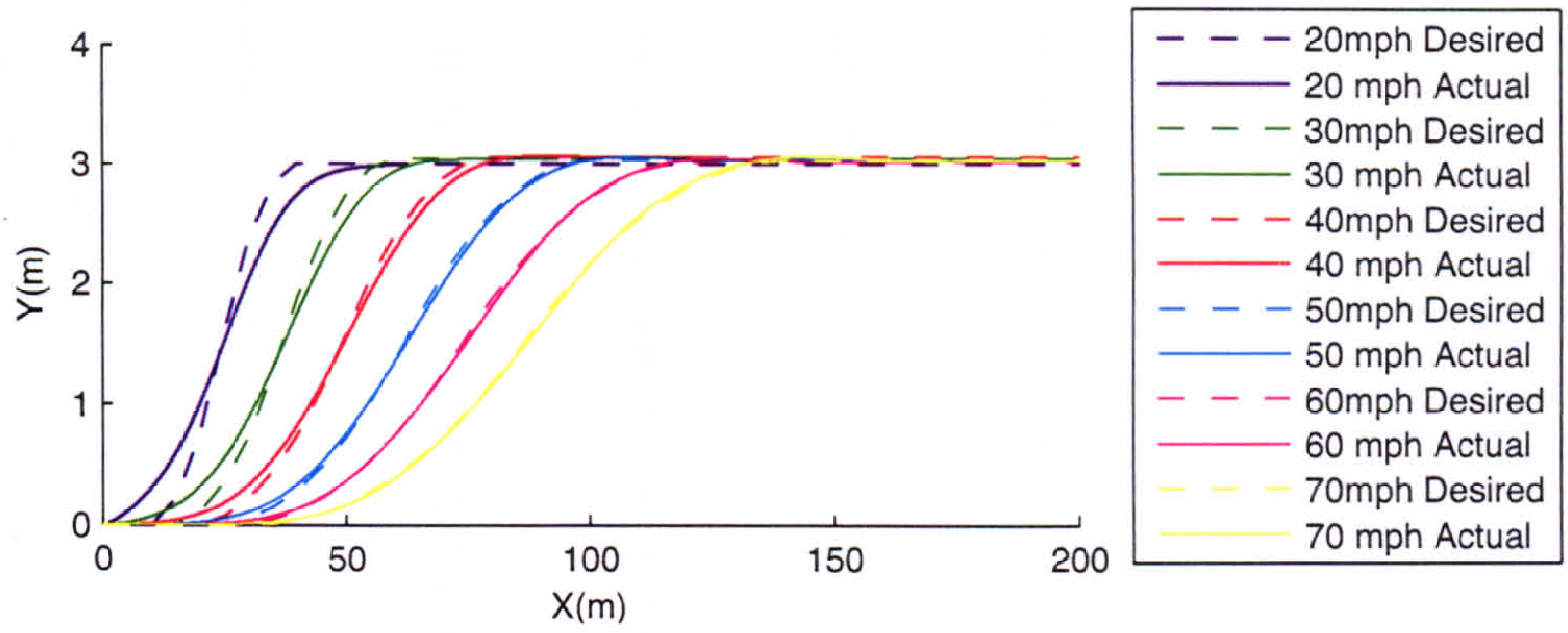


Figure 4.38: Trajectory of vehicle for 0.1g ELC

and yaw rate were different between the SLC and 0.1g ELC, the results were similar. This suggested that the controller was robust to a range of different inputs. For this sharper manoeuvre, there was still little or no overshoot when entering the second lane. Again corner cutting was decreased as speed increased, but lateral acceleration increased with speed.

The comfort levels were reduced compared to the SLC, as lateral and roll acceleration were increased due to the increased severity of the manoeuvre. In this event, the maximum roll acceleration for all speeds was not limited by the change of direction in the middle of the manoeuvre at low speeds, but by the final straightening up at higher speeds. This meant a higher maximum level of roll acceleration would be perceived at speeds above 50mph, possibly reducing the overall comfort feeling of the event.

Table 4.15: 0.1g evasive lane change results for look down system

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
ELC 0.1g 20mph	0.351	0.425	0.050
ELC 0.1g 30mph	0.207	0.767	0.042
ELC 0.1g 40mph	0.115	0.962	0.035
ELC 0.1g 50mph	0.074	1.114	0.035
ELC 0.1g 60mph	0.059	1.239	0.042
ELC 0.1g 70mph	0.054	1.376	0.053

The 0.5g ELC describes an event that the driver would instigate when speed of lane change is vitally important. Stability of the vehicle throughout the event is obviously paramount but comfort is of little importance. The trajectories of the vehicle for this range of events are shown in Figure 4.39, and the overall results are summarised in Table 4.16.

A noticeable difference between this and previous simulations was the overshoot,

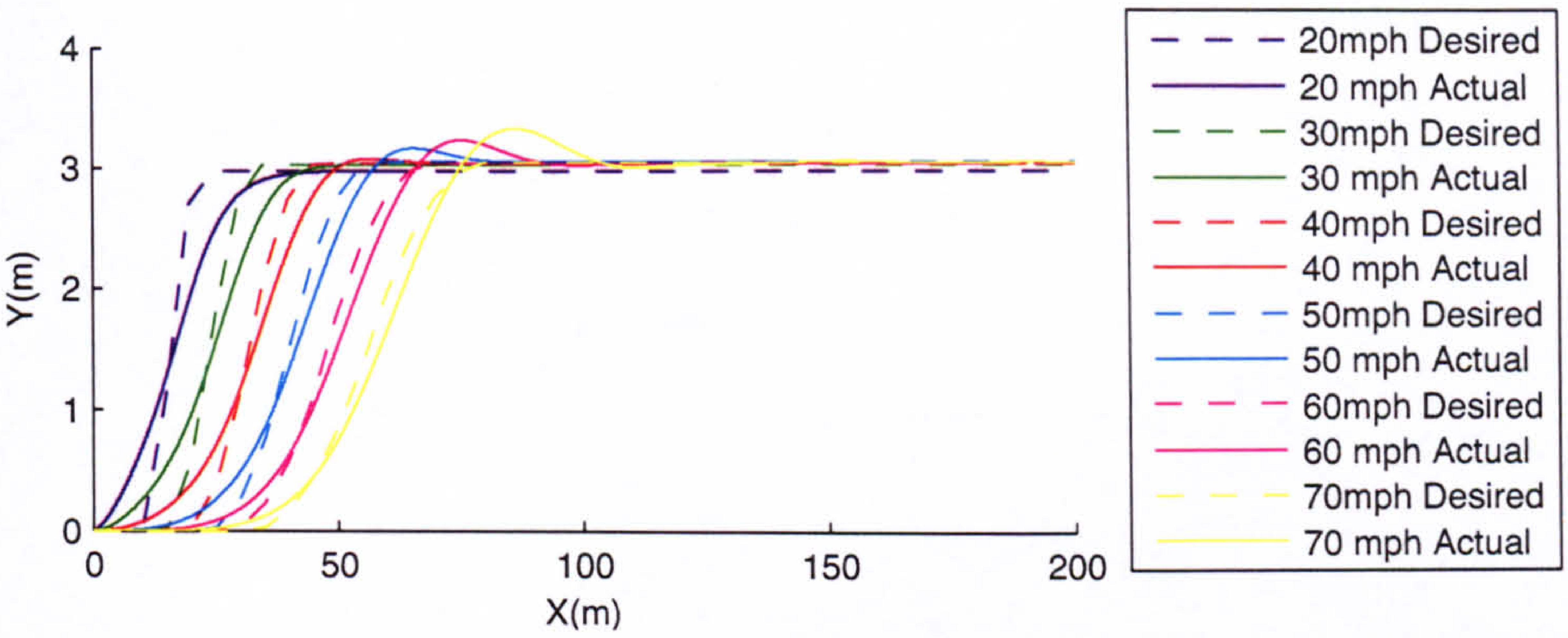


Figure 4.39: Trajectory of vehicle for 0.5g ELC

which occurred at high speeds. Again corner cutting decreased with speed, as seen in Figure 4.39, but at 70mph the maximum lateral error became limited by the level of overshoot. This remained within acceptable levels ($\approx 30cm$), but would be perceivable by the driver. The overshoot was quickly reduced, to ensure that the vehicle again tracked the desired trajectory, maintaining stability. While lateral acceleration was not affected by the overshoot, low speed events displayed significantly lower lateral acceleration values than the desired level of 0.5g; this was due to the degree of corner cutting.

Table 4.16: 0.5g evasive lane change results for look down system

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
ELC 0.5g 20mph	0.122	0.117	0.025
ELC 0.5g 30mph	0.589	1.714	0.154
ELC 0.5g 40mph	0.436	2.677	0.162
ELC 0.5g 50mph	0.344	3.698	0.201
ELC 0.5g 60mph	0.302	4.617	0.255
ELC 0.5g 70mph	0.306	5.482	0.379

This overshoot had an impact on the roll acceleration experienced by the vehicle. As the speed increased, so did the overshoot, and therefore the severity at which the system tried to regain the desired heading; this in turn increased roll acceleration.

4.5.3 Disturbance Results

Low Friction

Lateral control systems will be used during all types of environmental conditions from freezing roads, to heavy rain and even hot arid surfaces. It is important that the sensing systems are able to function in these conditions, and also that the control systems do not cause any undesirable vehicle performance. With this in mind, the look ahead control system was tested through the full range of manoeuvres in three conditions of surface friction: 0.85 for a dry standard road, 0.4 for a wet road and 0.2 for an icy surface (Khatun et al. 2002, Sakai and Hori 2000).

For the flat corners and the SLC manoeuvres the performance of the vehicle was unaffected by these changes in μ, as the desired lateral accelerations of the vehicle were still achievable even in icy conditions.

As the severity of the manoeuvre was increased the performance of the vehicle deteriorated. This becomes noticeable in the 0.1g ELC manoeuvres at speeds of 40mph and above. Below these speeds the desired lateral acceleration was within the performance capabilities of the vehicle; but at higher speeds the icy conditions meant that the desired lateral forces could not be generated by the tyres. This resulted in the vehicle not being able to turn-in quick enough, and so the desired trajectory was overshot (Figure 4.40). This overshoot became larger with speed, and eventually the vehicle became unstable at 60mph. In both wet and dry conditions the vehicle performed well for the entire speed range. No change in performance was noticed between the two higher μ conditions (0.4, 0.85).

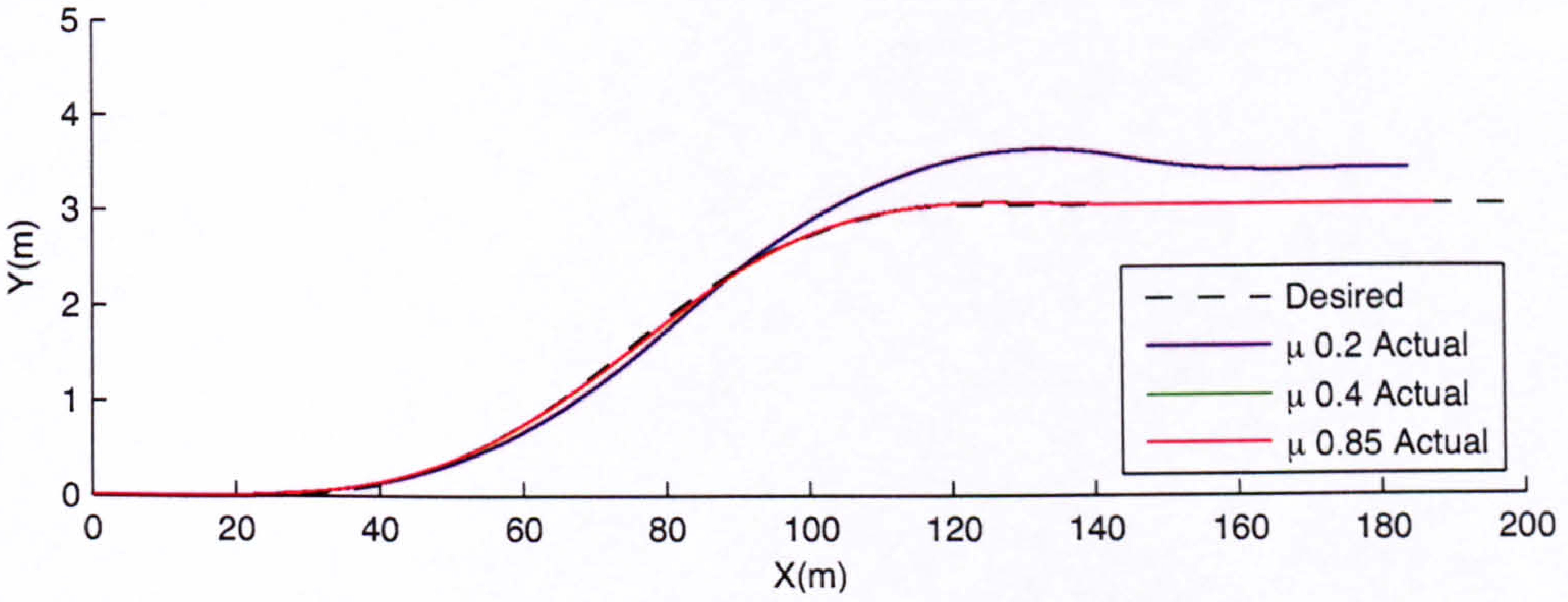


Figure 4.40: Trajectory of vehicle for 0.1g ELC at various μ

The 0.5 g ELC manoeuvre provided more of a challenge for the system. In icy conditions the vehicle became unstable even at low speeds, due to the unattainable high lateral forces required to maintain the desired course. In wet conditions larger overshoots were noticed as speed increased (Figure 4.41), although the response of the vehicle remained stable until 70mph.

From a vehicle dynamics point of view there was little noticeable change in the other performance attributes for events when the trajectory responses remained stable. As the

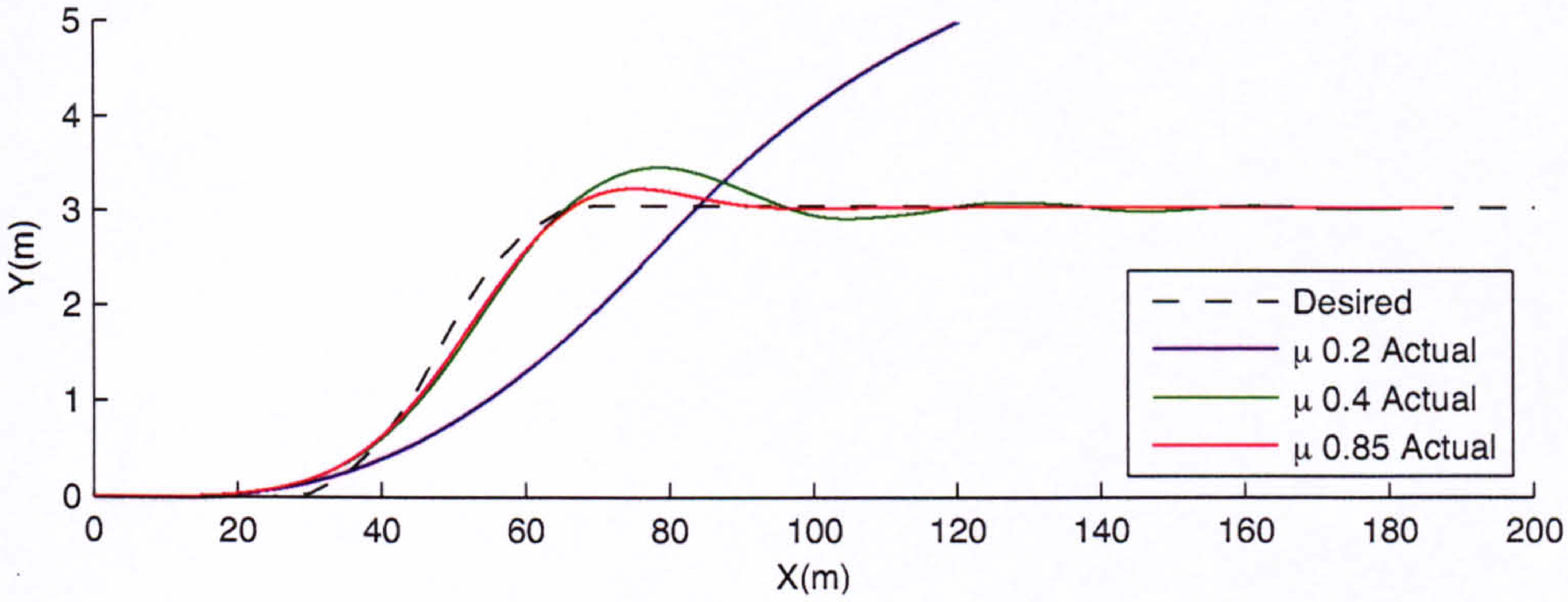


Figure 4.41: Trajectory of vehicle for 0.5g ELC at various μ

trajectory of the vehicle became more oscillatory, other vehicle dynamic measures were obviously affected, with higher yaw rates, lateral accelerations and levels of jerk that would be perceived by the driver.

These results may seem obvious - when the surface co-efficent of friction is 0.2 the maximum acceleration the vehicle can achieve is 0.2g. If we demand more from the vehicle the system should fail. While this is trivial in vehicle dynamics terms, from a human factors point of view it is important to highlight these limits to the driver. It is possible that drivers may assume that ADAS may improve the acceleration capabilities of the vehicle, they may therefore trust it to perform in situations beyond the vehicles limits. From this point of view it is interesting to see how the system performs in the preceding scenarios.

Superelevation

Superelevation is the method of adding banking to the road to generate additional cornering forces, allowing tighter corners to be designed into the road. In this research superelevation is modelled as an additional disturbance. The direction of the banking was varied, as well as the magnitude of the slope to simulate 'adverse camber'. Here, the additional cornering forces generated by the incline of the vehicle's mass work against the lateral control system. The elevation was also modelled for a straight section of road to simulate a disturbance in the road surface. Results of these tests are shown in Figures 4.42, 4.43 and Table 4.17.

The trajectories shown in Figure 4.42 show that the performance of the vehicle was affected by the elevation on a straight road. There was a small deviation from the desired path ($\approx$ 6cm), for the steeper elevation. Although this initial peak was reduced, there was a steady state error (at 120m) before the elevation profile was returned to zero (150m).

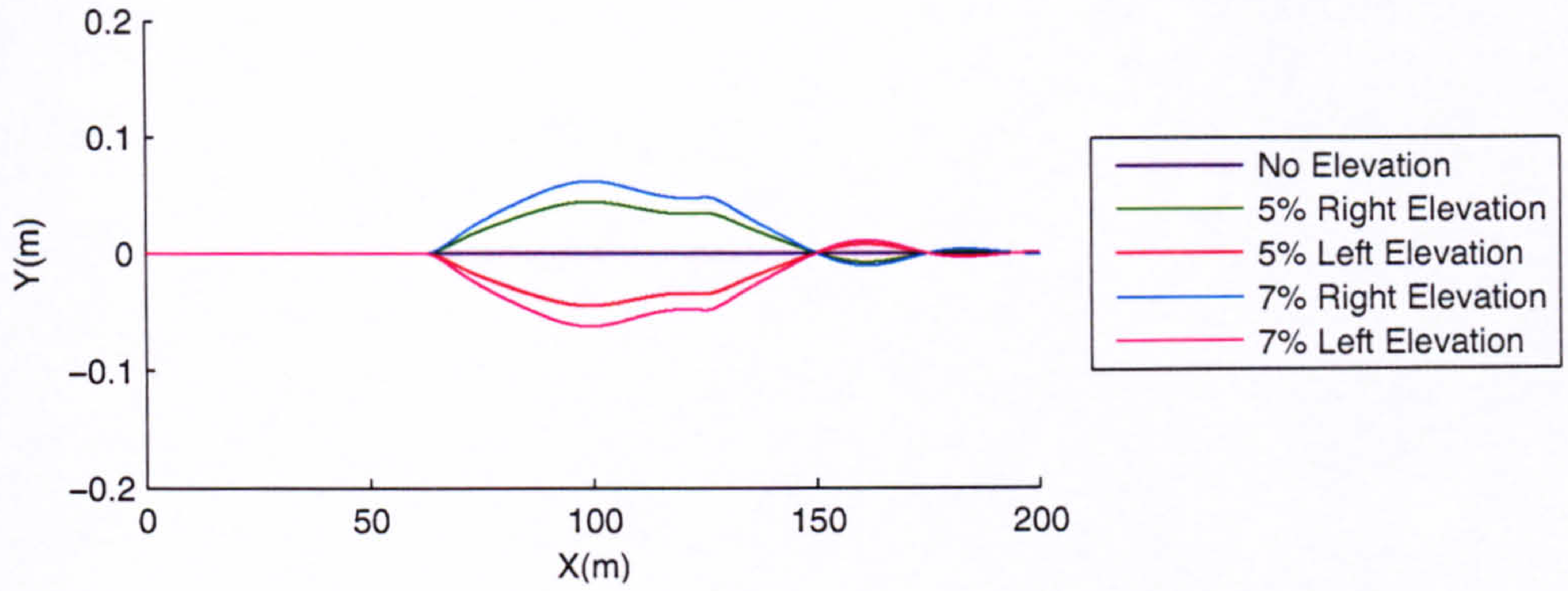


Figure 4.42: Trajectory of vehicle during an elevation disturbance on a straight road

Considering Table 4.17, it can be seen that these straight line disturbances have a marked effect on the comfort levels experienced by the driver. It is not clear how a human driver would react to mitigate against these accelerations. The levels experienced when under lateral control were in line with that of an 0.1g ELC. Further investigation and tuning may be required to reduce the level of response to this disturbance.

Table 4.17: Super elevation disturbance results

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
0% Elevation Straight	0.000	0.000	0.000
5% Right Elevation Straight	0.045	0.733	1.043
5% Left Elevation Straight	0.045	0.733	1.043
7% Right Elevation Straight	0.062	1.024	1.458
7% Left Elevation Straight	0.062	1.024	1.458
0% Elevation Corner	0.014	0.470	0.012
5% Right Elevation Corner	0.037	1.177	1.046
5% Left Elevation Corner	0.053	0.686	1.040
7% Right Elevation Corner	0.055	1.468	1.461
7% Left Elevation Corner	0.070	0.962	1.455

For the curved roads, the corner and elevation profile were delivered to the system out of phase, to provide the maximum disturbance. Initially the vehicle began to corner on a flat road before banking was added to assist cornering (right) and to oppose cornering (left). While the trajectory plot (Figure 4.43) appears to show similar lateral errors between left and right elevations, the results in Table 4.17 confirm that assisting elevation resulted in less lateral error, as the adverse camber had a greater effect than that of the corner cutting, generated by the control system. Roll accelerations were similar between

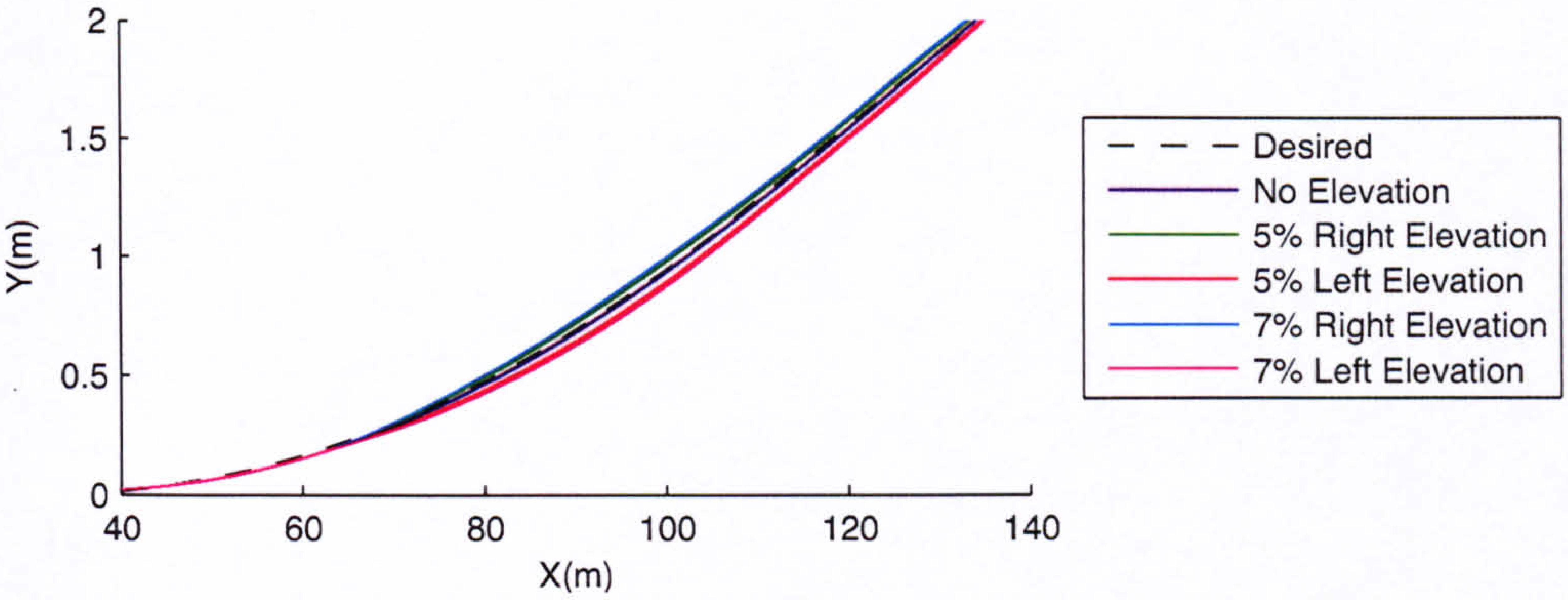


Figure 4.43: Trajectory of vehicle during an elevation disturbance on a curved road

both sides of elevation as it was limited by the initial onset of the corner, but lateral acceleration was higher with right side elevation, as the additional lateral forces increased the perceived level of acceleration.

Side Winds

Side winds are another form of disturbance, and while they can occur in all types of driving we only consider their impact while tracking a straight line, this allowed the effects of the side winds to be investigated in isolation. Side winds perpendicular to the vehicle (at 90°) and at 45° to its heading were considered. It was thought that this second test may cause additional yawing of the vehicle, rather than a purely lateral disturbance. All side winds were input to the vehicle as a two second impulse. A 20mph side wind represents a minor disturbance, whereas a side wind of 50mph equates to a large buffeting force. Results are shown in Figures 4.44, 4.45 and Table 4.18.

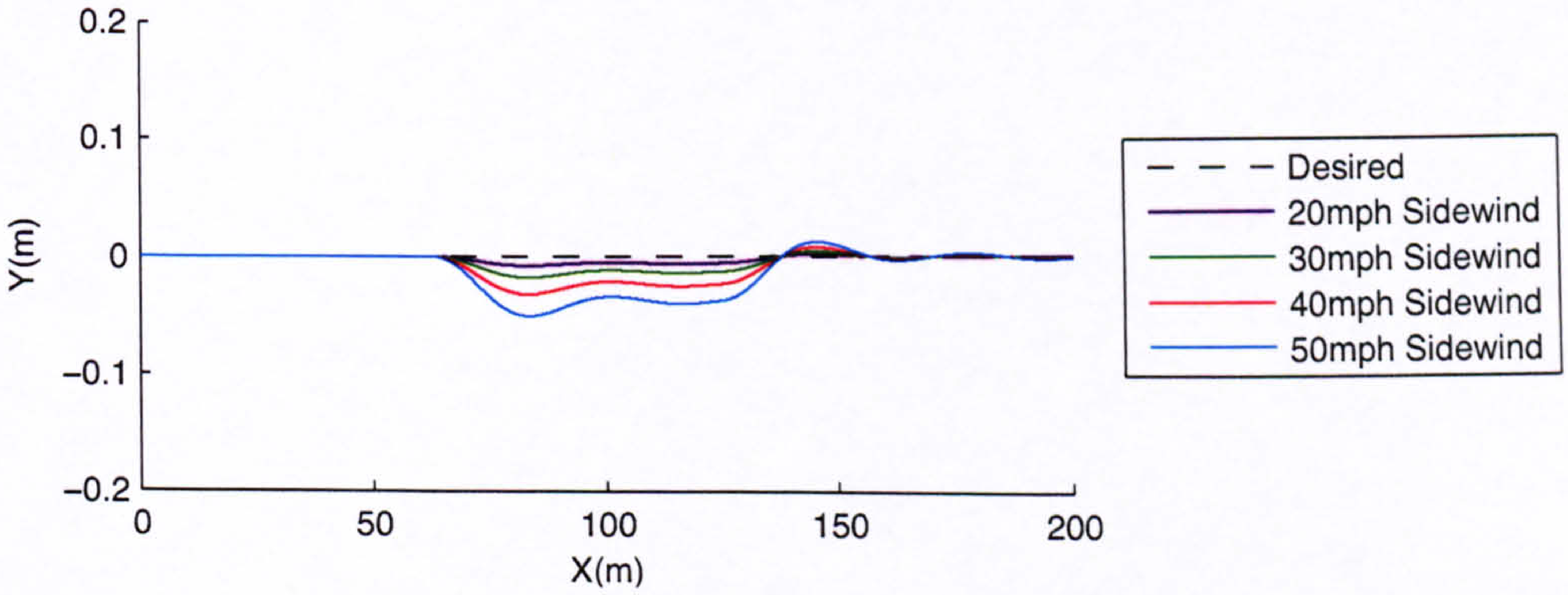


Figure 4.44: Trajectory of vehicle during a 45°side wind disturbance on a straight road

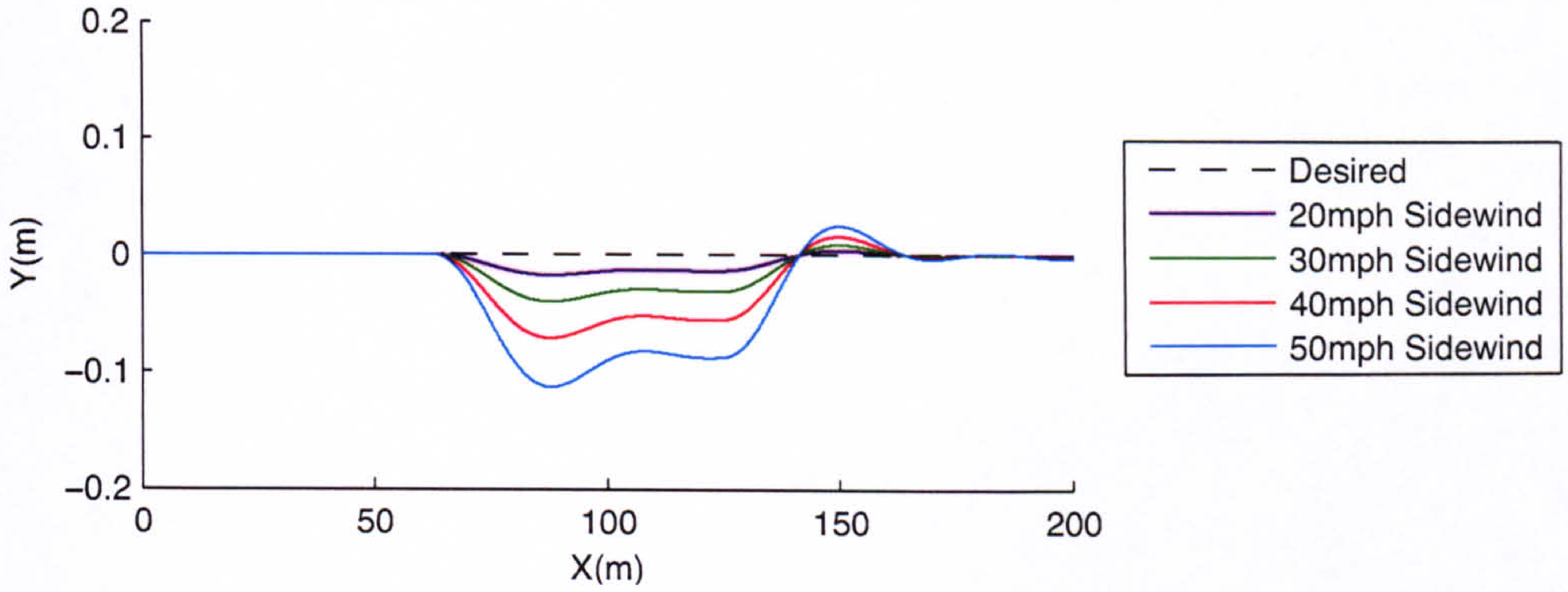


Figure 4.45: Trajectory of vehicle during a 90°side wind disturbance on a straight road

The system performed fairly well when subject to this form of disturbance, relatively low lateral errors were noticed. A 50mph gust of wind caused a deviation of ≈10cm and vehicle stability was never compromised. Lower levels of side wind caused little deviation. The lateral accelerations perceived were relatively low, given the magnitude of the disturbance. The angle of the side wind appeared to have little affect on the yawing motion of the vehicle, in fact varying the angle of the wind appeared to reduce the lateral acceleration and error generated. This may be due to any additional yawing motion counteracting the lateral disturbance, steering the vehicle away from the disturbance.

Table 4.18: Straight line side wind disturbance results

	Max Lateral Error	**Max Lateral Acc**	**Max Roll Acc**
	m	m/s^2	$^\circ/s^2$
20mph SW @ 45°	0.008	0.089	0.206
20mph SW @ 90°	0.018	0.143	0.298
30mph SW @ 45°	0.018	0.203	0.469
30mph SW @ 90°	0.040	0.325	0.676
40mph SW @ 45°	0.032	0.362	0.839
40mph SW @ 90°	0.072	0.580	1.206
50mph SW @ 45°	0.050	0.567	1.319
50mph SW @ 90°	0.113	0.911	1.889

Split-μ

A set of split μ tests was conducted to assess the system's performance when differing levels of grip were available. The 70mph 0.5g ELC was used as it was the most severe manoeuvre experienced. For a section of the road the μ parameter passed to the tyre model was reduced accordingly. This low μ zone was set up to cause as much disturbance to the vehicle as possible by affecting all tyres at different points of the manoeuvre (Figure 4.46).

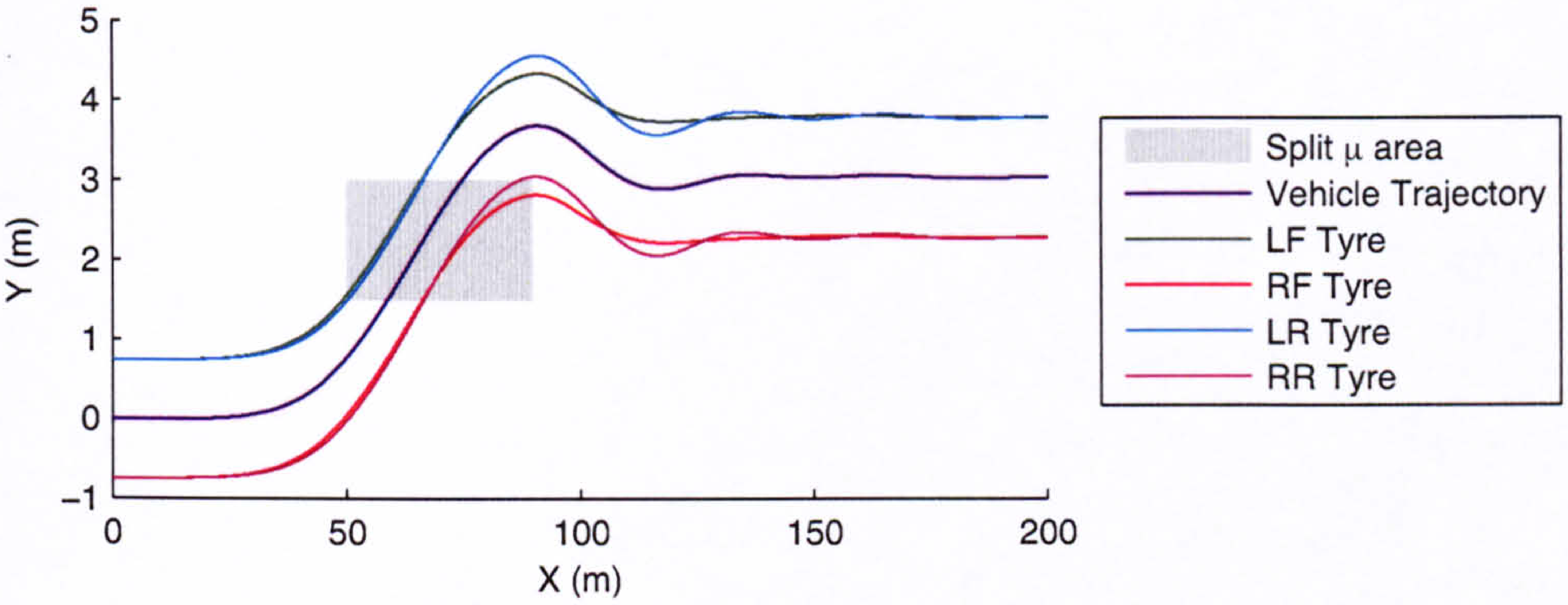


Figure 4.46: Trajectory of individual wheels during 70mph 0.5g ELC with split μ 0.85:0.4

The trajectory results in Figure 4.47 immediately show the effects of the split μ disturbance. Larger overshoots were noticed as the tyre could not generate the necessary lateral forces while in the low μ zone. Upon exit from the zone the large slip angle generated due to the increased steer angle provided the necessary lateral force to regain the desired path. The vehicle remained stable throughout this event, even with the low μ level set at 0.2. The overshoot experienced was more than desirable, but was still acceptable. For this manoeuvre, stability was the main concern, again comfort was of secondary importance, although lateral acceleration levels were largely unaffected compared to the constant μ tests.

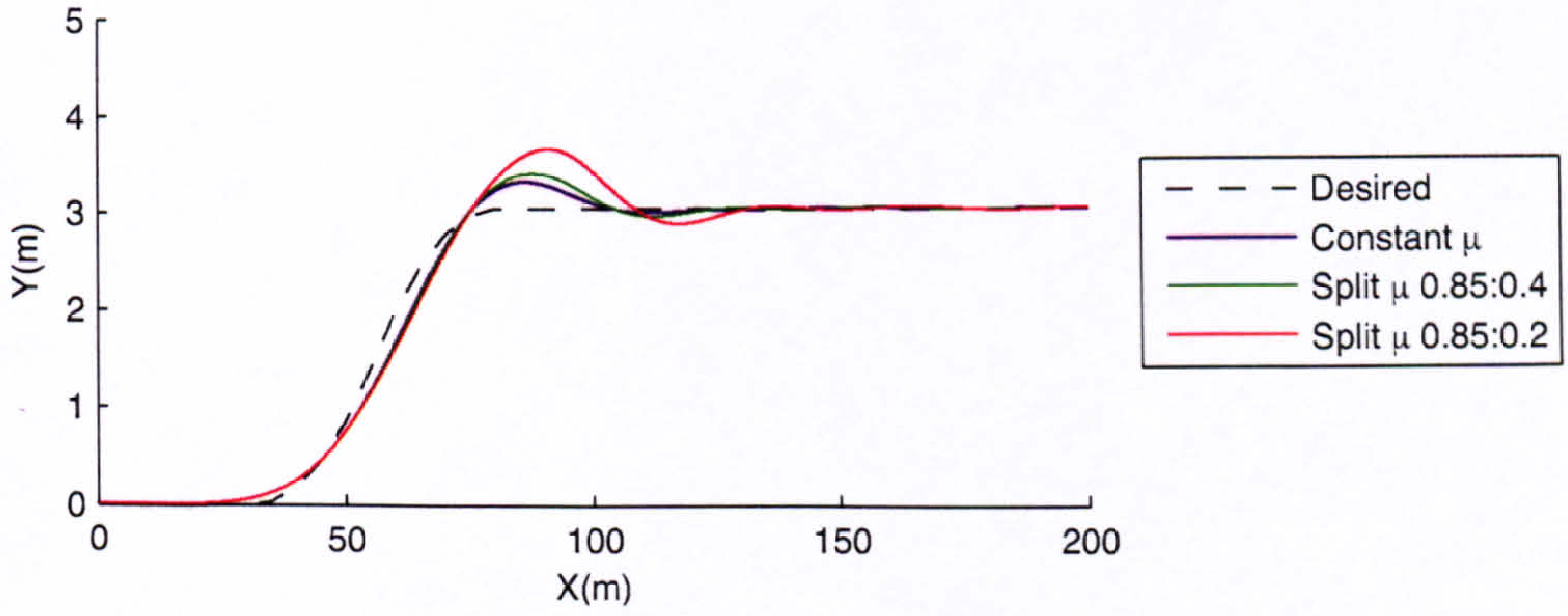


Figure 4.47: Trajectory of vehicle during 70mph 0.5g ELC with split μ conditions

4.5.4 Comparison with Look Down Scheme

Until now we have considered look ahead and look down control schemes in isolation. This has allowed us to demonstrate the success of each method and highlight individual features and problems with them. But to propose which method should be used in the driving simulator part of this research it was necessary to compare the performance of the two systems. While it is not practical to present and discuss results from all tests, a range of applicable simulations and results are discussed in this section. The low lateral acceleration manoeuvres were covered by a 50mph SLC, mid range by a 60mph 0.1g ELC and high lateral accelerations by a 60mph 0.5g ELC as the look down system is not capable of the 70mph 0.5g ELC. All manoeuvres were conducted without additional disturbances on a flat road, with a constant coefficient friction of 0.85. The look down system used in these comparative studies was the combined IMC and PID scheme developed earlier in this chapter.

At low speeds the controllers both performed well, and both were capable of all flat corner and SLC manoeuvres. Lateral error was higher with the look ahead system due to corner cutting; although both systems remained well within safe limits of the lane centreline. The lateral acceleration experienced was similar between controllers, suggesting similar comfort levels.

Figures 4.48, and 4.49 show the performance of the controllers for a 50mph SLC, this is typical of the low speed performance of the systems. Looking at the trajectory taken it was difficult to notice any difference between the two systems, both remained stable and well within desired limits.

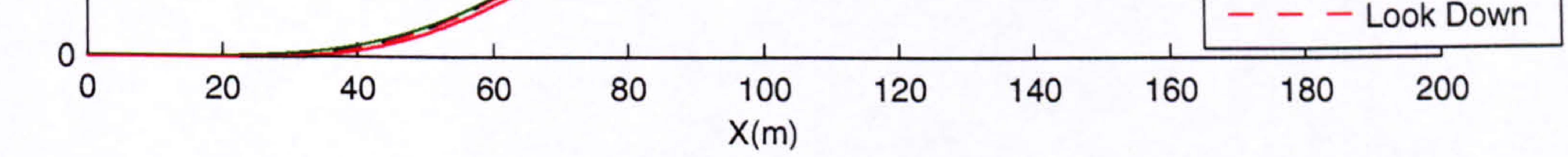


Figure 4.48: Trajectory of vehicles with look down and look ahead controllers for a SLC at 50mph

The lateral acceleration profile shown in Figure 4.49 gives more insight into differences between the systems. At this low lateral acceleration the maximum levels were of similar magnitudes, but already the smoother transition of the look ahead system was evident. Increased jerk was noticed in the look down system, as it was only able to react to changes in trajectory as they happened. This smooth transition apparent with the look ahead system was evident in other comfort measures including roll acceleration. Drivers would benefit from this reduced jerk through added comfort, and therefore possibly increased use of the system.

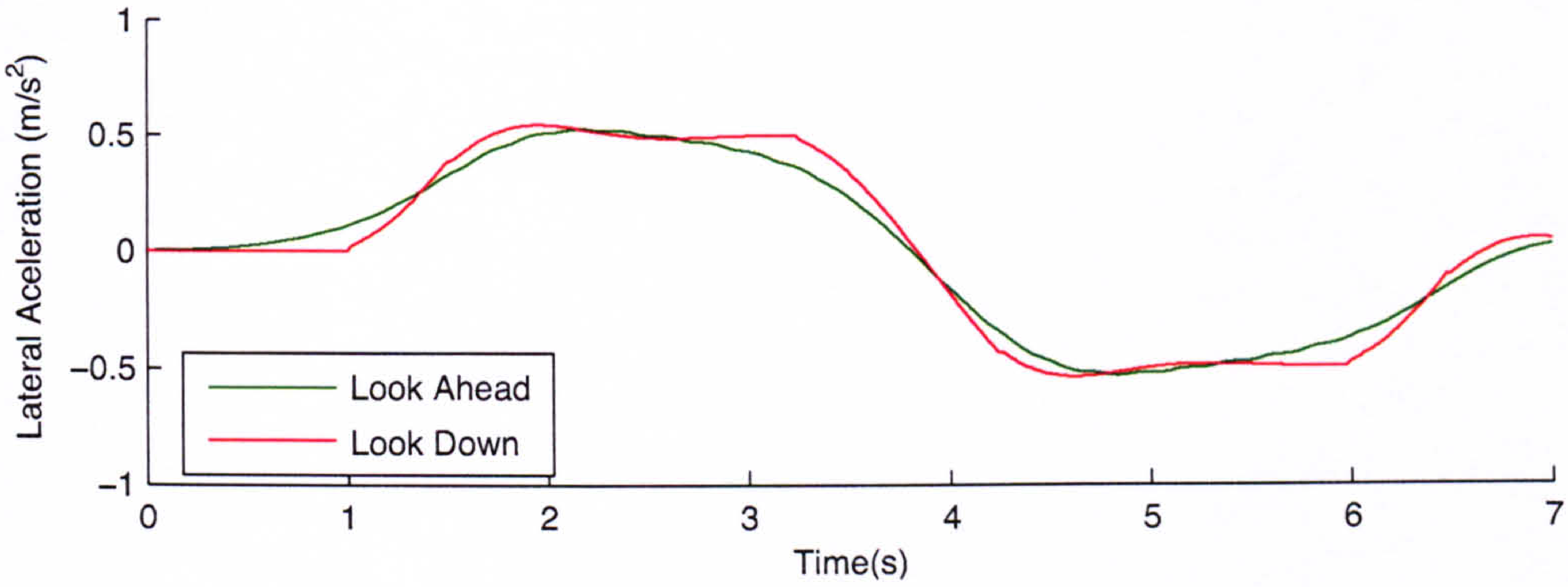


Figure 4.49: Lateral acceleration of vehicles with look down and look ahead controllers for a SLC at 50mph

The advantages of the look ahead system became more apparent as the severity of the manoeuvre was increased. Figure 4.50 - 4.51 again show that there was little difference between the trajectories taken by the two systems. Lateral error was slightly higher with the look ahead system, but it was still within acceptable limits.

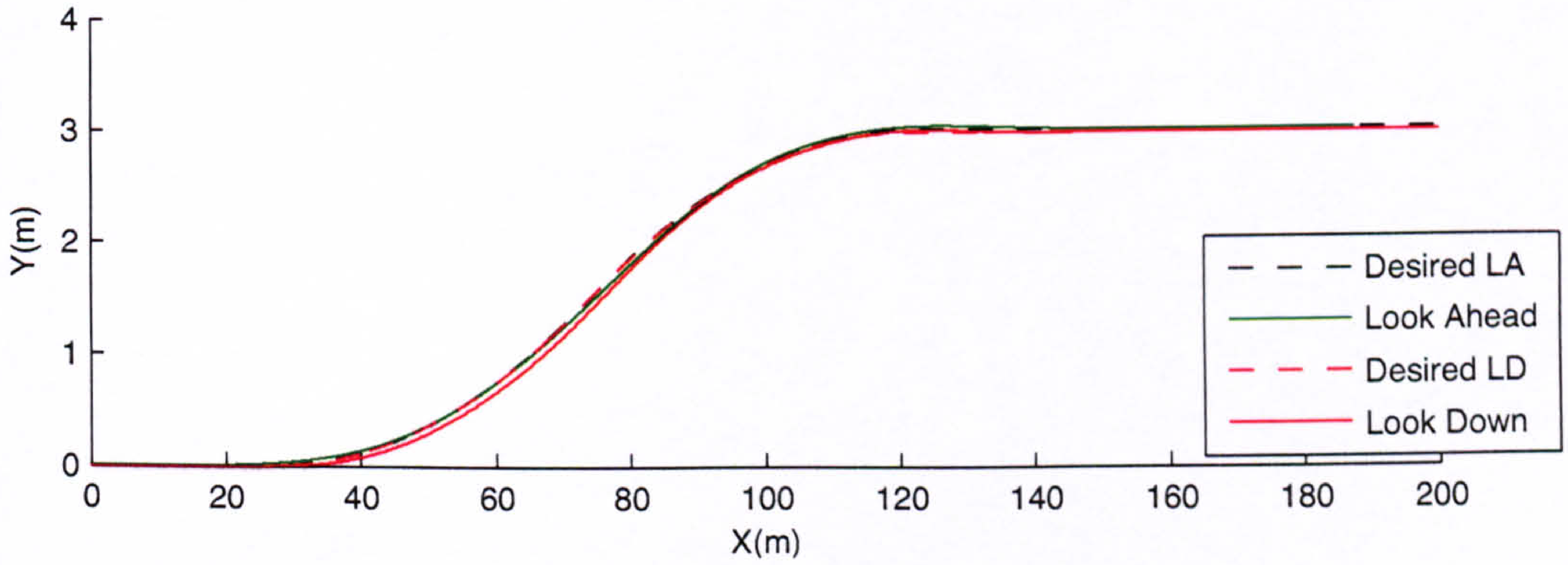


Figure 4.50: Trajectory of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC

Considering the lateral acceleration profiles shown in Figure 4.51, the jerky nature of the look down system becomes obvious. The initial spikes in the look down response were caused by the influence of the lateral error component of the controller, before the yaw rate tracking part of the controller stabilised the vehicle. This initial spike would be felt by the driver as an uncomfortable lateral jerk of the vehicle. Other spikes were noticed as the direction of the lateral error switches from one side to the other, again these jolts would be felt by the driver and passengers. The look ahead system on the other hand, had a much smoother acceleration profile, as it had the ability to react to changes in trajectory before they occurred.

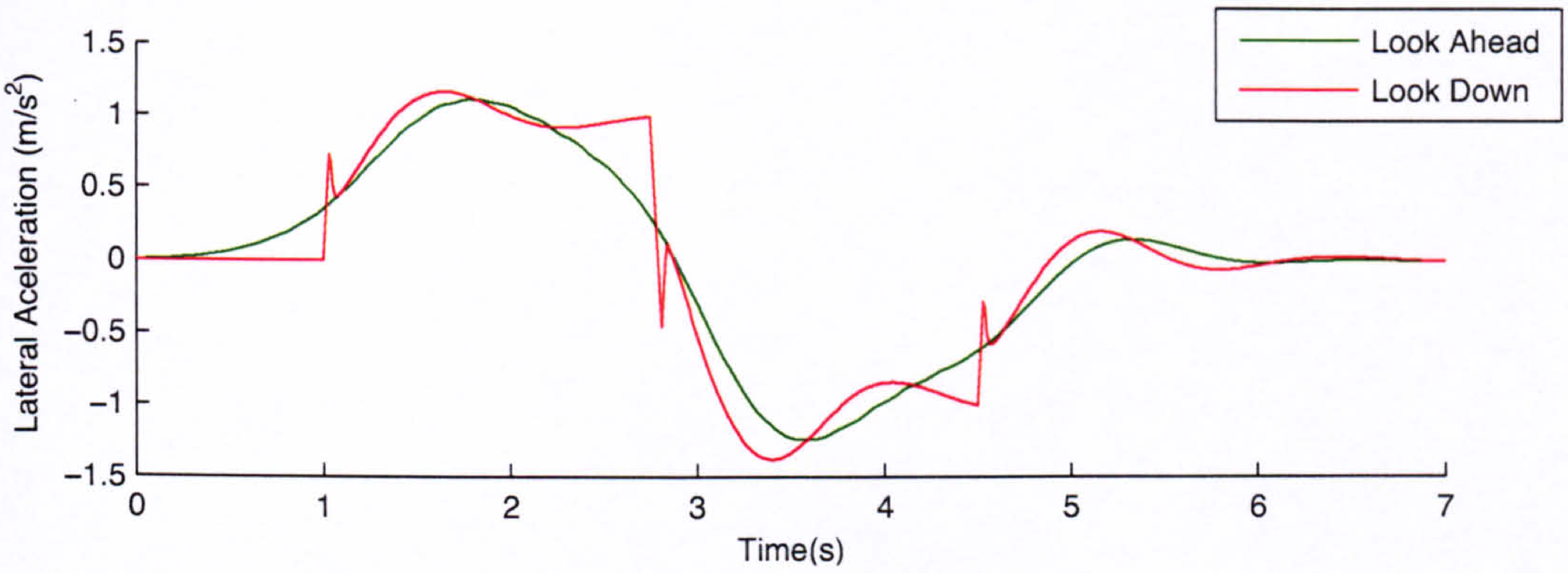


Figure 4.51: Lateral acceleration of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC

These findings are supported by the roll accelerations experienced by the vehicle (Figure 4.52). While the peak accelerations were short lived, the look down system generated very high instantaneous roll accelerations. These were related to the lateral accelerations that were generated to maintain the desired trajectory. They may result in uncomfortable feelings for the driver, although this is difficult to quantify given the short exposure periods.

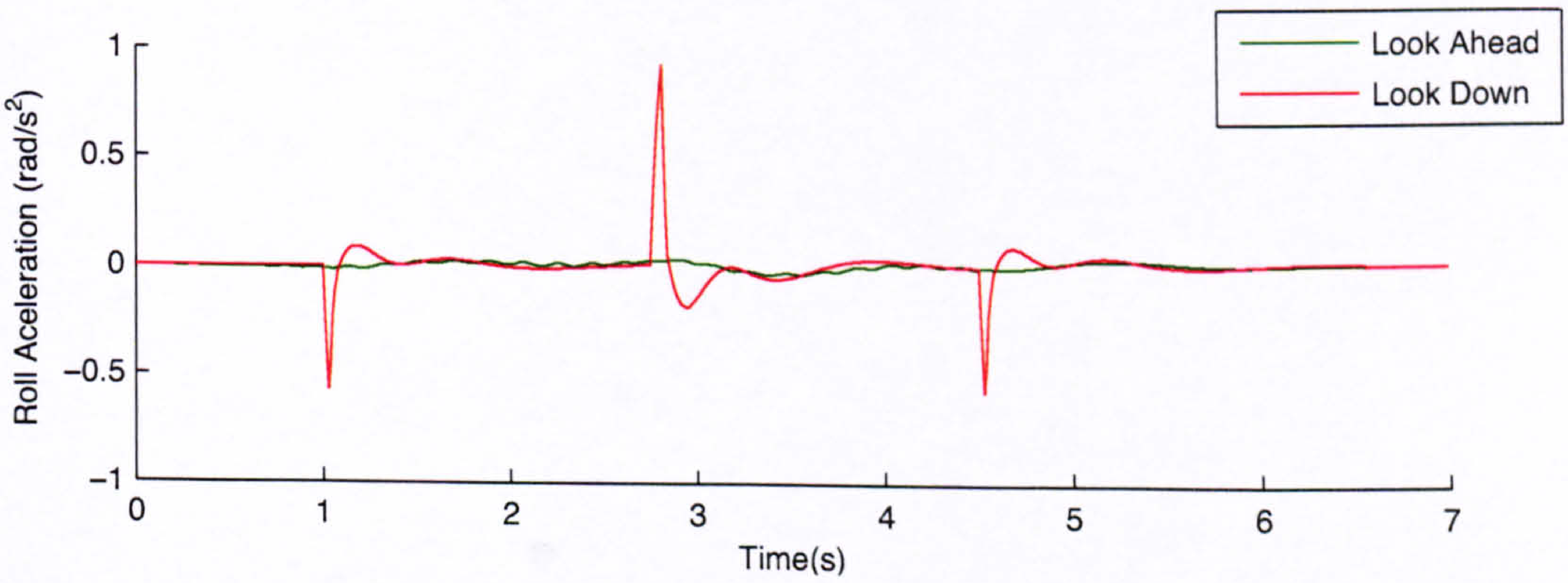


Figure 4.52: Roll acceleration of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC

The cause of these spikes in acceleration can be worked back to the control input to the vehicle (steer angle), shown in Figure 4.53. The look down system appeared quick to react, but was only able to react after the look ahead system. So instead of reacting to a more gentle ramp input, the look down system was forced to react to a step input. This led to large overshoots in the desired control action, resulting in acceleration spikes that would be perceived by the driver.

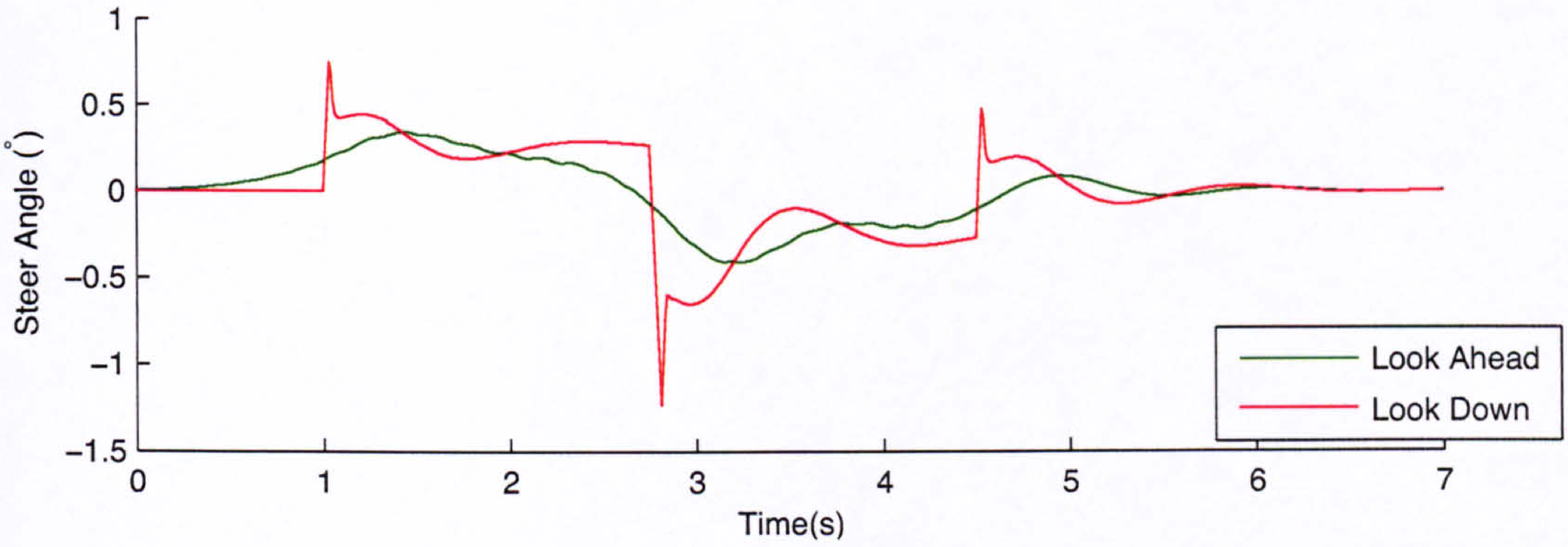


Figure 4.53: Steering angle of vehicles with look down and look ahead controllers for a 60mph 0.1g ELC

The look down system has been shown to be incapable of the 70mph 0.5g ELC, so the 60mph event was used to compare the controllers. For the first time differences were noticed in the trajectories of the two systems. The look down system was unable to react quickly enough, and so large overshoots were generated. The lateral error of the look down system (0.4m) actually became larger than that of the corner cutting look ahead system (0.3m).

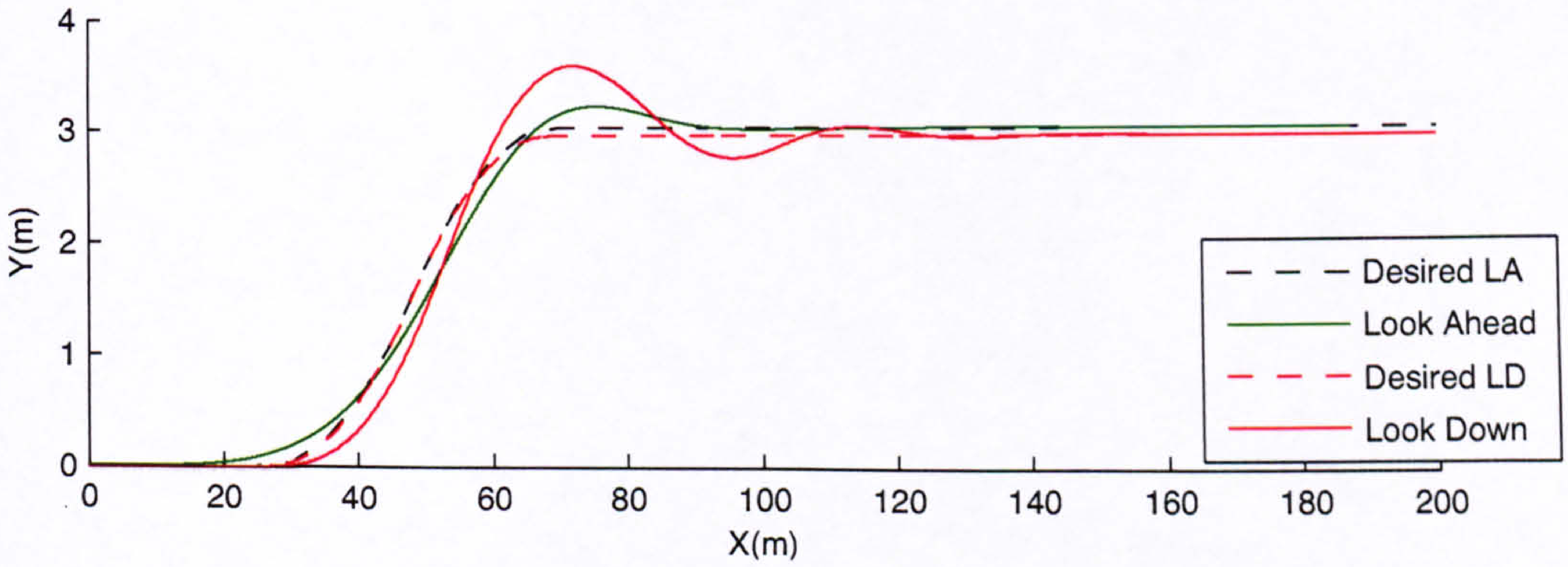


Figure 4.54: Trajectory of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC

These features were also apparent in the lateral acceleration response of the two systems (Figure 4.55). The look down system appeared to have become less jerky, this was purely because the steering rate limit had been reached and the system was unable to generate lateral acceleration quickly enough. The look down response still had relatively high jerk levels, especially when the lateral error crossed zero. Also the peak values of lateral acceleration were now much higher than those experienced by the look ahead system.

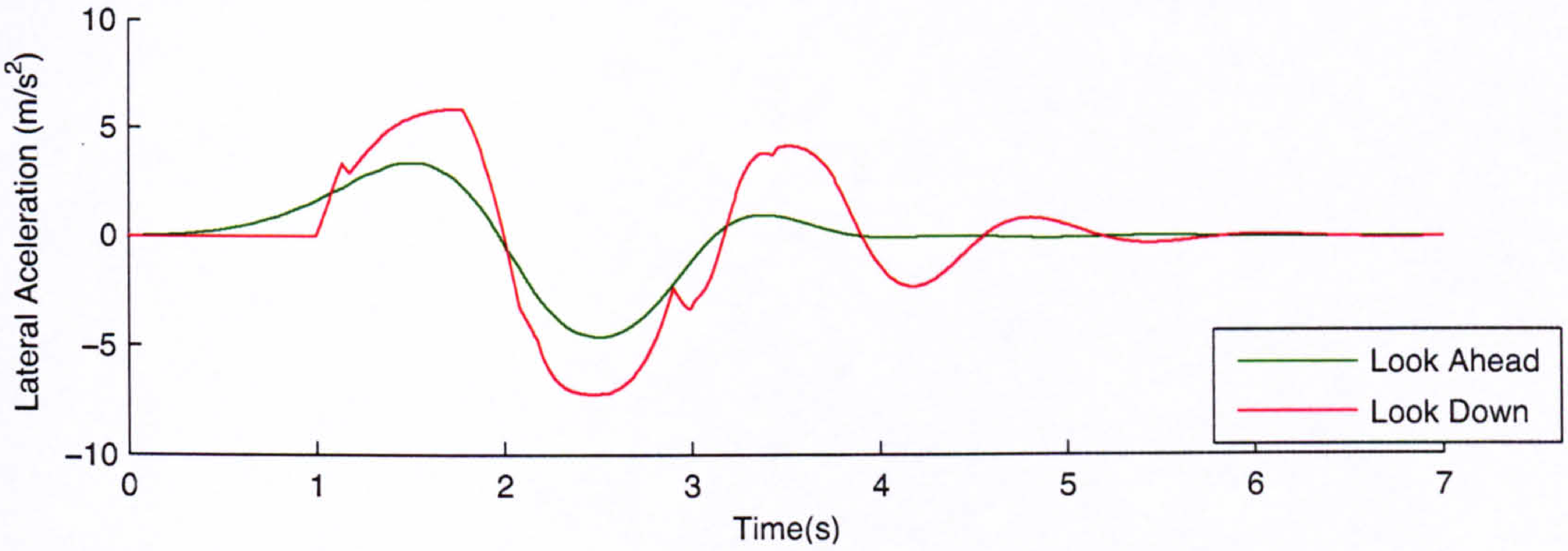


Figure 4.55: Lateral acceleration of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC

The roll acceleration of the two systems is shown in Figure 4.56. Again, it is obvious that the look down system provided a much less comfortable response than the look ahead system, as the large spikes noticed in the 0.1g ELC were increased in magnitude and maintained for longer periods of time.

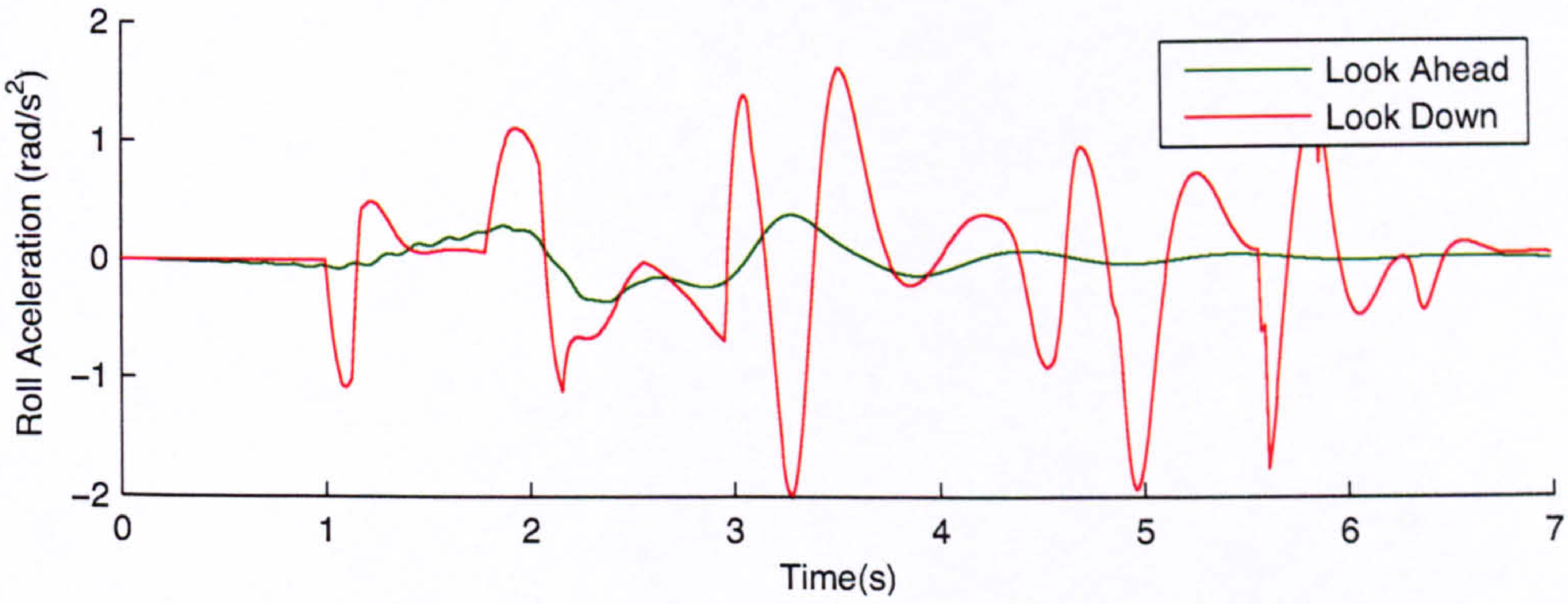


Figure 4.56: Roll acceleration of vehicles with look down and look ahead controllers for a 70mph 0.5g ELC

The result of these factors would be a much less comfortable experience for the driver and passengers when the vehicle is equipped with the look down system. Currently ADAS are marketed as both safety and comfort aids and as such the comfort levels experienced with a lateral control system are vitally important to its success. It was therefore decided to use the look ahead system in the driving simulator studies.

4.5.5 Summary of Results

Development of this look ahead system has highlighted the effects of the various tuning parameters:

- An increased look ahead distance increased the corner cutting of the system, but reduced the lateral acceleration experienced throughout the manoeuvre. For the scenarios tested here a look ahead distance of 30m provided the ideal trade-off between these two factors.
- An increased number of look ahead points resulted in a better approximation of the desired road trajectory. Diminishing returns were noticed in the reduction of lateral error when the number of preview points was increased above 7.
- As gains were increased, the speed of response of the system improved, this increased lateral acceleration, but reduced corner cutting.

Once tuned the system was capable of the full range of manoeuvres with acceptable levels of comfort and lateral errors. The additional disturbance manoeuvres that were performed demonstrated some interesting performance characteristics of the system:

- Low friction testing demonstrated little change in the vehicle performance for the low acceleration manoeuvres. As the severity of the manoeuvre was increased, the lower μ meant that the desired lateral forces could not be generated. High speed 0.1g ELC events were not possible in icy conditions, and high speed 0.5g ELC events were not possible in wet conditions.
- Superelevation and adverse camber testing showed acceptable levels of lateral deviation and lateral comfort,
- The side winds caused the vehicle to deviate from the lane centreline by up to 10cm. The system also displayed a steady state error which could be unnerving for the driver, although stability was maintained throughout the manoeuvre.

When compared to the look down system developed previously, results were impressive; while the lateral error displayed by the look ahead system was generally slightly larger, the lateral and roll accelerations perceived were always lower than the look ahead system.

Chapter 5

Driving Simulator Development

Chapter 5 discusses the benefits of the University of Leeds Driving Simulator (UoLDS) when used to develop and test ADAS. Also detailed are the steps that were taken to effectively integrate the ACC and Lane Keeping System(LKS) developed in previous chapters, with the simulator. A novel Human Machine Interface (HMI) is implemented for the LKS, through which the driver will interact with the system. Current technologies are refined to create an ideal HMI solution for the ACC. The chapter also details the development of five new simulator scenarios, designed to investigate the impact of the systems on the driver.

Previous chapters have considered the design and performance of ADAS. Using a range of off-line simulations it has been possible to assess the system's impact on the vehicle dynamics, and suggest possible limitations of such systems. In order for these ADAS to be received well by the public, it is vital that they are designed and implemented in a way that they instil confidence in the driver. They must also provide the driver with a positive experience. To test these, and other driver related issues, driver interaction with the systems is required. The UoLDS at the Institute for Transport Studies provides the ideal platform for such tests. It boasts a high fidelity 8dof motion system capable of accurately rendering vehicle accelerations, and a fully enclosed simulator cabin with immersive visuals.

This chapter looks at simulator development in detail. The simulator is introduced and its merits discussed, before the simulator's vehicle dynamics model is explained including its development to replicate the work carried out in previous chapters. The integration of the longitudinal and lateral control algorithms is then explored in detail. The main focus of this work is to ensure a driver centred approach is applied throughout, as should be applied when integrating a control system with a real vehicle. Roadway scenarios are developed to examine driver response to the ADAS. Chapter 6 then investigates the design, run through and analysis of the simulator experiments.

5.1 The University of Leeds Driving Simulator

The Institute for Transport Studies at the University of Leeds is home to the UoLDS. This is a relatively new facility, which has been developed from knowledge gained from development of the previous Leeds Advanced Driving Simulator (LADS), which was operational from 1994 to 2005. The LADS was a fixed based simulator that was used extensively for driver behaviour and transport safety research. It was used in 25 major externally funded projects, with sponsors including U.K. Government agencies, U.K Research Councils, European Agencies and Jaguar Cars.

In 2004 the U.K. Government awarded the Institute Science Research Investment Funding (SRIF), to enhance the LADS through a new vehicle cab, an enhanced projection system and a large amplitude motion system to provide realistic dynamic cues. This newly developed simulator became UoLDS, Figure 5.1.

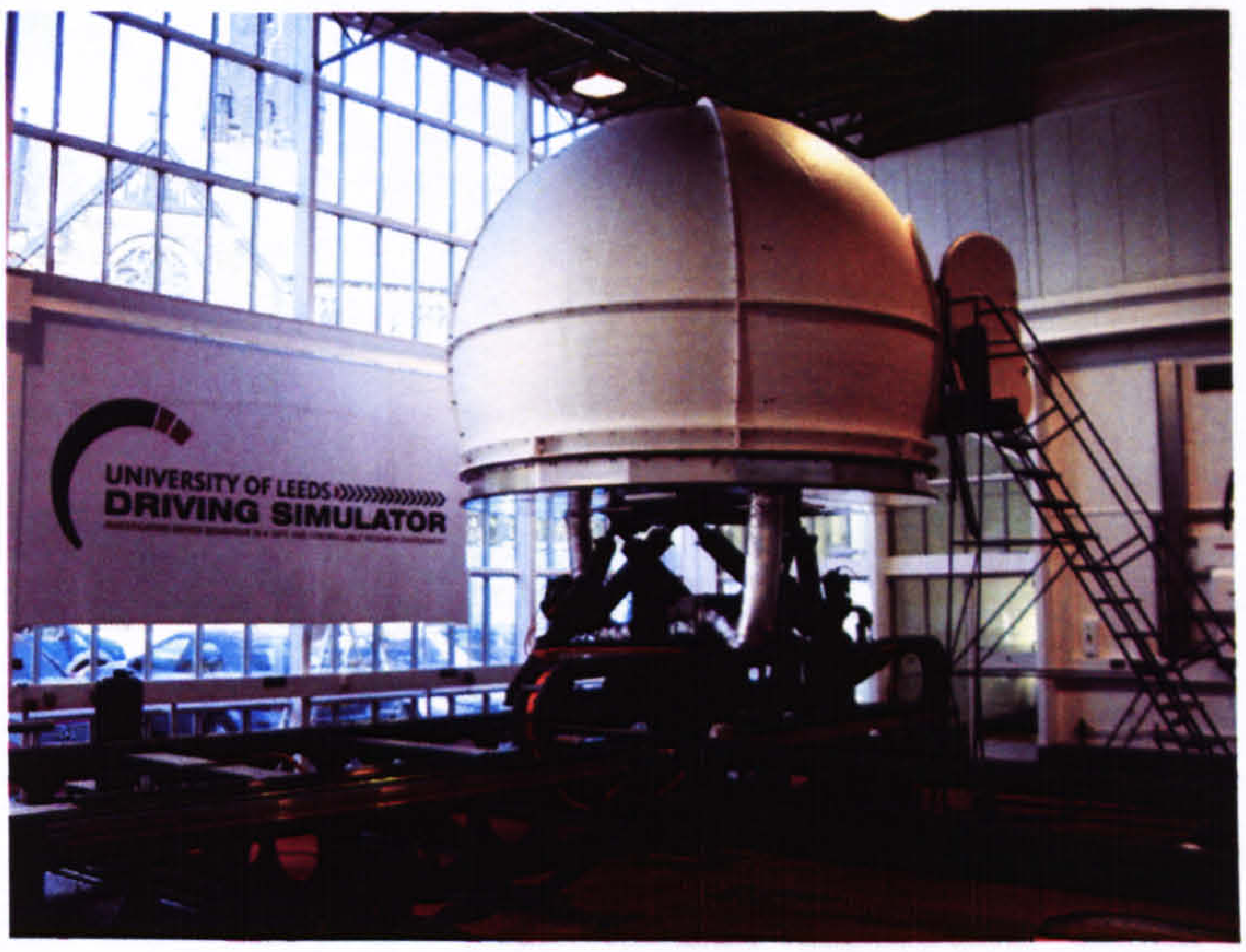


Figure 5.1: University of Leeds Driving Simulator

5.1.1 Motion System

The aim of a driving simulator is to realistically replicate the driving experience, to create a safe and repeatable environment in which to test road, vehicle, and driver conditions. It is the aim of any simulator to be as 'realistic' as possible. This quality can be enhanced by a range of aspects of the simulator. The LADS was a fixed-based facility, built around a complete Rover 216GTi, with its driver controls and dashboard instrumentation fully operational. The visuals were projected to provide an immersive horizontal field of view of 230°. While this proved to be a useful research facility, simulator sickness was sometimes experienced. This is thought to be caused by the brain becoming confused when it receives a visual 'cue' (an action or event that is a signal for somebody to do something) and does not receive the other cues (motion or audio) that would validate the visual. This conflict of sensory cues may result in simulator sickness that manifests itself in terms of a subject becoming nauseous and/or disorientated (Mourant and Thattacherry 2000). While it is relatively simple to replicate audio cues in the form of engine, braking and tyre noise; motion cues are an altogether more complicated task. Work has shown that correct motion cues are one of the most important factors when it comes to the driver interpretation of the simulator (Newton and Best 2006). This motion is also vital for research into the driver's perception of ADAS. Without some sort of motion system the driver would not feel any acceleration and would not be able to compare the levels of comfort with and without the ADAS.

Motion cues can be generated in a number of ways, but most commonly through a hexapod (Stewart platform). This is capable of generating accelerations in 6dof, as would be experienced by any road vehicle. It therefore provides a good initial solution to the problem. Hexapod simulators exist around the world and while they have been used to good effect, they have some limitations. It must be remembered through this discussion that the driver can only perceive accelerations, not velocities or displacements. So while a hexapod may be able to generate much larger roll and pitch angles than a vehicle may ever be subjected to, this is not immediately important. Hexapods are generally limited by two factors:

1. The maximum level of acceleration in each dof.

2. The stroke of the actuators, which governs the amount of excursion.

The maximum level of achievable acceleration is usually quite high for a given hexapod. Problems are more often generated by limited stroke of the actuators, which limit the sustainability of each acceleration. This is especially important in the lateral and longitudinal direction where average levels of acceleration ($\approx$0.2g) can be maintained for relatively long periods of time (>5s). If a hexapod is to sustain these, and more severe accelerations using purely translational motion, the actuator stroke would have to be extremely large. Also if the simulator is asked to sustain an acceleration for a longer period, this translational cue would quickly fade out to zero. This is unacceptable, but a hexapod can trick the brain into believing that a translational acceleration is being sustained thanks to its use of gravity. When holding the driver at fixed pitch or roll angle, it is possible to generate a sustained longitudinal or lateral acceleration. The limitations with this method are twofold 1) There will be a rotational acceleration experienced by the driver in rotating the simulator to this angle, and 2) The maximum sustained acceleration is defined by the maximum angle of rotation of the hexapod, 90°is equivalent to 1g. Usually a hexapod is limited to move up-to 45°or less, generating a maximum acceleration of 0.5g.

This rotational acceleration, or tilt co-ordination must occur below a driver's perception threshold, otherwise they will sense that they are rotating rather than translating. Groen and Bles (2004) claimed a driver can perceive rotational accelerations greater than $3°/s^2$, meaning that the simulator would need to take 15s to rotate to 45°without the driver noticing. Prior to this time the acceleration must be generated by the translational motion of the hexapod. For translational accelerations of this magnitude some rotational acceleration above this threshold is required as the duration of the acceleration is generally much shorter than 15s. The translational component must be faded out as the angle increases, to prevent the sudden jerk at the end of the actuator stroke. Once the rotational component has taken over, the translation motion can return to its neutral position; this is termed washout. Washout must occur at accelerations lower than the perception thresholds, otherwise confusing inverse accelerations will be transmitted to the driver. Therefore, a hexapod has two means of producing a translational acceleration: one which is quick to react but only short lived, and one which is slow to react but sustainable. The means of replicating sustainable accelerations is termed the 'classical washout algorithm'. The response of such a system to a 0.2 g step change in acceleration is shown in Figure 5.2. It can be seen that the response has a good onset (initial) cue and is well sustained, but there is a period where the translational component is decreasing and the rotational component is still only ramping up. This leads to a noticeable sag in the level of total acceleration transmitted to the driver.

There is a trade off in the level of this sag and the amount of rotational acceleration that it is possible to transmit to the driver without perception. The other option is to somehow generate some additional acceleration to overcome this sag. In some simulators this is done by the addition of either a single or two axis gantry, or table system. This translation table generally has a large amplitude, and is capable of fairly high levels of acceleration,

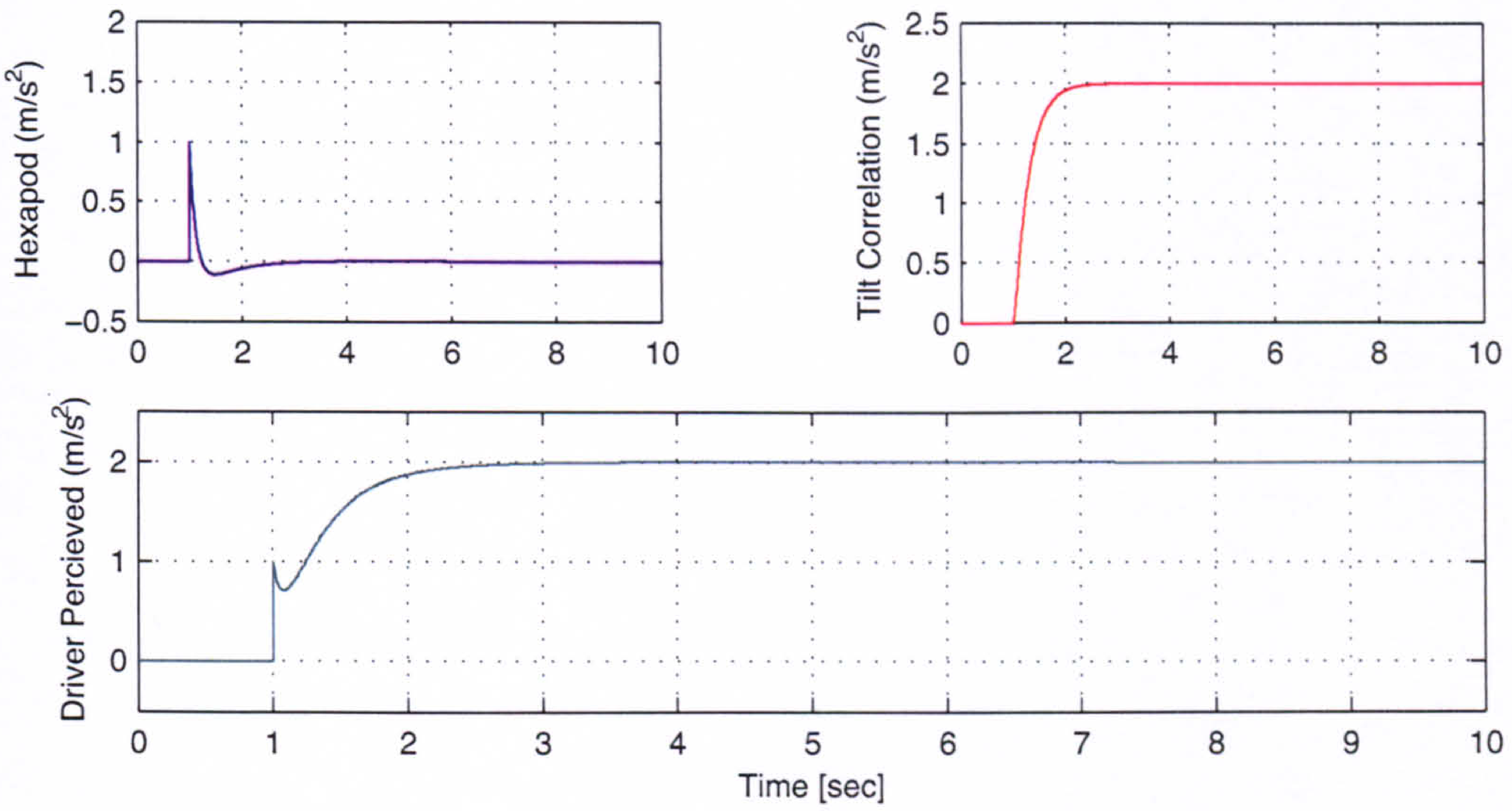


Figure 5.2: Response of a hexapod to a step change in acceleration

that can be sustained for periods longer than those generated by the translational component of the hexapod. When used in conjunction with a hexapod, the system can reduce the sag experienced in the step response (Figure 5.2). There are now three components to any translational acceleration generated by the simulator, 1) the translational motion of the hexapod (high frequency), 2) the translation motion of the table (medium frequency), 3) the rotational motion of the hexapod (low frequency). The influence of these components can be tuned through a range of low and high pass filters, to provide a consistent smooth response to a wide range of acceleration inputs. For these reasons the UoLDS was designed to use a motion base with a hexapod and XY translation table, to generate realistic accelerations in both lateral and longitudinal directions. The UoLDS motion base design is shown in Figure 5.3, characteristics of the system are given in Table 5.1.

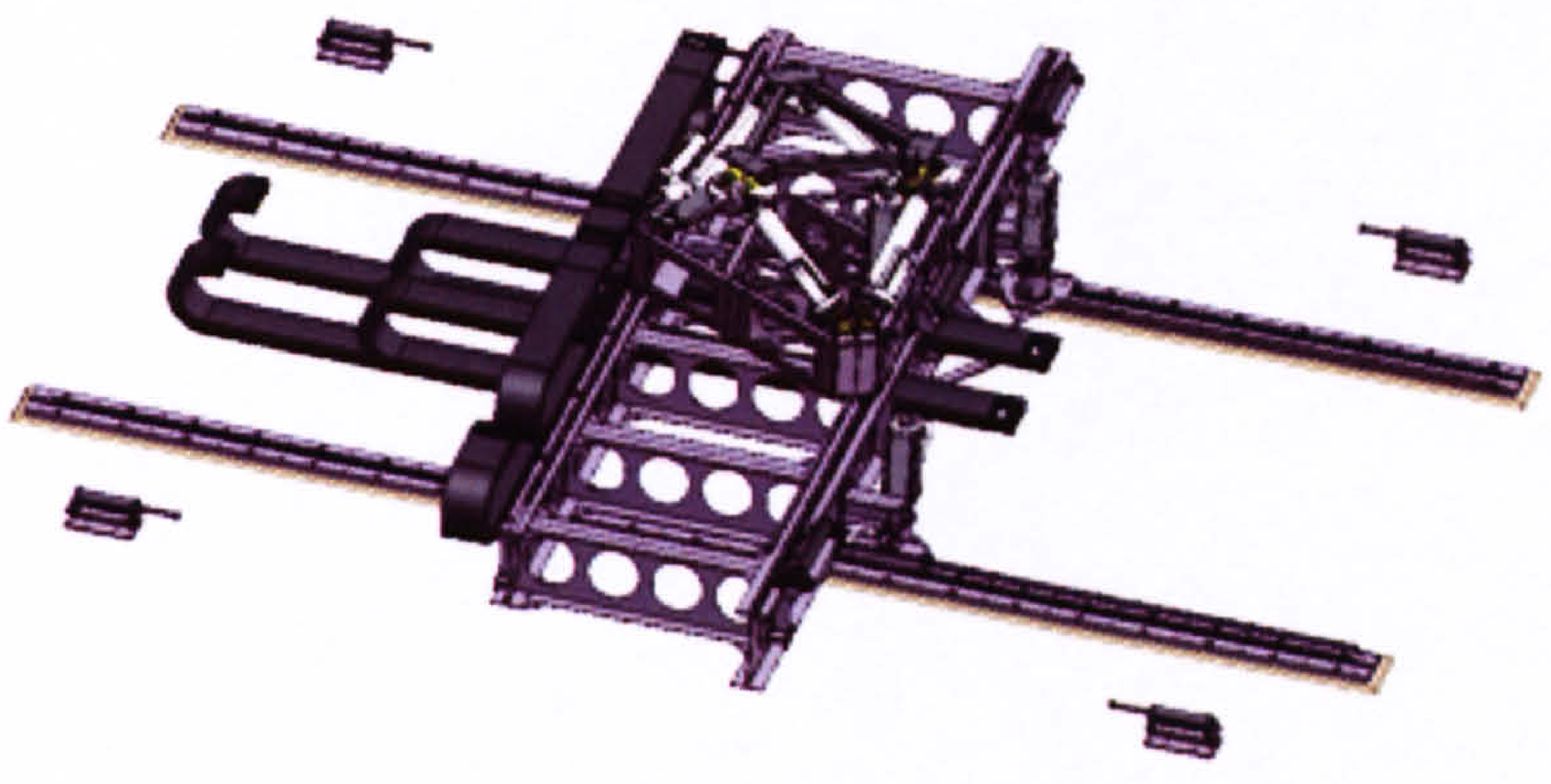


Figure 5.3: UoLDS motion system design

Table 5.1: Dynamic characteristics of the UoLDS motion system

		Excursion	Velocity	Acceleration
Hexapod	Surge	-408 / +307 mm	±0.8 m/s	$\pm 6.5 m/s^2$
	Sway	-318 / +328 mm	±0.8 m/s	$\pm 6.0 m/s^2$
	Heave	-300 / +333 mm	±0.6 m/s	$\pm 6.0 m/s^2$
	Pitch	-20°/ +22°	±40°	$\pm 300°/s^2$
	Roll	±21°	±40°	$\pm 300°/s^2$
	Yaw	±23°	±50°	$\pm 350°/s^2$
XY Table	Surge	±2500 mm	±2.0 m/s	$\pm 5.0 m/s^2$
	Sway	±2500 mm	±2.0 m/s	$\pm 5.0 m/s^2$

Motion System Tuning

Tuning of the motion system was based on the worst-case scenarios, dependent on the dynamic characteristics of the motion system. Since the UoLDS is used for driver behavioural studies, scenarios could be created to fit both the research requirements, and the motion limitations of the simulator. For this study only motorway driving conditions were required. Tuning of worst-case acceleration was therefore much more manageable than, for example, a vehicle handling study where large accelerations are often experienced. In motorway scenarios, high levels of acceleration and rate of change of acceleration are uncommon and so the longitudinal limits were set to $1.5 m/s^2$ in acceleration and $2.8 m/s^2$ in braking. Lateral accelerations were limited symmetrically to $2.2 m/s^2$. Using these constraints as design objectives a Matlab®/Simulink® model of the filters and algorithms governing the motion of the system was used to calculate the optimum system parameters. To minimise perceived rotational acceleration, whilst also minimising sag, the most relevant parameter within the classical washout algorithm was the low-pass cut-off frequency of the hexapod. Initial testing suggested that the optimum value in our case was 0.5Hz in both pitch and roll degrees of freedom. Whilst this still gave rotational accelerations that were comfortably higher than perceptual thresholds, this value appeared to give the least 'rolly' feeling to driving the simulator, without overly compromising sag. Other parameters were selected to maximise acceleration, whilst remaining within the physical limits of the motion envelope. The system was tuned both longitudinally and laterally.

5.1.2 Vehicle Cab

With efficient generation of motion cues in place, it was important that the rest of the simulator was designed to the same high standards to provide a fully immersive and realistic driving environment; the vehicle cab of any simulator is key to this. The UoLDS cab is based around a 2005 Jaguar S-type, with all of its driver controls fully operational. The automatic transmission S-type was donated to the University under Jaguar's Vehicle Donation Scheme. The vehicle's internal Control Area Network (CAN) is used to transmit driver control information between the Jaguar and one of a network of eight real-time Linux-based PCs, each playing a role in the overall simulation.

The Jaguar is housed within a 4m diameter, fibre-glass, spherical projection dome. As the laboratory space in which the simulator now resides is not new, the small diameter of the dome was selected in order to maximise the available motion envelope, whilst still providing a relaxed eye-point for the observer. (Jamson et al. 2007)

5.2 Vehicle Model Integration

The vehicle dynamics of the fixed based LADS was based on Newtonian mechanics and represented mathematically by 36 ordinary differential equations. This model effectively encompassed all 9dof that were considered in Chapter 2, as well as additional heave of the body. It was coded in C++ and used a Runge-Kutta integration method. The model had a simple brush tyre model which would not accurately simulate the tyre's performance at the limit of linear handling; significantly limiting the capabilities of the simulator. As the vehicle needed to accelerate from rest, the slip calculations were protected against low speed instabilities by the method proposed in Bernard and Clover (1995). The model had a manual gearbox and a power steering model from Jaguar Cars. Apart from these features the model was conceptually very similar to the off-line 9dof model developed in Simulink® in Chapter 2. The LADS model had been used for some time with a high degree of success, but as the simulator had a fixed base, it was impossible to get a true feeling of the vehicle dynamic performance. This LADS vehicle dynamics formed the basis of the model that was initially deployed on the UoLDS.

This proved a good starting point, although initial tests of the UoLDS demonstrated a lag in the generation of lateral and longitudinal accelerations. For the purpose of this research it was important that the vehicle dynamic performance of the simulator was similar to that of the Simulink® model, that had been used in the design of the control algorithms. For these two reasons it was decided to update the UoLDS vehicle dynamics.

Initial thoughts were to use the real-time code generation of Matlab®/Simulink®to convert the off-line simulation model into a realtime C++ solution, that could be used directly on the simulator. This would give the best correlation with the off-line model, and provide a new interface through which future changes and additions could be made to the vehicle dynamics in Simulink®, before being converted into real-time C++ code.

This idea was investigated, but due to the complexity of the model, the interface between the existent C++ code and the rest of the simulator, it was disregarded. Initial conversions did not result in working code, and closer inspection of this code revealed a complicated structure, which would have been difficult to integrate with the simulator. A decision was taken to code the new vehicle dynamics model in C++, using the LADS existing code as a base but develop the following additional features:

- Modularise the code into the following individual C++ files to allow simple modifications to components:
    - Steering Model
    - Slip Calculations
    - Tyre Model
    - Powertrain
    - Equations of Motion
- Parameterise the model to allow simple changes to vehicle data-sets
- Add Pacejka 'Magic' tyre model
- Add automatic transmission and improved engine model
- Improve slip calculations to reduce lag and low speed instability

The method provided the dual benefit of integration of the core elements of the off-line model, and the ability to easily upgrade the model in future. With the code modularised into subsystems, it was simple to upgrade each one in isolation. The modifications and differences in these subsystems are now discussed.

5.2.1 Steering Model

In the off-line simulations steering input was denoted simply as the angle about its z-axis that the road wheel moved. This worked well for simple control of the vehicle, but in a real vehicle the steering system is more complex than a direct (fixed ratio) link between the steering wheel and the road wheel. Most cars, especially executive vehicles which are more likely to be equipped with ADAS, have power steering systems, which use a pump or electric motor to reduce the force required by the driver to turn the steering wheel. Drivers also obtain feedback from the steering wheel which is generated due to forces at the tyre and transmitted through the steering system. Through work on the LADS a

Simulink® power steering model was acquired from Jaguar. This calculated not only the steering ratio but also the feedback torque that was to be supplied back to the driver. This model was converted into C++ code and integrated with the rest of the vehicle model. A torque motor was then used in the simulator cab to transmit this torque back to the driver.

5.2.2 Slip Calculations

In the off-line simulations, we were not investigating how the vehicle performed when setting off from rest and coming to a complete stop. Again, in the simulator study this is not of direct relevance to the results; but it is important to the overall feel of the simulator. In order to get the best possible results, it is important that each driver feels that the simulator replicates real driving. The first experience of the simulator for any driver will be accelerating from rest, so it is vital that this does not create a bad impression. In the slip calculations used in the off-line simulations the rolling velocity of each wheel is divided by its longitudinal velocity (Equation 5.1).

$$\sigma = \frac{-(u - R_r\omega)}{u} \tag{5.1}$$

When at rest, this longitudinal velocity is obviously zero which leads to instability in the equations. Bernard and Clover (1995) propose a method to overcome this instability with fairly successful results. This method was used successfully on the LADS but when used on the UoLDS, some low speed longitudinal oscillation was noticed as a vibration in the motion base. For this reason it was decided that additional low speed damping was required. Genta (1997) treated the tyre as a circular spring at low speeds, and added a damping term to the low speed approximation of slip, based on tyre relaxation length.

5.2.3 Powertrain

The LADS Rover 216GTI vehicle cab had a manual transmission, and so the powertrain model was built with a simple linear clutch dependent on angular position of the pedal, and a five speed ratio gearbox, from which the driver would select the appropriate gear. The Jaguar vehicle cab in the UoLDS came with an automatic transmission and changes to the model were required to reflect this. These modifications were drawn from the powertrain model in the Simulink® off-line model which was again converted into C++ code before being integrated with the rest of the vehicle dynamics.

The full vehicle model was validated using non-realtime comparison tests with CarSim and the Simulink® vehicle model discussed earlier. These off-line simulations allowed repeatable consistent manoeuvres to be performed without the use of a driver. As expected the results were very similar to the 9dof off-line vehicle model. The low speed oscillations noticed in the off-line simulations were slightly reduced but the steady state performance of both models suggested a good correlation. The tyre model was identical so any minor differences noticed were put down to the use of a smaller time step and different integration method in the on-line model.

5.3 Longitudinal Control Integration

In Chapter 3, the development of the longitudinal control scheme was discussed, results were positive and the system was capable of handling a range of lead vehicle manoeuvres. While this system worked well in the non-realtime simulations, there were features of an ACC system that were not modelled, as they were not important to the core performance of the longitudinal control algorithm. To integrate the controller with the simulator, and provide a realistic driving experience it was important to ensure the ACC contained all necessary features, these included:

- Incremental set speed
- Incremental headway options
- Out of range warnings
- High level state logic

These additional features and their impact on the overall controller are discussed briefly in the following sections

Incremental Set Speed

In the off-line simulations the longitudinal controller was tested at set speeds of 20, 30, 40, 50, 60, and 70mph, which reflected a wide range of motorway conditions. For use in a real driving scenario it was necessary to allow the driver to select a set speed from a continuous range. It was decided that the initial set speed should be that at which the vehicle was travelling when the system was enabled (as in a conventional cruise control system). This would ensure smooth transition of control from the driver. If the driver wished to change this set speed, they could do so by an increment of 2mph. The interface between the ACC and the driver is looked at in detail in Section 5.3.2

Incremental Headway

There are a wide range of driving styles: some drivers like to react quickly and follow at a short headway to the lead vehicle, whereas others like to follow with a long headway and react slower. For this reason, it was important to make sure that the controller was adaptable to different following types. In most ACC systems this is done by giving the driver a range of headway options. The driver can then choose the headway at which they feel most comfortable. For the purpose of this study, three options were offered to the driver, they were 1.0s, 1.75s, 2.75s. The choice of this option affected not only the desired headway, but also the switching of the control scheme from speed control to headway control (control bound).

Out of Range Behaviour

Off-line tests demonstrated the reduced performance of the longitudinal controller when the lead vehicle deceleration was outside the system's capable range (-2.0m/s^2, 1m/s^2). This was one area that needed further investigation using the simulator. The maximum deceleration of the system would become the threshold below which the driver would need to intervene, disabling the system and applying additional braking. This state of the controller was termed the *danger* state. It was defined as when Time to Collision (TCC) is less than or equal to Time To Speed (TTS). TTC is the time it would take for the subject to collide with the lead vehicle given their relative speeds and headway (Equation 5.2). TTS is the time it would take to reduce the subject vehicle's speed to that of the lead vehicle at the maximum deceleration available (Equation 5.3).

$$TTC = \frac{h_{wm}}{u_s - u_l} \tag{5.2}$$

$$TTS = \frac{u_l - u_s}{-a_{x(max)}} \tag{5.3}$$

Testing Procedure

All developments to the control logic were first tested using the Simulink® off-line simulations. They were then coded in C++ and fine tuned using a software development tool called *PREVIEW*. The tool ran the full simulation on a single PC using the mouse and keyboard to control the vehicle. This meant that changes could be made quickly before being finally validated in the full simulator. While the preview tool lacked any motion cues, it was invaluable to the integration of the controller as live headway and other data could also be visualised whilst testing. Figure 5.4 shows a sample screenshot from *PREVIEW*. Test data could also be displayed on the left of the screen showing headway, lead vehicle speed, lead vehicle acceleration, etc.

Figure 5.4: Sample output from *PREVIEW* development tool

As well as being key to the integration of both the longitudinal and lateral control algorithms, *PREVIEW* was also used in the development of the scenarios for this study. Again this gave the benefit of simple quick testing of changes, without the use of the full simulator.

5.3.1 High Level State Logic

With these vital additions to the longitudinal control scheme, state logic was required to ensure the controller performed as designed. This control logic is shown in pictorial form in Figure 5.5. The main states of the ACC and their switching logic are shown. The colour denotes part of the on-screen display which is discussed in detail in Section 5.3.2. The states were set up as follows:

Disabled Normal driving, no longitudinal control, the driver has control of the brake and accelerator.

Enabled - No Leader Here the ACC works as a normal cruise control system. There is no leader within a given range of the subject vehicle, so the vehicle tries to maintain its set speed.

Enabled - Leader As soon as a lead vehicle enters the range of the system ,the ACC tries to maintain the set headway and lead vehicle's speed.

Enabled - Danger When the TTC is less than or equal to the TTS a collision is imminent and driver braking is required, the controller enters the danger state. The controller immediately exerts the maximum braking level available (-2.0m/s) until the driver applies a greater brake torque.

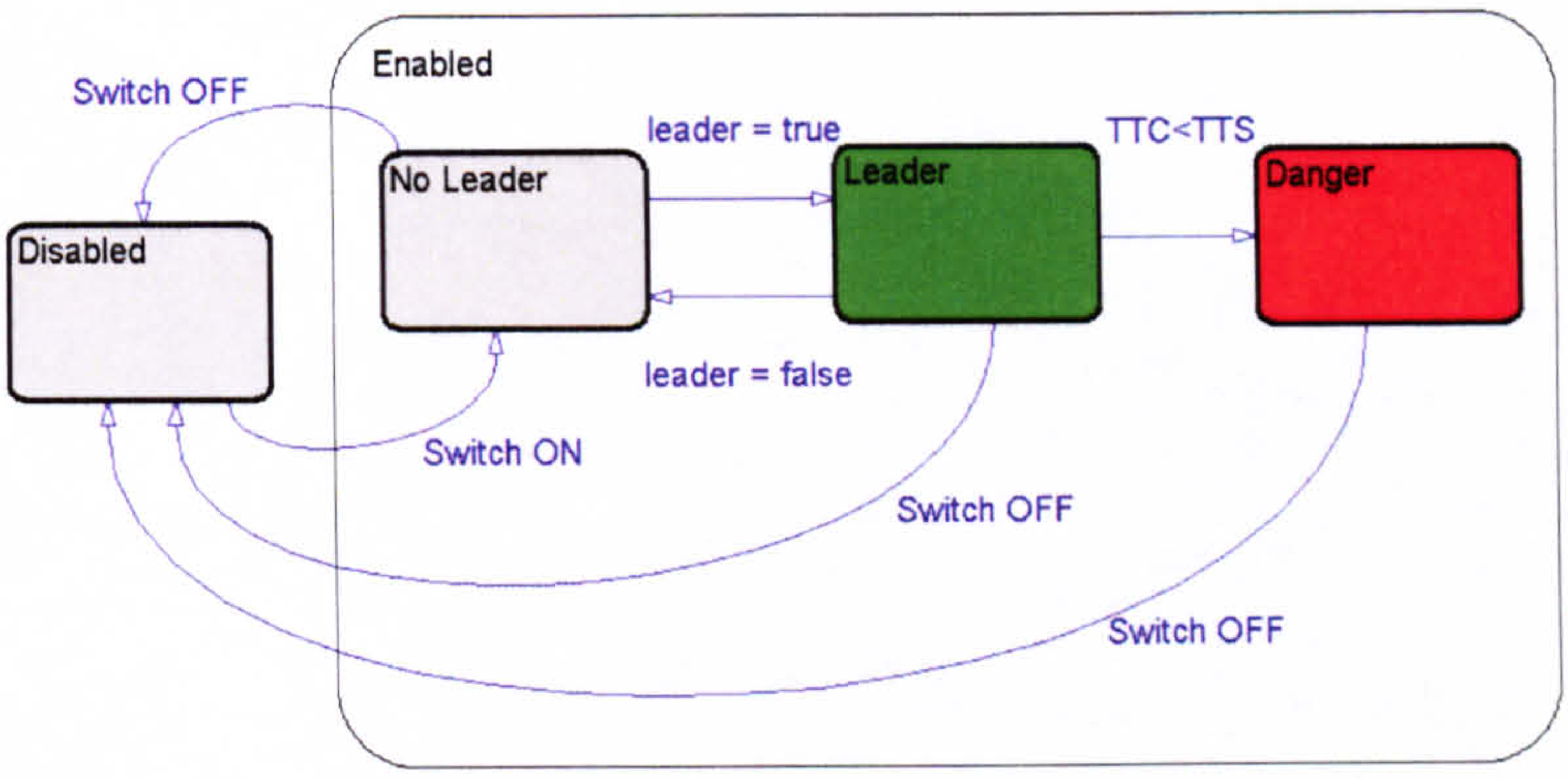


Figure 5.5: State logic of the ACC

5.3.2 Human Machine Interface

To integrate ADAS successfully with the vehicle, it is important that the driver is informed of their state and functionality. Feedback can help an operator learn how a system or the environment is changing (Vakil and Hansman-Jr 2002). With this in mind, it was important to design a simple and efficient interface between the ADAS and the driver. The Jaguar cab was equipped with ACC controls. These were located on the right side of the steering wheel (Figure 5.6). The Jaguar's CAN was used to send signals from these buttons to the control PC. The control PC communicated over Ethernet with the master renderer PC where the simulation was run.

There were buttons to set and cancel the ACC, as well as buttons to increase and decrease set speed. On the back of the steering wheel there were buttons to increase or decrease the desired headway. The controls and their functionality are described in Table 5.2.

Points to note from this table, include the fact that the accelerator pedal was disabled during ACC operation, only the brake pedal or cancel button could be used to disable the system. This differs from a commercially available system, in which drivers can still use the accelerator to increase vehicle speed until the accelerator is released and the set speed is again maintained. Disabling the accelerator meant that drivers would effectively be under control of the system more often, allowing an increased number of events to be

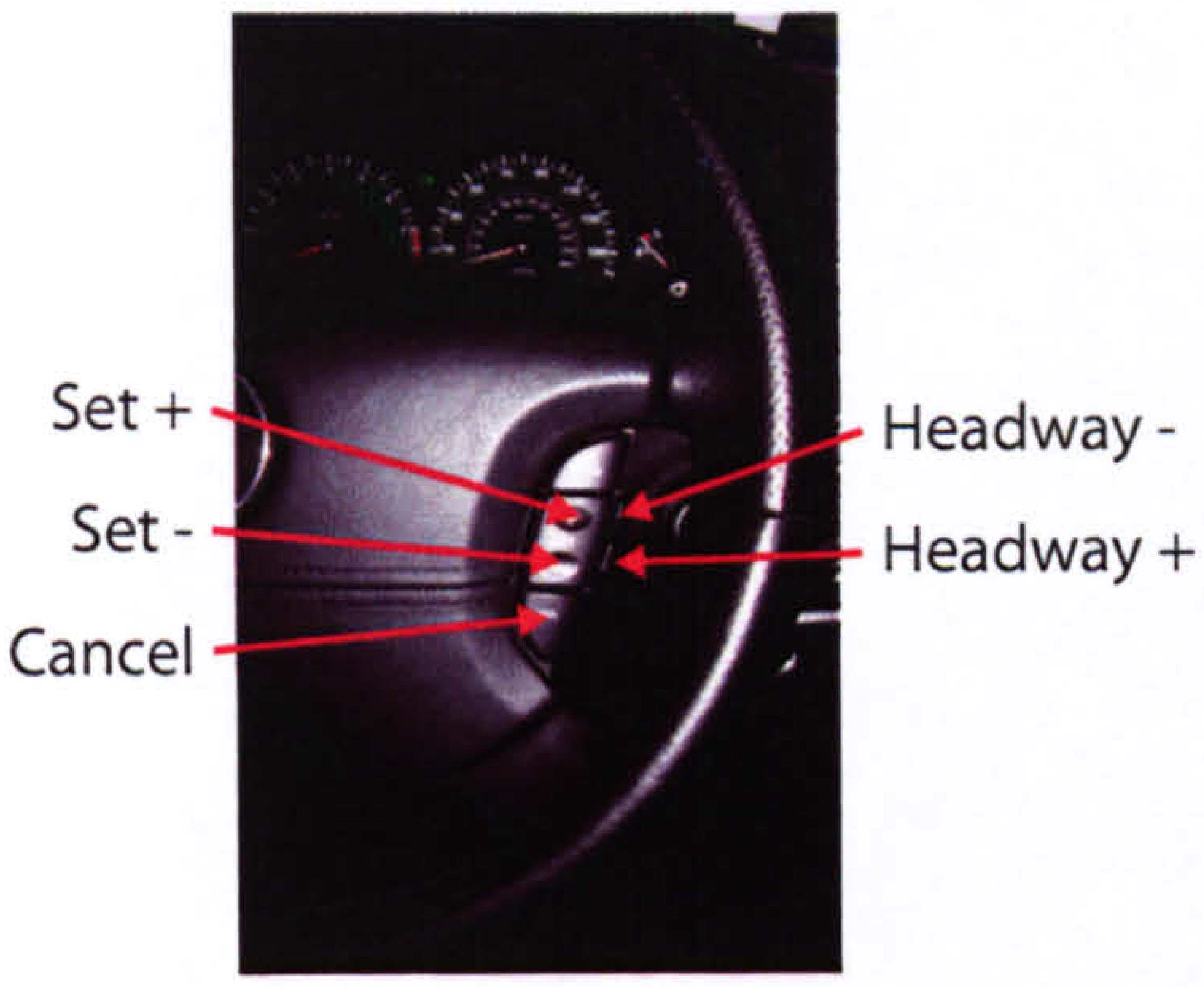


Figure 5.6: ACC steering wheel controls

Table 5.2: ACC controls

Location	Control	Function in 'normal' driving	Function under ACC
Steering Wheel	set +	enable ACC	increase set speed
	set -	enable ACC	decrease set speed
	cancel	none	disable ACC
	headway +	none	increase headway
	headway -	none	decrease headway
Foot Well	accelerator	acceleration	none
	brake	braking	disable ACC

monitored. Also both the Set + and Set - buttons were used to enable the system, in this case, instead of changing the set speed they merely caused the system to maintain the vehicles current speed.

Headway adjustment was the only control which required refinement during the integration. On the back of the steering wheel there was a rocker switch which could be activated by pressing up or down. First thoughts were to implement it so that pressing up would increase the headway. After testing, it was decided to reverse this decision as an increase in headway actually meant slowing down and backing off from the lead vehicle. With the up button used to decrease the level, the headway control felt much more intuitive.

With the inputs from the driver to the ACC fully functional, the next step was to develop the interface through which the ACC would communicate information back to the driver. This was performed using a Graphical User Interface (GUI), and audible warnings. The first question was, what should the system tell the driver? For instance, does the driver need to be informed of their speed or will they look back to the speedometer on the dashboard? Is their actual headway important, or would they rather just know they are under control and following at a safe distance? It is important to provide the driver with enough information to use the system effectively; but not so much as to distract the driver from the driving task.

Figure 5.7: Examples of ACC displays in production vehicles, from left to right *Audi, BMW, VW*

To aid in the design of this GUI, examples of other ACC systems currently employed on road vehicles were considered. Three examples are shown in Figure 5.7. Audi's was the most basic showing headway as a horizontal line. This was considered counter-intuitive to the idea of a vertical button to adjust the headway and so discounted. The other two used markers equivalent to chevrons seen on UK motorways to suggest headway spacing. This seemed more intuitive, and was the basis around which the ACC interface was developed. The GUI was to be displayed on an LCD screen installed in the Jaguar cab. While this screen was large and clearly visible to the driver, its location was not in line with these other ACC display designs. In all three of the designs in Figure 5.7 the display is located at the centre of the instrument console, meaning that the driver can look at its output as they normally would the speedometer. They can also check the speedometer and ACC information in one glance. The Jaguar instrument console does not have the means of displaying ACC information to the driver, so a LCD screen was installed to the left of the console (Figure 5.8). Due to the LCD location it was decided to display current and set speed information on the LCD, to prevent the driver from constantly looking back at the speedometer.

One advantage of the LCD screen over a standard dot matrix display was the availability of colour. It was hoped to use different colours to inform the driver of changes in state, as these changes may need to be acted upon quickly by the driver. The two main colours used were red and green. Red symbolises danger and is commonly used in transportation applications at traffic lights and vehicle brake lights. Green symbolises go and again is

Figure 5.8: Location of the LCD screen for ACC display

used at traffic lights. In this context red was used to show the danger state of the ACC, where as green was used to show the enabled state. Grey and yellow were also used for other parts of the GUI. The final design for the ACC GUI is shown in Figure 5.9. The four states earlier described in the state logic are shown.

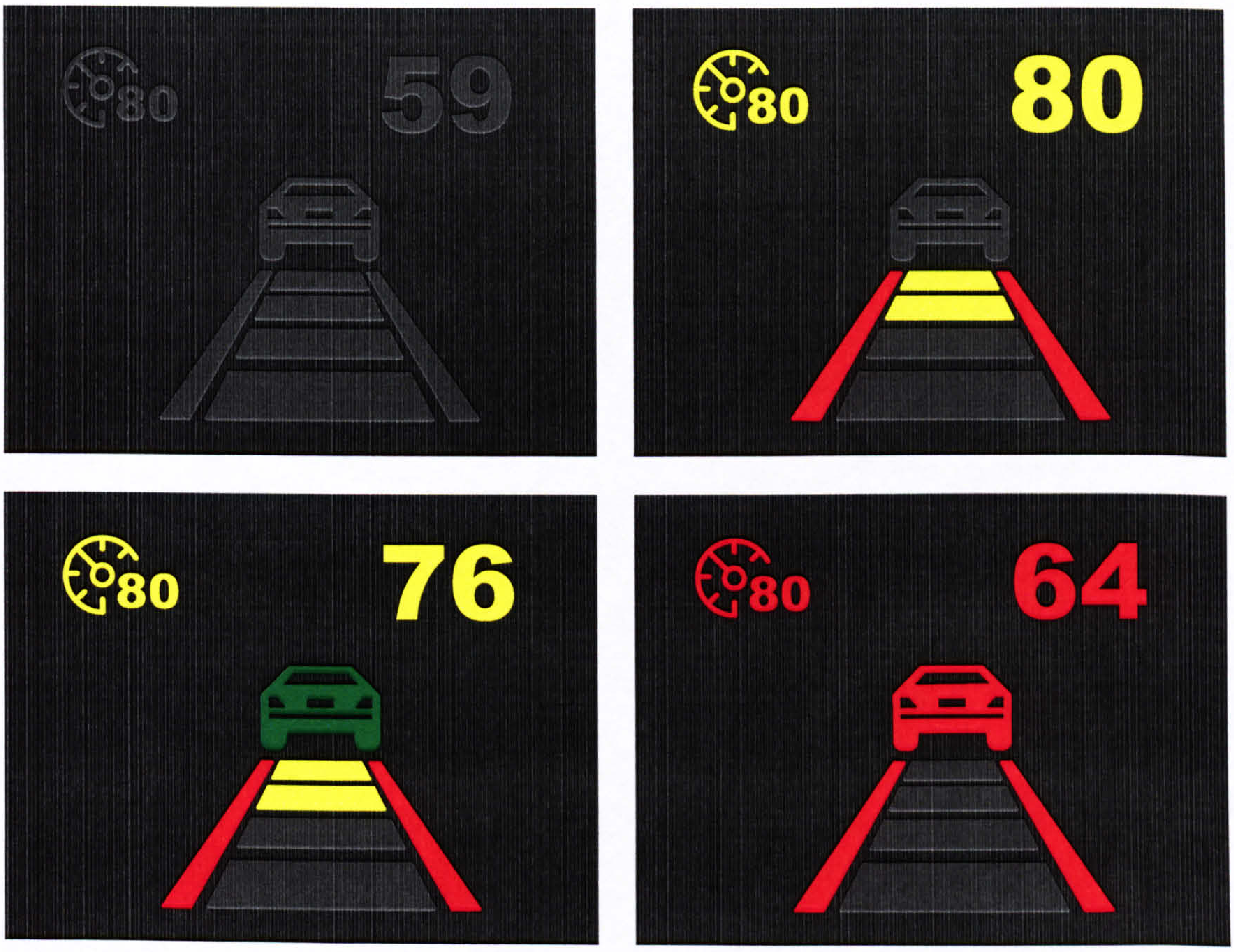


Figure 5.9: ACC GUI in its four states, *Disabled, Enabled - No Leader, Enabled - Leader, Danger*

As the danger state was one that requires immediate driver intervention an audible warning was also sounded. This was a short beep designed to alert the driver but not to distract them. Figure 5.10 shows the total integration of the ACC system with the vehicle and driver.

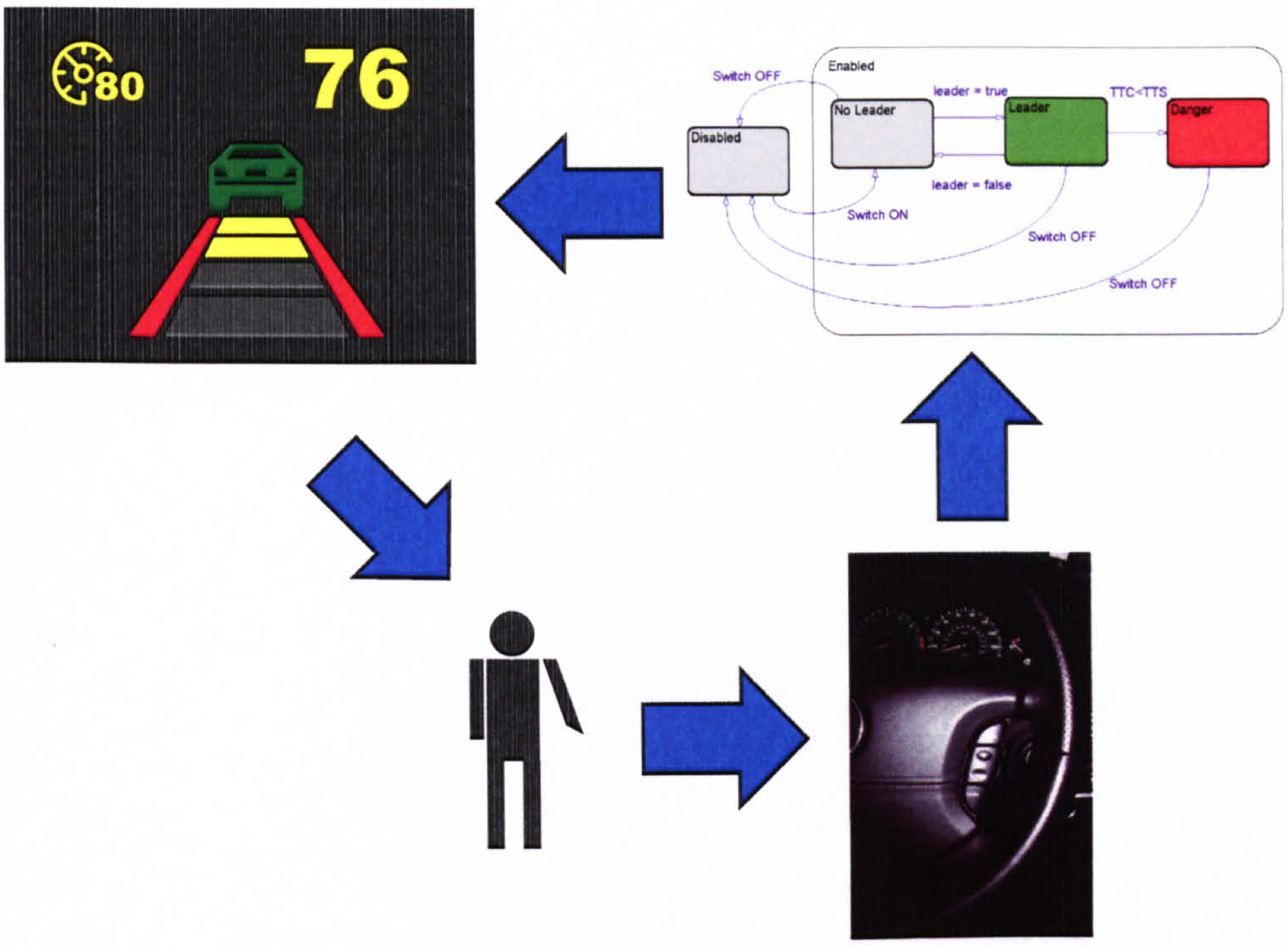


Figure 5.10: Integration of ACC, including driver

5.4 Lateral Control Integration

With the ACC fully integrated on the driving simulator, work moved to the lateral control system. Again work from the off-line simulations was used as a basis to the final solution. From the outset the following decisions were made about the functionality of the system.

- Only lane keeping would be available; any lane changes would have to be performed manually by the driver.
- A look ahead scheme would be used. (Section 4.4)
- The system should provide full control of the steering.

During off-line simulations the look ahead controller had performed a range of lane keeping and lane changing manoeuvres with high degrees of success. For the purpose of the simulator study it was decided to remove lane changing functionality from the system leaving a Lane Keeping System (LKS). It was thought that as the concept of an automatically steered car would be so new to the driver, one which changed lanes automatically may be too difficult to assimilate. The fact that the driver would have to perform lane changes manually would also hopefully mean that they were more aware of the controller and remained in the loop. This LKS is more in line with current systems available on the market. As discussed in Section 1.4.2 some manufacturers offer a lane keeping assistance system that provides an assistive torque to the steering system if the vehicle is about to cross the lane boundary. This LKS is the next step forward in that it provides the total steering torque required to track the trajectory of the lane.

5.4.1 Input Integration

In Section 1.4.2 vision based systems were shown to be capable of recognising lane markings and interpreting them for use in ADAS. In the simulator, the roads and markings are predefined and while the driver cannot see any more than in normal driving, the simulator stores this road database and can access it at any time. Road information is stored in the form shown in Table 5.3.

Table 5.3: Sample road data from the LADS

Section	Type	End Distance
R1.1	L1000	252
R1.2	straight	504
R1.3	straight	756
R1.4	R1000	1008
R1.5	L1000	1260
R1.6	L750	1512

The road is split into 252m segments which are either straight or curved. Curved roads are described by the direction of the curvature, and the radius of curvature, for example; road section 1.4 is a left hand curve with a radius of 1000m. This table is used to describe the centreline of the road, the three lane centrelines follow the same trajectory at a constant offset (5.4, 8.9 and 12.4m giving a lane width of 3.5m). All roads have zero camber and superelevation. With this information it was possible to calculate the co-ordinates at any point along any lane in a similar way to the off-line simulations.

5.4.2 Output Integration

Obviously in the simulator there are no road wheels, the only part of the steering system that is present is the steering wheel. During manually controlled driving, a potentiometer is used to measure the steering wheel angle and a torque motor is used to replicate feedback forces that the driver would feel due to the self aligning effect of the tyres. Under LKS control it was decided to disable the steering system as a moving wheel would add further complexity to the already detailed experiment. This was performed using the following methodology:

- When the LKS was enabled the steering wheel feedback torque was set to 0.
- The steering wheel angle input to the vehicle dynamics model came directly from the LKS control algorithm.
- In the briefing at the start of each drive, the driver was informed that they should manually reset the wheel to the central position when the controller is enabled.

Each subject driver was briefed on this method and had time to practice its use before conducting the experimental drive.

5.4.3 Fade-In of Control Action

If the driver was travelling along in a lane with a constant lane position error, then they enabled the system and there would be an instantaneous step input of error to the controller. This caused the system to generate large steer angles to reduce this error, and as a result there was a large, uncomfortable lateral jerk experienced by the vehicle and driver. To reduce this jerk it was decided to fade the control action in over a period of time. The initial steer angle was stored and linearly reduced to zero while the control action was linearly scaled from zero to its maximum over the same 3s period. While there was still some jerk, it was reduced, providing a more comfortable feel to the system.

The effect of this fade in of control action, was to control the position of the vehicle within a similar time period as without the fade, but with less jerk and a less oscillatory response. The effect could be described as adding damping to the control input, rather than the output, this meant that the high gains and quick response of the system could be maintained for the rest of the operational period of the LKS.

5.4.4 High Level State Logic

While the LKS did not have as many states or parameters as the ACC, governing state logic was still necessary. This is shown in pictorial form in Figure 5.11.

Disabled LKS off, driver controlling lateral position.

Engaging Fade in of LKS control action, this state lasts for 3s during which time the controller cannot be disabled.

Engaged LKS on and controlling lateral position of vehicle.

Unavailable Lane keeping not possible due to poor road markings. Driver in control of lateral position.

This *Unavailable* state is one of the key ideas that the simulator study was designed to investigate. While the sensors and vision systems can provide the necessary path and trajectory information for lateral control there are some scenarios where the vision systems may fail, even in motorway scenarios. Lane markings in the UK are generally of a high standard, but roadworks can mean that these markings are negated and/or replaced. These scenarios where driver intervention is required shall be investigated in this simulator study.

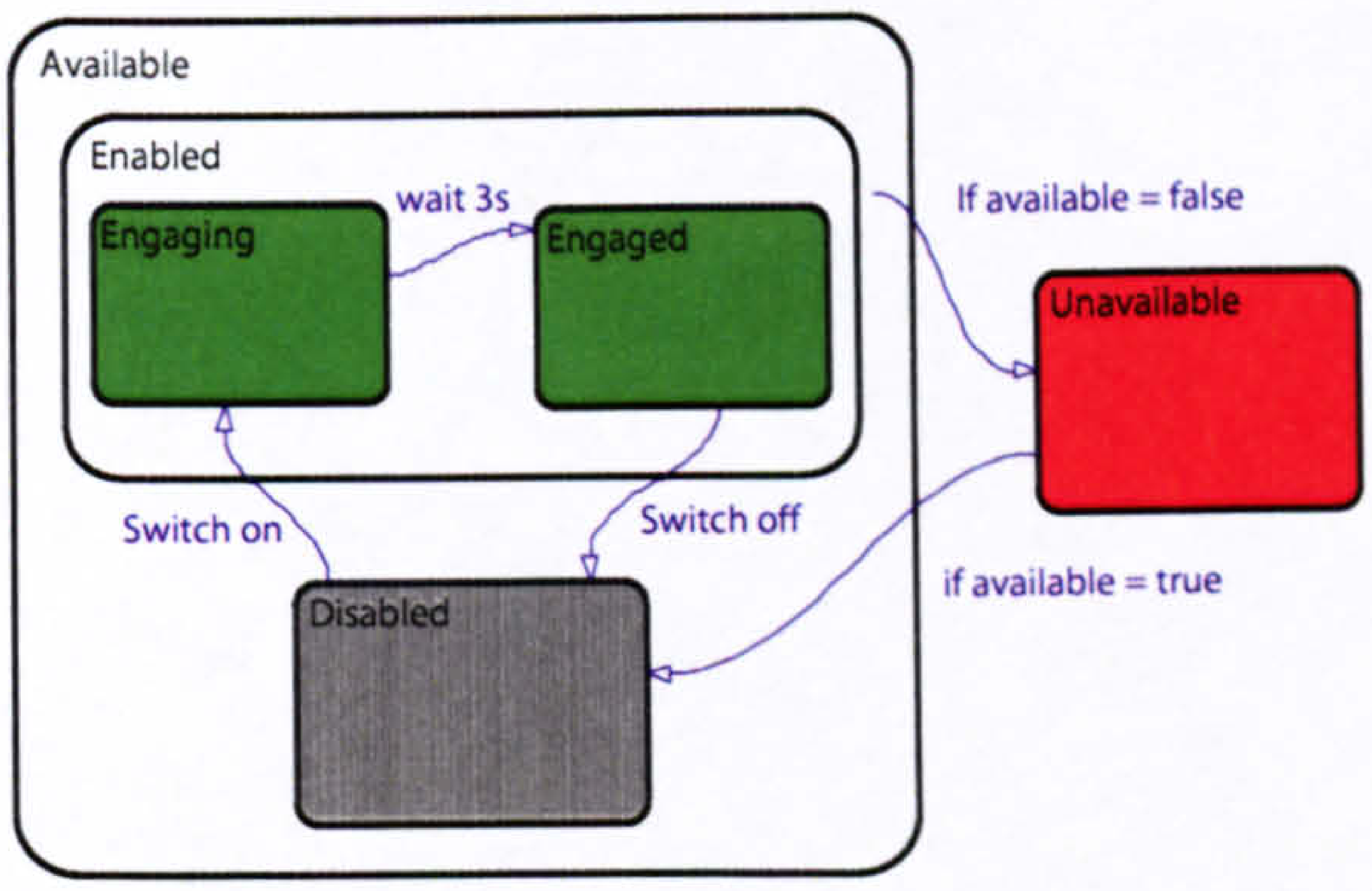


Figure 5.11: State logic of the LKS

5.4.5 Human Machine Interface

As there was less functionality to the LKS than the ACC, the Interface between driver and system was somewhat simpler. The driver could only enable or disable the system, there were no other parameters for them to control. Similarly to the ACC, a button on the steering wheel was used to enable and disable the system. While the ACC controls were on the right of the wheel, this button was located on the left (Figure 5.12). A small black sticker of a steering wheel was used to clearly mark the button. It was thought that if the driver wanted to change lanes it would be confusing to have to press a button first, then perform the manoeuvre, so the turn indicator was also used. If the indicator was depressed, the system would become disabled, allowing the driver to perform a lane change as normal. Once into the lane the driver could then re-enable the LKS using the steering wheel button.

Figure 5.12: Steering wheel button to enable/disable the LKS

Again a GUI was used to convey the state of the controller to the driver. Figure 5.13 shows the three different displays, the colour of the wheel refers to that shown in the state logic diagram (Figure 5.11). The GUI was green for both the *Engaging* and *Engaged* state, because it was not necessary to inform the driver of any difference between the two states. When entering the *Unavailable* state, the GUI would display a red wheel and also sound a warning tone to alert the driver that their intervention was required.

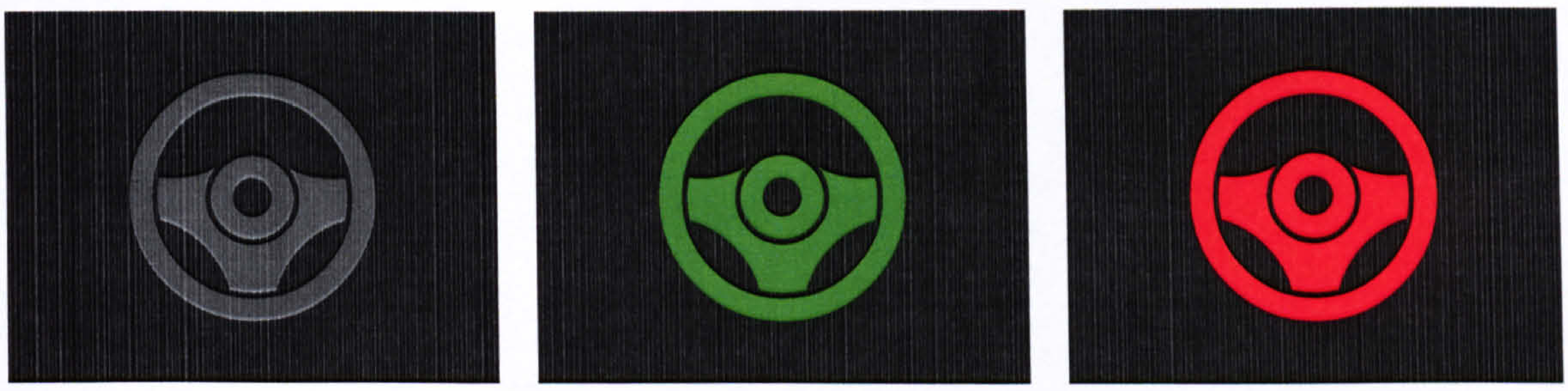


Figure 5.13: The three states of the LKS GUI, from left to right: *Disabled, Engaged, Unavailable*

5.5 Scenario Development

With both the ACC and LKS fully integrated into the UoLDS, attentions turned to the design of an experiment that would produce results to validate findings of the off-line simulations and investigate the interaction of the driver and ADAS. A range of scenarios were developed, which were tested and refined before being pieced together into a full road section. The development of these scenarios are discussed in this section, before the full experimental protocol is summarised.

5.5.1 Adaptive Cruise Control Scenarios

The scenarios for the ACC simulator study were designed to further investigate issues raised in the off-line simulations, whilst also assessing the driver's perceptions of the ACC in a wide range of conditions.

Acceleration in Bend

One of the interesting conclusions from the off-line simulations came from the use of ACC on curved roads. Lead vehicle acceleration whilst cornering caused the subject vehicle to increase its speed (if they had a high set speed). This caused a lateral deviation from the desired path, if the steering angle was not altered accordingly. It was thought that the driver would subliminally adjust the steering. The driving simulator is the perfect tool to validate this theory, and the Acceleration In Bend (AIB) event is designed to examine this. During the sharpest corner in the road the lead vehicle accelerates. If the subject's set speed is higher than the lead vehicle's initial speed, the subject will accelerate whilst cornering (Figure 5.14).

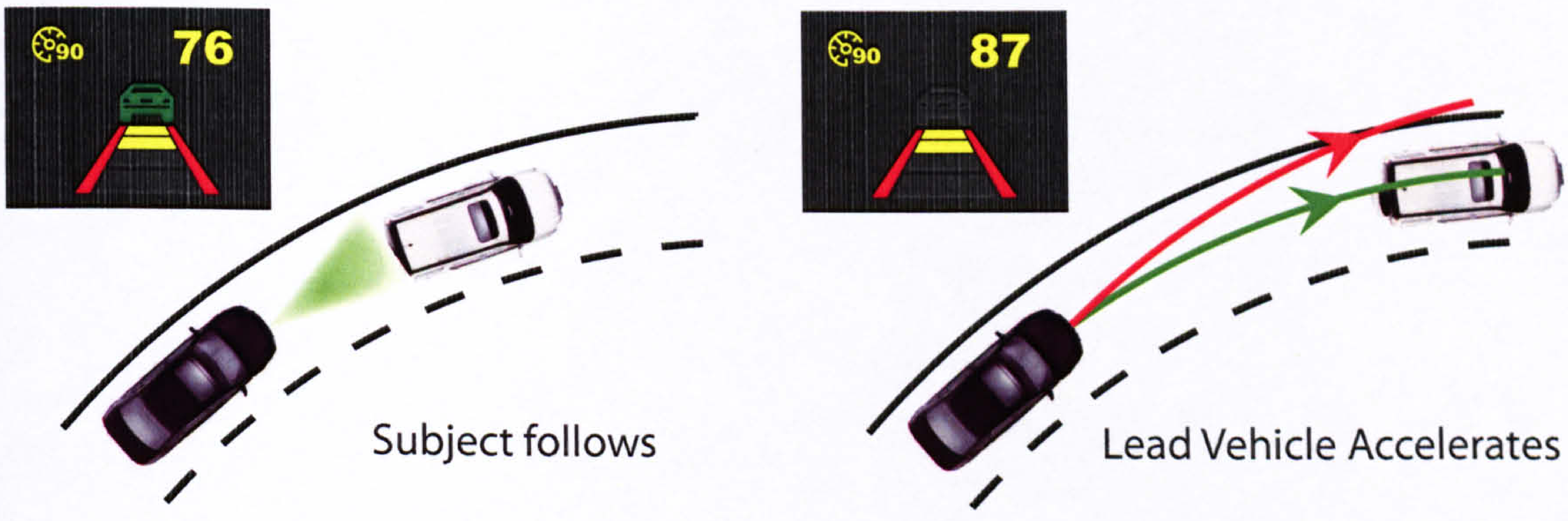


Figure 5.14: Overview of the acceleration in bend (AIB) event

If the vehicle is not following a lead vehicle or is following at a speed similar to their set speed this event will not trigger. This scenario presented an important trade off, should the driver be forced to travel with a high set speed to trigger more events? Or should they drive as they normally would reducing the number of successful events, but create a more realistic test? In this case forcing the driver to travel with a high set speed would involve them manually adjusting this before each event. This would pre-warn them that something was about to happen, and may effect the validity of results. For this reason the driver was asked to drive normally, simulator data was then also validated with visual observations to check the success of each event.

To assess the performance of the driver in this scenario, Time To Lane Crossing (TTLC) was measured. TTLC is defined by Lin and Ulsoy (1995) as the the time required for a vehicle to run off the road boundary assuming no further steering intervention will be taken by the driver. It is a metric that has been used in the validation of active safety systems to assess the 'lane tracking margin' of a vehicle. Steering and brake response were also measured to see if the driver attempts to decelerate, or adjusts the steering.

Lead Vehicle Deceleration

The following two events were designed to monitor the driver's interaction with the ACC. Both Lead Vehicle Deceleration (LVD) and Car Cutting In (CCI) are similar means of assessing the driver's reactions to the danger warning, this meant that more results could be obtained, while the driver was less likely to become used to the repetition.

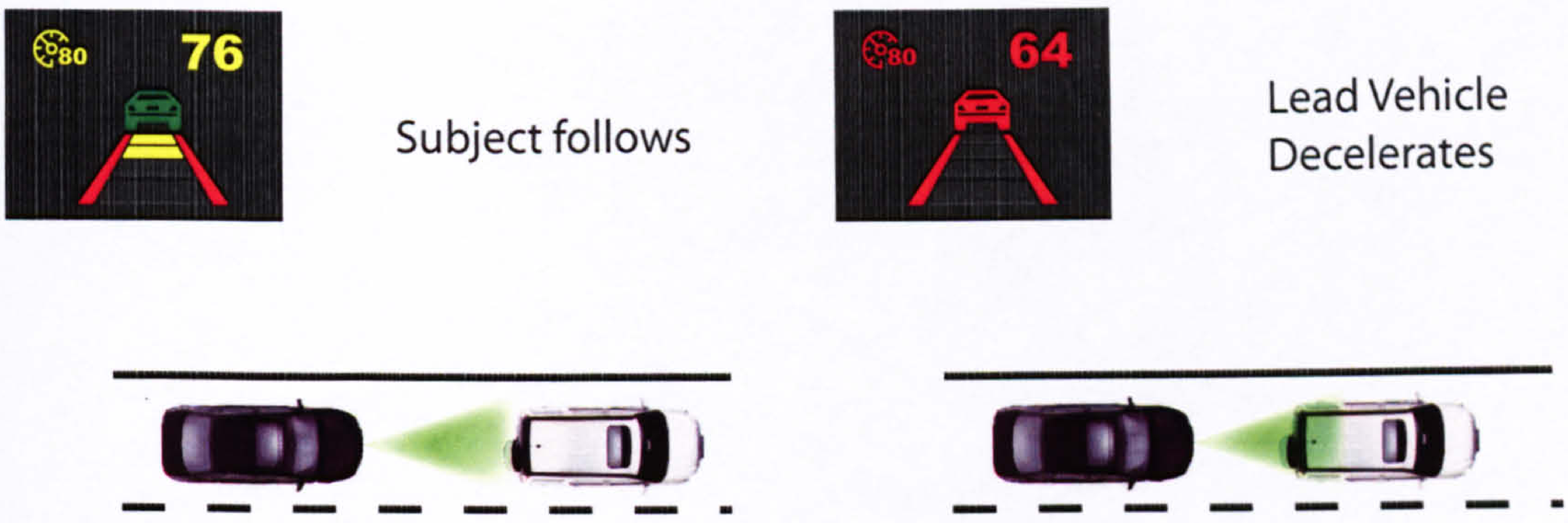


Figure 5.15: Overview of the lead vehicle deceleration (LVD) event

Once the subject hit a way-point in the road, the deceleration of the lead vehicle was set at a level to cause the subject vehicle's ACC to enter the danger state (Figure 5.15). These events always occurred on straight road sections. Initially the lead vehicle's acceleration was set to -3.0m/s^2 for a duration of 3s, causing a danger event when following the lead vehicle with a small headway at high speed. But for longer followers, with slower speeds no driver intervention was required. For this reason the level, and duration of acceleration were scaled to ensure that more events would trigger.

$$Duration = \lim_{\to 5.0}(2.0 + h_w) \tag{5.4}$$

$$Acceleration = -\frac{u_s}{6.0} \tag{5.5}$$

Equations 5.4 and 5.5 show the final values for duration and acceleration which resulted in consistent danger warnings for a wide range of following behaviour. Brake Reaction Time (BRT) was used as a measure of how the driver reacted to the event. This was taken as the time from the start of the event to the time when a brake pedal force was detected. Time To Collision (Equation 5.2) was also monitored throughout the event as a safety measure.

Car Cutting In

The Car Cutting In (CCI) was developed to again test the driver's reaction to the danger state of the controller. The event involved a 'drone' vehicle in the neighbouring lane 'cutting in' in front of the subject and then decelerating (Figure 5.16). Unlike the LVD event this did not rely on the subject following a lead vehicle. The event could also be triggered at a consistent headway, with an independent level of acceleration.

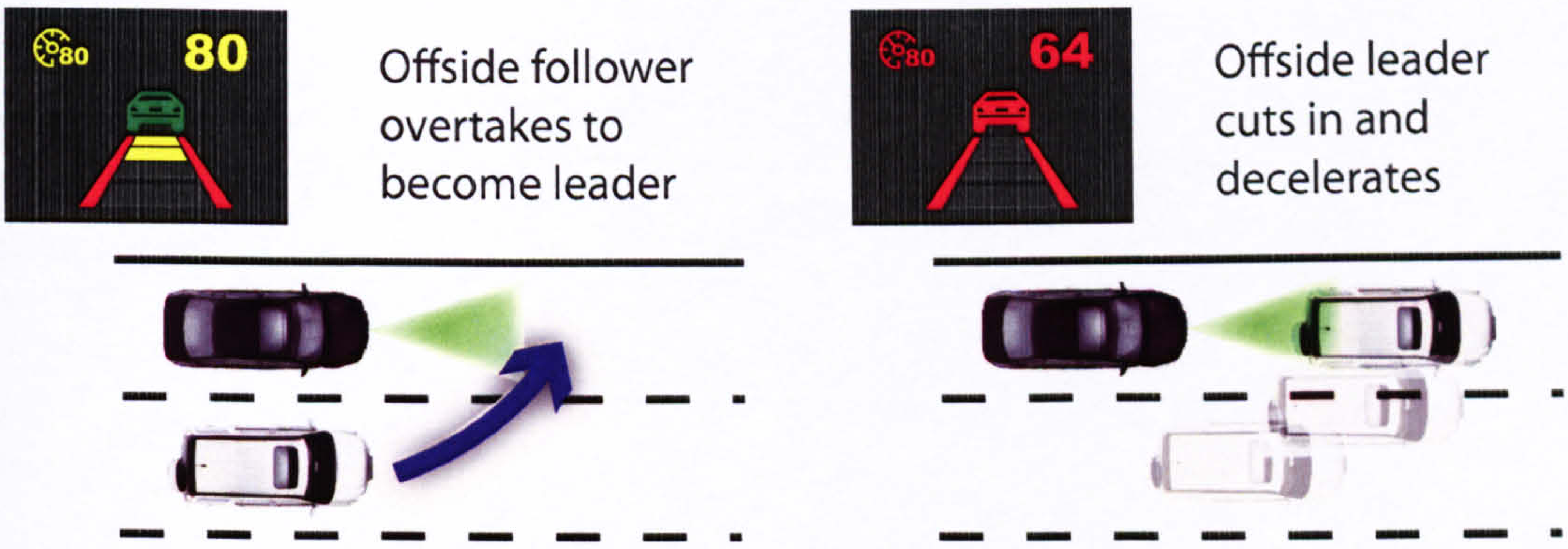


Figure 5.16: Overview of the car cutting in (CCI) event

This event had the benefit of being independent of the subject's headway, and is also more representative of real world scenarios. Again BRT was monitored as well as TTC and headway.

5.5.2 Lane Keeping System Scenarios

The LKS study in the driving simulator was designed to investigate the driver's acceptance of the system. There are periods of normal motorway driving interspersed with repetitions of two roadwork scenarios during which the drivers need to interact with the system.

Lane Drop

Lane drop is a severe manoeuvre in which three lanes of traffic were condensed into one over a period of 300m (Figure 5.17). To make drivers react to the event immediately all warning signs and information were removed from the preceeding road. Drivers were only able to react to the start of the works, or the other 'drone' vehicles changing lane. As there were only cones marking the lane drop, the lane lines beyond these cones were still visible. The effect of this was that the LKS would continue to keep the vehicle in its current lane, causing the subject to drive straight through the road works. To prevent this from happening the driver must disable the system and change lane manually. Time to get into the single lane was monitored, as well as reaction time and Heading Recovery Time (HRT). HRT is defined as the time taken to reduce the heading of the vehicle to within 1°of that of the lane centreline, after completion of the event. A lower value suggests the driver was more in control of the lane change manoeuvre.

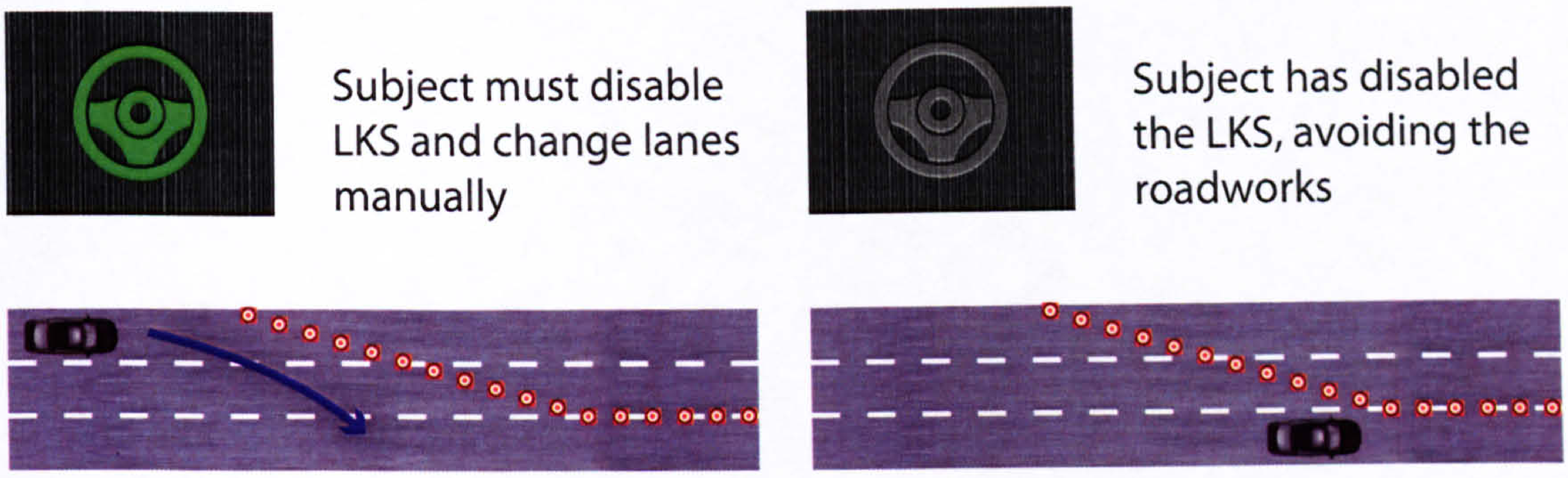


Figure 5.17: Overview of the lane drop event

Narrow Lanes

The second scenario was narrow lanes. This manoeuvre was less severe than the lane drop. Each lane was shifted to the right, and the lane width reduced. These works are usually set out to allow work to the hard shoulder or central reservation without disruption to traffic flow. Again all warning signs and information were removed from the proceeding road to ensure that drivers had to react quickly.

Usually when this type of road works are used on UK motorways, the original lane lines are painted over, but in some cases they are still visible (Figure 5.18). It was assumed that this scenario would confuse the LKS visual system causing the LKS to become *Unavailable*. The driver needed to be aware of this and either disable the system before the lane started to narrow or take over as soon as the LKS became *Unavailable*. Lane position during the scenario was monitored as well as reaction time and HRT after the narrowing section of the road.

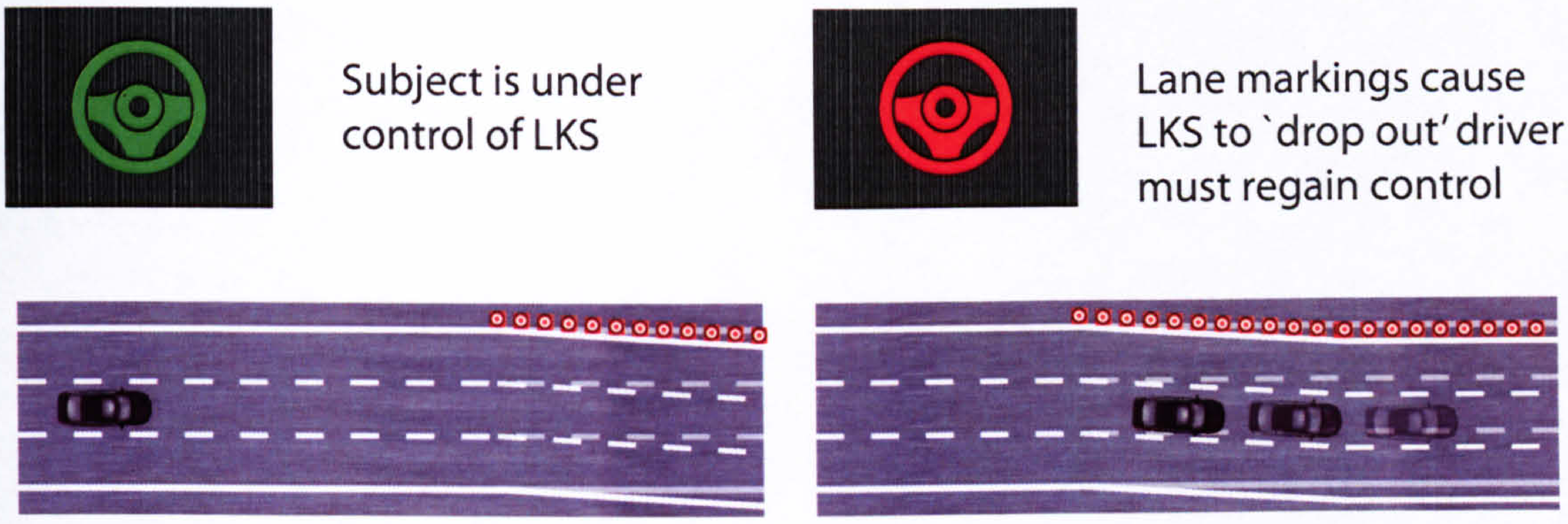


Figure 5.18: Overview of the narrow lanes event

The scenarios developed in this chapter are combined to form the experimental study. The study protocol and results are discussed in the following chapter.

Chapter 6

Driving Simulator Experimentation

Chapter 6 details the driving simulator experiments that were performed as part of this research, from implementation to analysis. The road layout and traffic scenarios are combined in a way to allow drivers to experience both standard and evasive operation of the systems. A structured questionnaire is developed to assess the system's acceptability, as well as the driver's trust, experience, and general opinions of the systems. Objective results from the simulator study are presented and discussed comparing assisted to unassisted driving, and attempts are made to validate these results with findings from the subjective questionnaires. Initial results of the study were presented at 20th International Symposium: Dynamics of Vehicles on Roads and Tracks, and have since been published in the journal of Vehicle System Dynamics (Auckland et al. 2008).

The scenarios developed in the previous chapter together with subjective questionnaires form the basis of an experimental run. This run protocol is now explained in detail. The results from both the objective scenarios and subjective questionnaires are presented and analysed, and their limitations and constraints discussed.

6.1 Experimental Design

6.1.1 Subjects

As with any scientific study an increased number of subjects would have been beneficial to improve the significance of the results. However, in this study, both time and financial constraints dictated a sample size of 10 subjects. It was thought that this would be enough to demonstrate typical trends shown by the data and indicate ideas for further investigation.

It was decided that all subjects should be experienced drivers, familiar with motorway scenarios, as the experiment would at times require evasive driving. All subjects were unfamiliar with the simulator. The subjects had a broad age range of 24 - 63, nine of the subjects were male and one female. Subjects were each paid £15 for their involvement which lasted in total about 1:45 hours.

6.1.2 Protocol

Upon arrival at the simulator facility, the subject was directed to the briefing room and told about the simulator (Briefing is included in Appendix B), and how to drive it in normal operation (no ADAS). They were informed about how it feels to drive, i.e. the automatic gearbox and other controls. The subject was then informed about this study, they were told that we were investigating their interaction with two different ADAS, but they were not yet informed about each system's functionality.

Once in the simulator dome the subject was briefed on the ADAS system that they would be driving with first; 50% of subjects drove with ACC first, the other 50% drove with LKS first to counter balance any learning effects that occurred. Once the subject was comfortable with the ADAS, its functionality and operation (including the possible need for driver intervention) they were seated in the driving seat and the controls were pointed out. The researcher then took up his position in the rear left passenger seat so that they were on hand to assist the subject if necessary, but also out of the line of sight of the subject, so not to disturb them. A practice simulation was then loaded, this involved the same road layout and traffic volume as in the experimental drive but with no scenarios (road works, or traffic manipulation). The subject was instructed to join the motorway and drive normally. Once comfortable with the controls and response of the vehicle, it was suggested that the subject should familiarise themselves with the capabilities of the simulator, by performing lane change manoeuvres and hard braking. This would ensure that the scenarios would not be the first time they experienced high accelerations.

Once the subject confirmed they felt comfortable with the performance of the simulator they were told to enable the ADAS. Again this time was used to familiarise the subject with the system. Those with the ACC were told to practice enabling and disabling the system using both the buttons and brake pedal, vary set speed using the buttons, and investigate different headway settings. Those with the LKS were told to practice enabling and disabling the system using both the designated button and turn indicator. Once confident with these task's subjects were asked to try more complicated functions. For the ACC this meant pulling in and out of lane to investigate the acceleration and braking performance. For the LKS this involved disabling the system using the turn indicator and performing a lane change before re-enabling the system. When completely comfortable with the performance of the ADAS, the driver was asked to pull over and come to a stop. The total practice drive usually took 20 minutes with time split fairly equally between normal and ADAS driving, during this time the researcher was happy to advise and answer any questions that the subject had.

The subject was then informed that the next drive would be monitored, and during this time they should drive as they normally would, assuming they were alone in the vehicle, although the researcher remained in the cab to monitor and assist in emergencies, such as simulator sickness or malfunction. This experimental drive took approximately 20 minutes during which time they would experience repetitions of the relevant scenarios. The road layout is discussed in more detail in Section 6.1.3. Upon completion of this experimental drive, the subject was asked to complete a subjective questionnaire on the ADAS they had just driven with; the design of which is discussed in Section 6.1.4.

The practice road was again loaded into the simulator, but this time the other ADAS was selected. Subjects were then given time to familiarise themselves with this ADAS, again using the method defined above. After this shorter practice drive the experimental road was loaded, and the subject was instructed to drive as they normally would, assuming they were alone in the vehicle. Again the researcher remained in the cab to monitor and assist in emergencies. At the end of this final drive both the subject and researcher left the simulator, and returned to the briefing room where the second ADAS questionnaire was completed.

6.1.3 Road Layout

Each experimental drive took place on a carefully constructed roadway that was designed to obtain as much information as possible without becoming repetitive. Each road contained a baseline section during which the ADAS was disabled and GUI set to a black screen. The driver was still subject to the scenarios during this section. Data from the section was used as the control, against which the effects of the ADAS could be measured.

Sample ACC Road Layout

The ACC road was split up into 4 sections, one of these sections would be the baseline with no controller available, while the driver was asked to enable the controller for the other three. In each section there was one repetition of each scenario (AIB, LVD, CCI). While each road section was identical, the placement of scenarios in each section was not consistent to reduce the feeling of repetition, and continually surprise the subject. So in total there were four repetitions of each scenario for each subject, one of which was the control. A sample road layout is shown in Figure 6.1; locations of the scenarios are displayed and the baseline section highlighted.

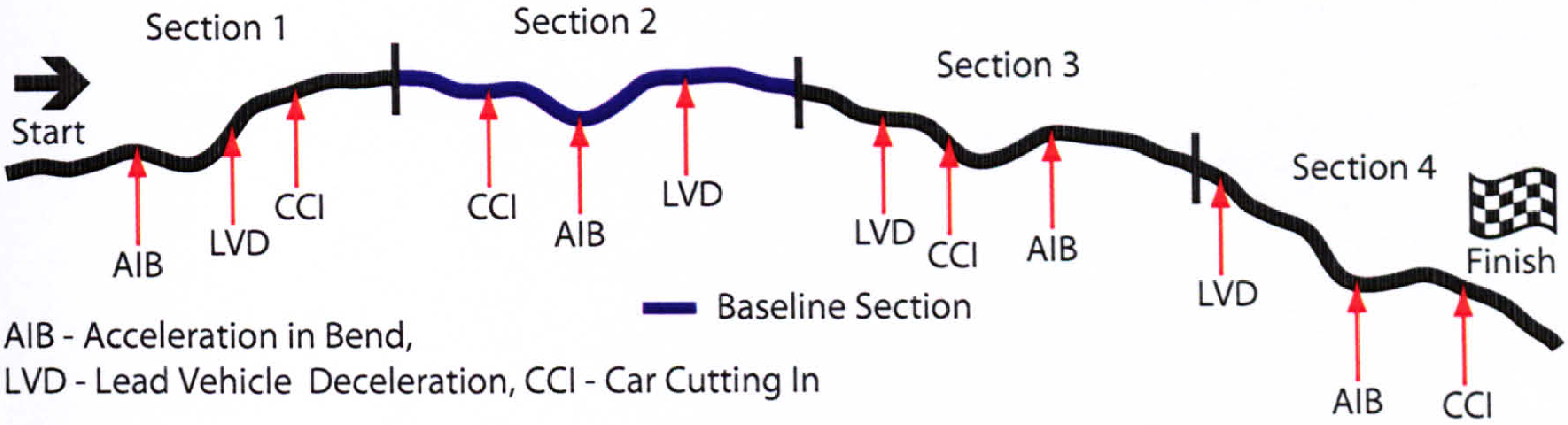


Figure 6.1: Schematic of an ACC road layout

Sample LKS Road Layout

The LKS contained three road sections, again one of which was the baseline section with no controller available, while the driver was asked to enable the controller for the other two. In each section there was one repetition of both the lane drop and narrow lanes scenarios. Unfortunately pre-designed road geometry meant that these roadwork scenarios had to occur in the same place in each section. There were three sections in the LKS road rather than four to negate any learning effect that might be created due to the scenario placement. A sample road layout is shown in Figure 6.2; locations of the scenarios are displayed and the baseline section highlighted.

Subject Road Allocation

As well as varying which ADAS was tested first between subjects; the baseline section placement was also varied in order to mitigate against the learning effect of repetition of the scenarios. Table 6.1 details the road layout for each subject, this counterbalancing of both factors is evident.

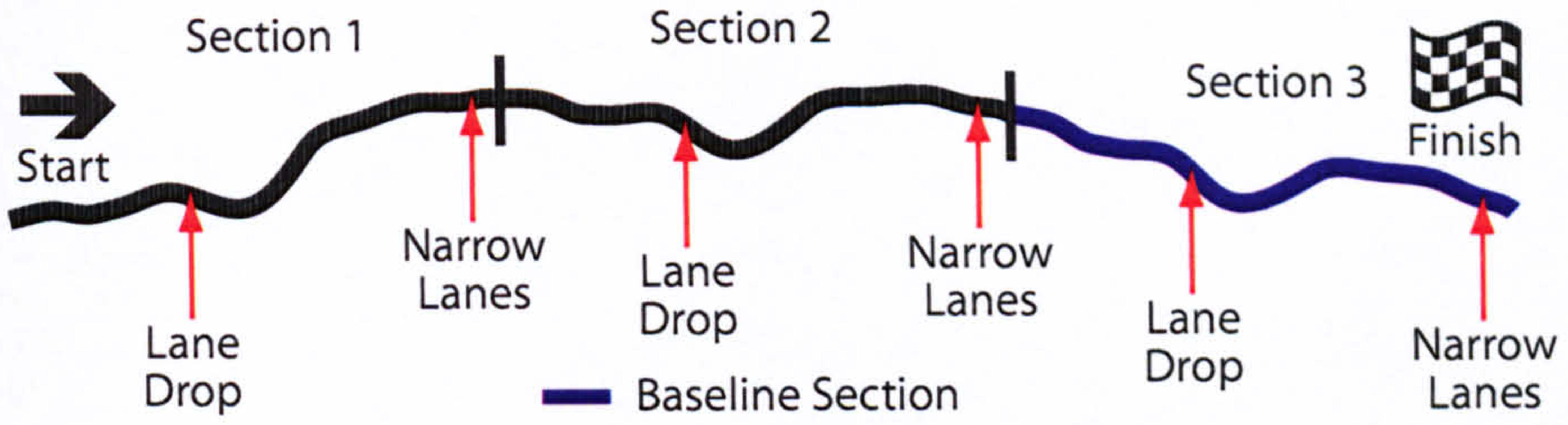


Figure 6.2: Schematic of an LKS road layout

Table 6.1: Experimental design including counterbalancing of events

Subject ID	Subject Age	First ADAS	ACC Base Section	LKS Base Section
1	24	ACC	3	3
2	29	LKS	2	2
3	26	ACC	1	1
4	26	LKS	4	2
5	28	ACC	3	3
6	37	LKS	2	1
7	53	ACC	1	2
8	27	LKS	4	3
9	63	ACC	3	1
10	29	LKS	2	3

6.1.4 Subjective Measures

Subjective evaluation of each ADAS was obtained directly after each drive. The subject was asked to complete a structured questionnaire in which they were asked to rate the system over a wide range of criteria:

Acceptability

Whereas excellent system performance may be sufficient for the technician, it is important that the equipment is appealing for, and accepted by the driver (Van Der Laan et al. 1997). This paper proposes a method where acceptability is split into two dimensions, 'useful' and 'satisfying'. This method was used in this research, the subject was asked the following questions:

> *Having had some experience of the system, please indicate how acceptable you find the system by ticking the box that most accurately expresses your feelings on each line.*

1	useful						useless
2	pleasant						unpleasant
3	bad						good
4	nice						annoying
5	effective						superfluous
6	irritating						likeable
7	assisting						worthless
8	undesirable						desirable
9	raising alertness						sleep-inducing

These 5 point ratings were coded between +2 and -2 for items 1, 2, 5, and 7, and between -2 and +2 for items 3, 6, and 8. Items 1, 3, 5, 7, and 9 relate to the usefulness of the system, and items 2, 4, 6, and 8 relate to the satisfaction experienced. These scores were then averaged for all subjects to yield an overall system practical evaluation.

Concentration

It was thought that it would be interesting to see how the driver felt their levels of concentration were affected when using the ADAS. It was hoped that their levels of performance in the tasks that required intervention could be correlated with this perceived level of concentration. Subjects were asked whether their levels of attention in a range of scenarios were increased or decreased when driving with the ADAS. Questions were again presented with a 5 point scale, allowing comparison between systems and also between assisted and non-assisted driving

Experience

Similar to acceptability, drivers will only buy the ADAS if they have a positive experience. Subjects were again asked to rate the overall experience of each system, on a 5 point scale. The subject was asked to compare driving with the system to driving without the system (the baseline section of the drive). It was then possible to compare results between ADAS systems and also between assisted and non-assisted driving. In this section the driver was also asked about the suitability of the GUI and audible warnings.

Trust

If a driver is to use the system effectively, it is important that they must trust the system. Highly trusted automatic controllers may be used frequently, while operators may choose to control a system manually, rather than engage untrusted automatic controllers (Muir 1989). Trust of a system can be split up into specific dimensions: performance, process and purpose. Lee and Moray (1992) suggest that changes in the dimensions of trust 'performance' and 'process' contribute to overall feeling of trust. These dimensions were highlighted in this questionnaire. The subject was asked to rate the extent to which they agreed with the following statements by placing a mark along a line between the two extremes 'strongly disagree' and 'strongly agree'.

- The performance of the system enhanced my driving safety. (Performance)
- I am familiar with the operation of the system. (Process)
- I trust the system. (Overall)
- The system is reliable. (Performance)
- The system is dependable. (Process)
- I have confidence in the system. (Overall)

The dimension of each statement is shown in brackets (this was not revealed to the subject). The distance to each mark was converted into a percentage and the sum for all statements was given as the drivers trust rating in the system.

6.2 Results and Analysis

The driving simulator experimental results are shown and discussed in the following section in the form of bar charts which compare the experience of controlled driving to that of manual driving. For each metric, the mean for all specific events and subjects of both controlled and manual driving is plotted as a bar. The standard deviation of each is shown as an error bar. A two sample t-test is also performed on each metric, the results of which are quoted in each figure. The tests assess the significance of the results; the p-value quoted is the probability of obtaining a value of the test statistic that disproves the trends shown by the means. Take Figure 6.3 with a p-value of 0.18, there is an 18% chance that a randomly chosen TTC value from assisted driving will be higher than a randomly chosen TTC value from manual driving.

The significance level (α) for these tests is set at 0.05. If a p-vlaue is lower than this number we can say that the result is statistically significant. For the example of Figure 6.3 the result is therefore not significant.

6.2.1 ACC Scenarios

Lead Vehicle Deceleration (LVD)

In this simple longitudinal scenario it was hoped that drivers would react to the danger state of the controller, avoiding possible collisions. To monitor this, the minimum Time To Collision (TTC) throughout the event was recorded. This is defined as the distance between the vehicles divided by their velocity differential. Also brake reaction times and minimum headway were monitored. These values were compared to the baseline (non-assisted) drive for the same driver. The mean of all subjects is shown in Figures 6.3 - 6.5.

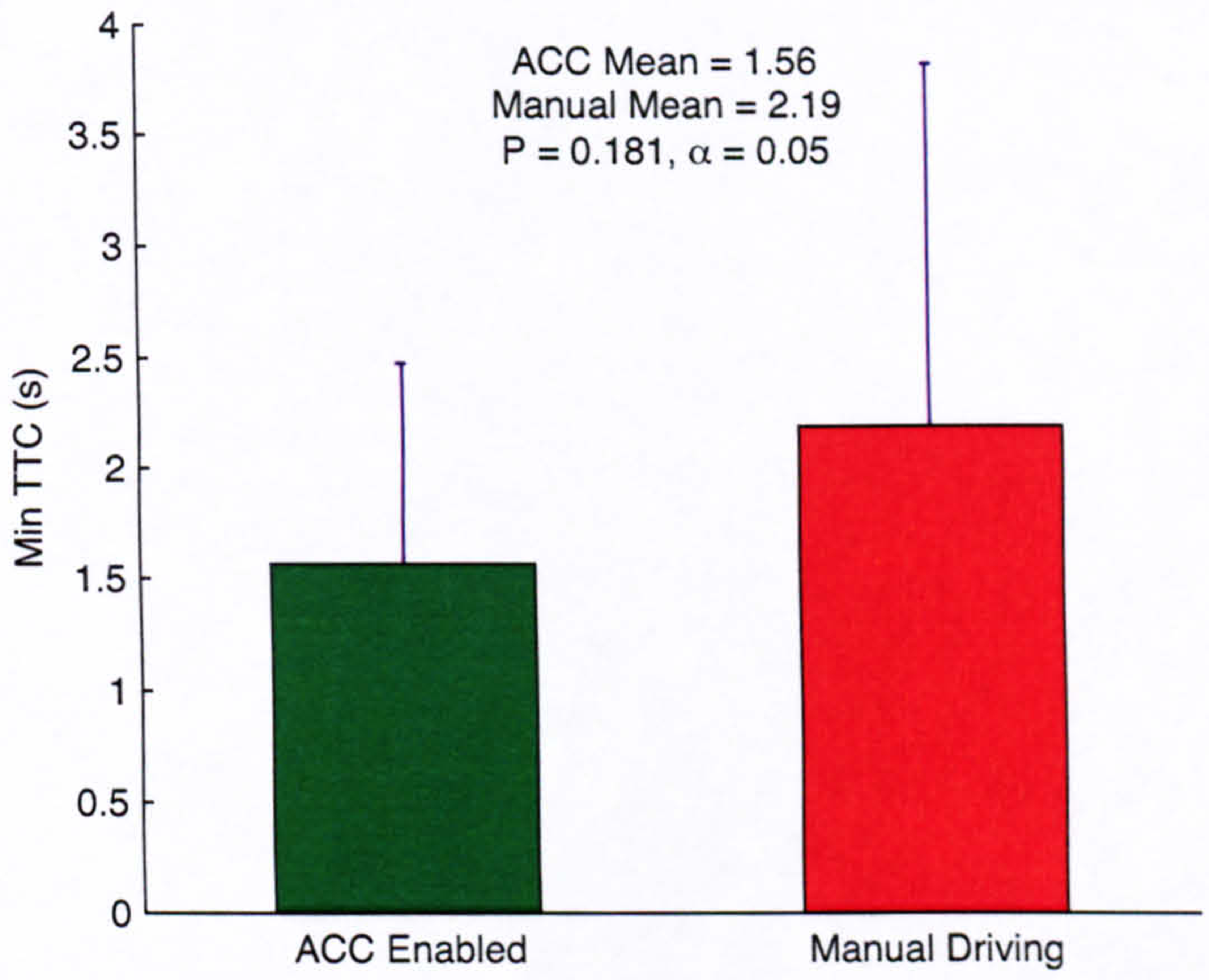


Figure 6.3: Time to collision data for LVD scenario

TTC was on average decreased when driving with ACC (Figure 6.3). This means that the driver had less time to adjust their response accordingly, and that collision is therefore more likely. While the result of ACC and manual driving is not significantly different, this trend suggests that the safety of the driver was reduced for this type of event. This may be caused by the driver trusting the system to apply the necessary level of braking. Given the lead vehicle deceleration was outside the capable range of the system, the ACC could not maintain the desired level of braking, and driver intervention was required. As soon as the system realised that this intervention was required it alerted the driver through an audible and visual warning, but the driver then took time to react to this before applying the brakes manually.

Results from the minimum headway response of the vehicle validate the trend suggested by the TTC metric (Figure 6.4). The lower headway experienced under ACC demonstrates that the subject was generally closer to the lead vehicle at some point

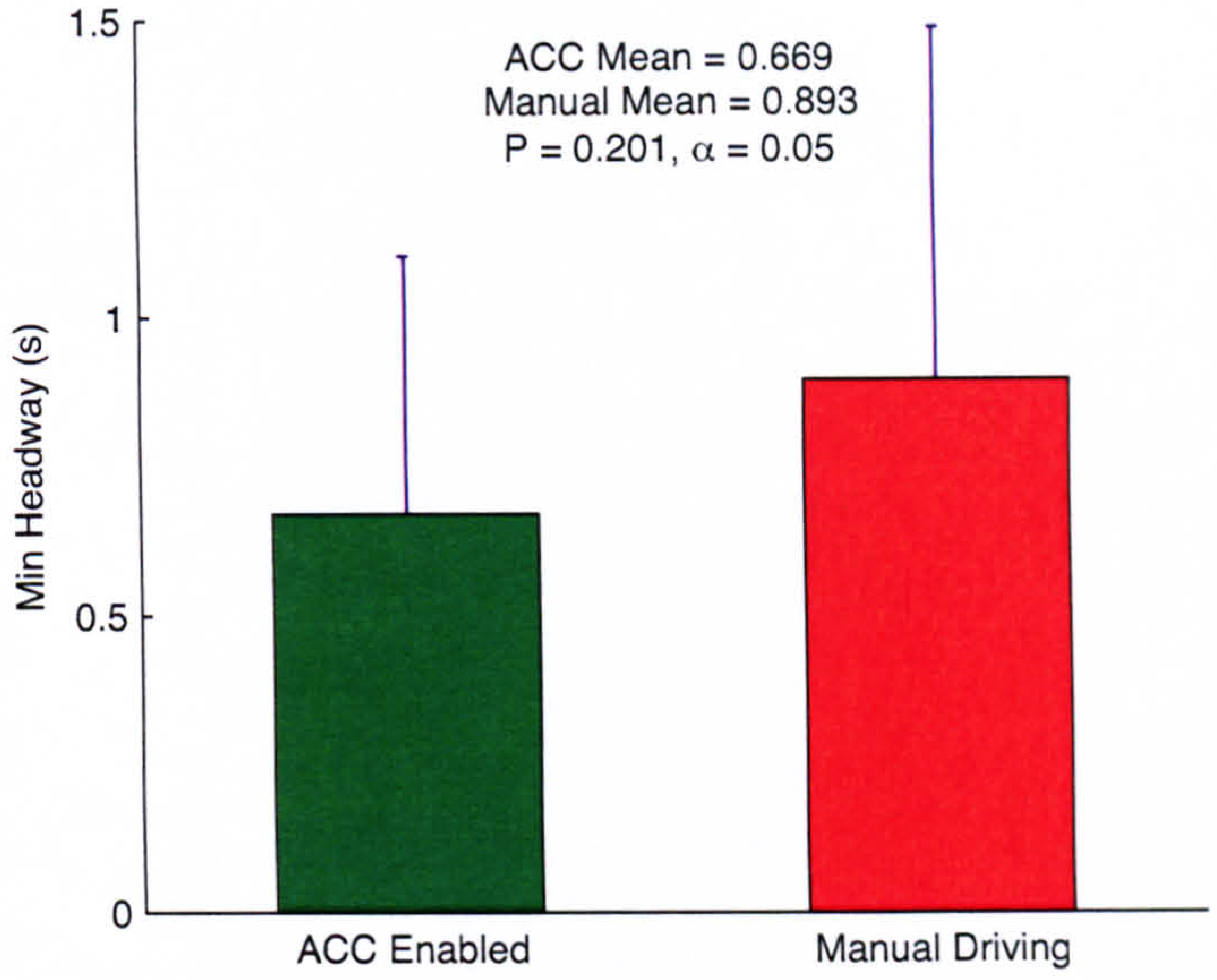


Figure 6.4: Minimum headway data for LVD scenario

through the manoeuvre, than when under manual control. It should be noted that this result was less significant than the TTC result. While the standard deviation was relatively high for both ACC and manual driving, no collisions were experienced in any LVD events.

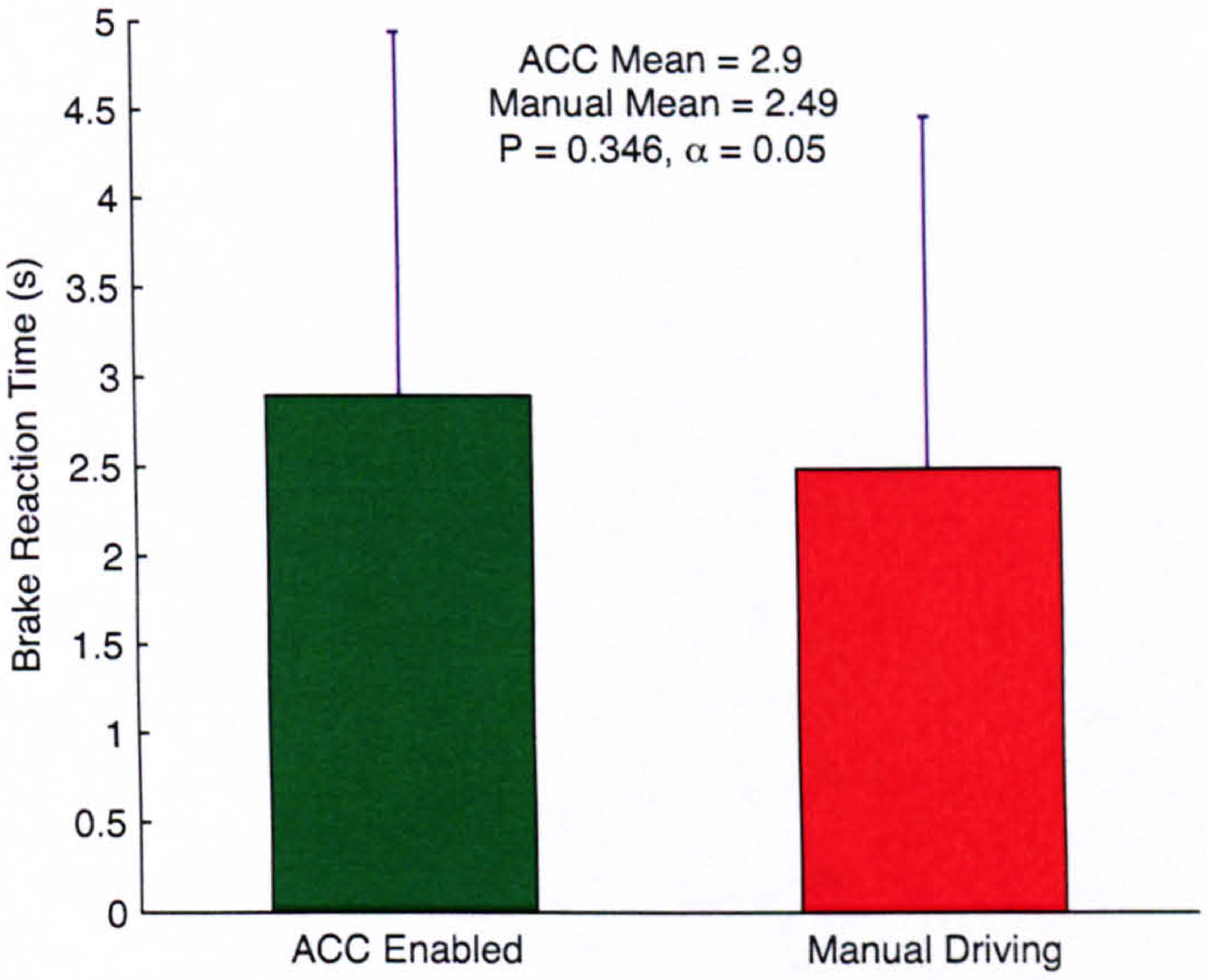


Figure 6.5: Brake reaction time data for LVD scenario

Brake Reaction Time (BRT) was slightly increased when using the ACC (Figure 6.5). Again this substantiates the findings of the previous two metrics, and suggests that the driver's trust in the system caused them to wait for a danger warning before braking. The increased BRT may be due to a combination of this and the reaction time to the danger warning, In some cases the driver did not demonstrate this level of trust in the system, instead they applied the brakes before the danger warning was active.

Car Cutting In (CCI)

While the nature of the CCI and LVD events were similar, the results show different trends, where the ACC seems to reduce the safety of the vehicle for the LVD event, the opposite is the case for the CCI event.

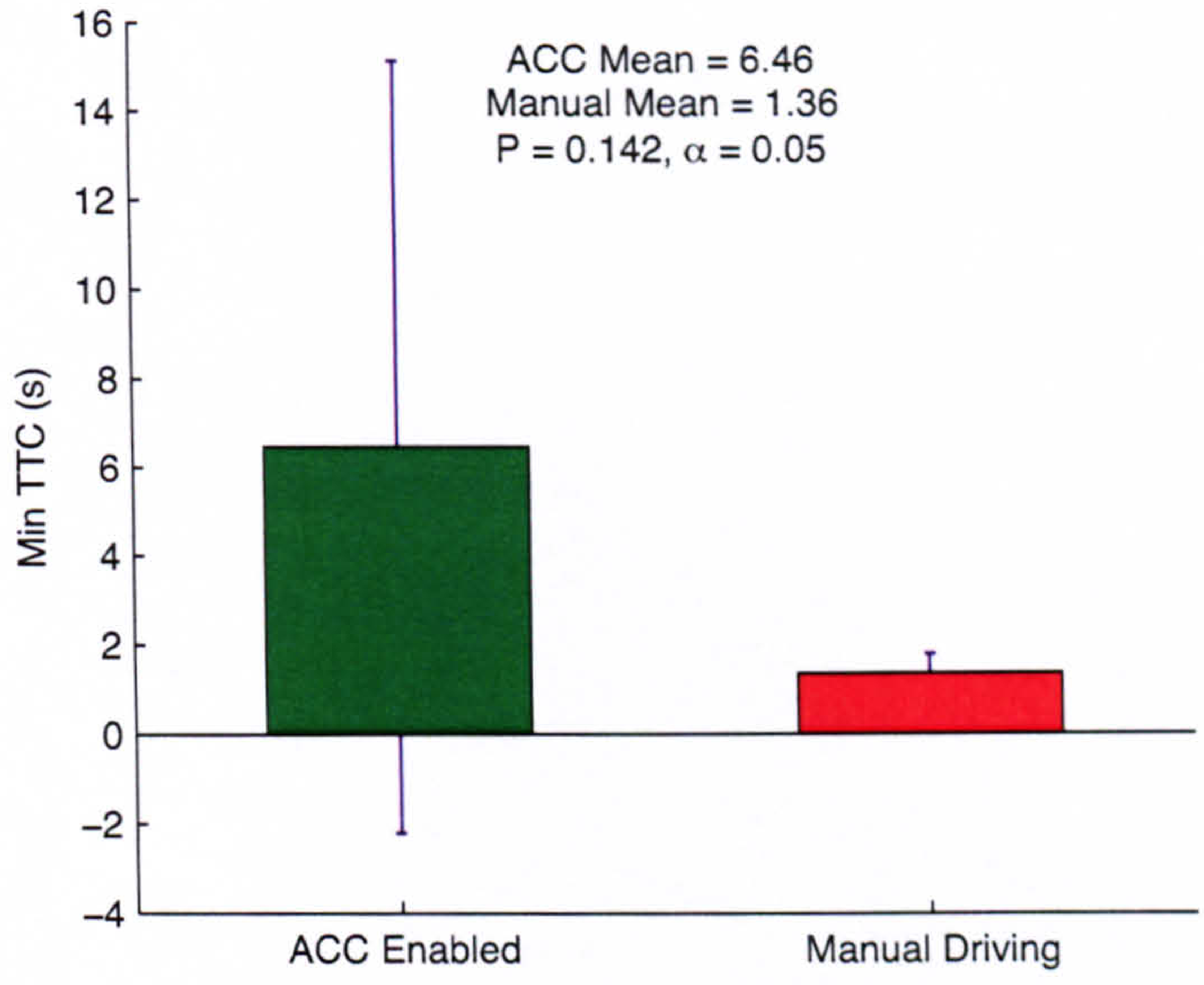


Figure 6.6: Time to collision data for CCI scenario

The TTC values shown in Figure 6.6 display a higher mean for controlled, than for manual driving. This would suggest that collision was less likely under ACC. This could be due to a number of factors, the most likely cause is the ability of the ACC to reduce the speed of the subject vehicle, as soon as the lead vehicle enters the lane, as the headway gap was so small. This initial small headway would not trigger a danger warning, as the speed of the lead vehicle was still greater than the subject. But the ACC would try to increase the headway by reducing the subject's speed. In manual driving the driver would see that the lead vehicle was travelling faster than the subject vehicle, and may assume headway would be increased as the leader pulls away. After a short period of time the leader then decelerated. The ACC system had more time to decelerate due to the increased headway, and the driver had more time to respond to a danger warning emitted by the system.

The minimum headway experienced throughout the event (Figure 6.7), validates the findings of the TTC metric; although controlled and uncontrolled results are more similar

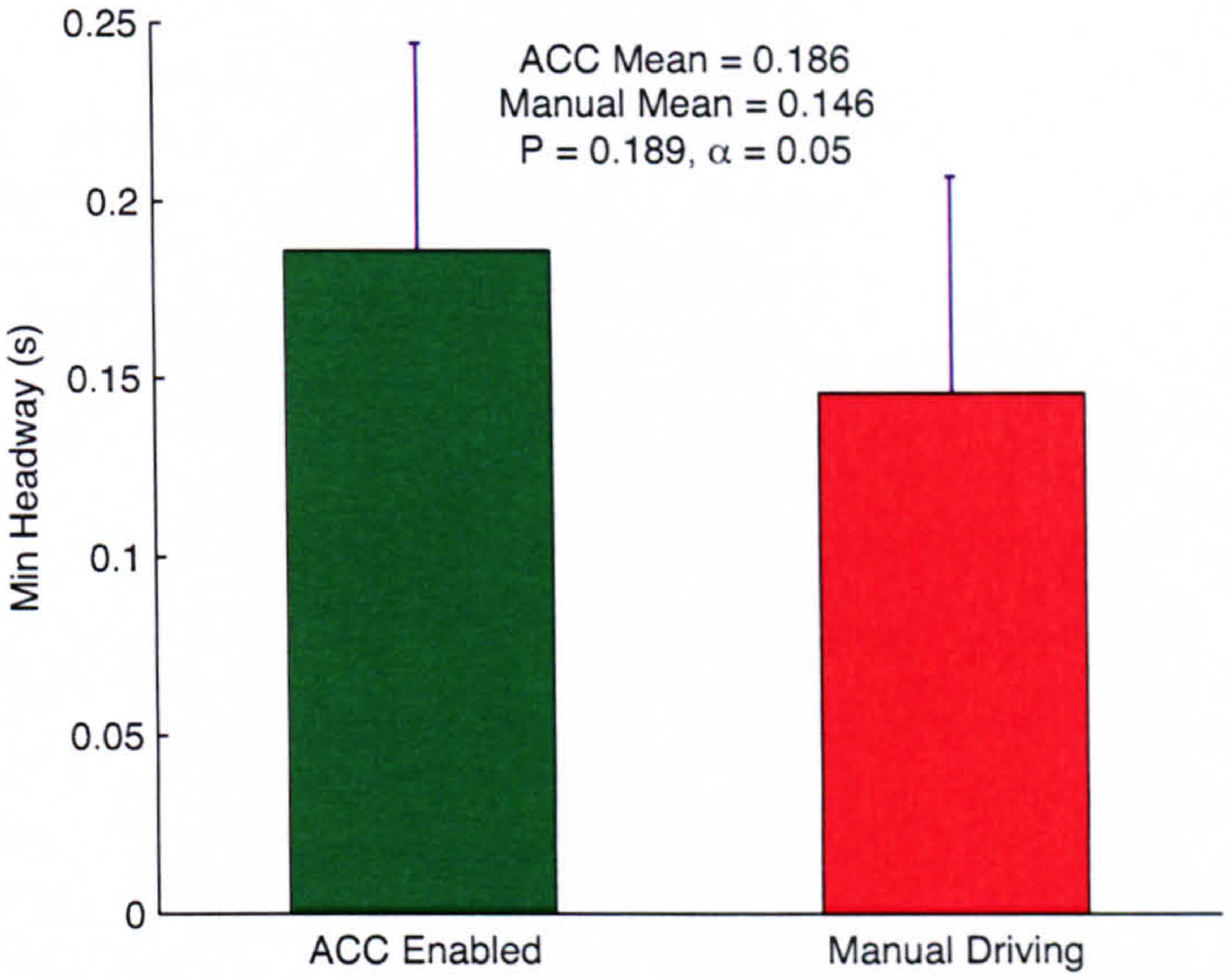


Figure 6.7: Minimum headway data for CCI scenario

than were seen for TTC. This may be due to the nature of the measure, as TTC is effected by lead vehicle speed which varies significantly in this scenario. Headway on the other hand depends only on the time gap between vehicles. It should be noted that for both controlled and uncontrolled driving these values are much lower than desirable, significantly compromising the safety of both vehicles.

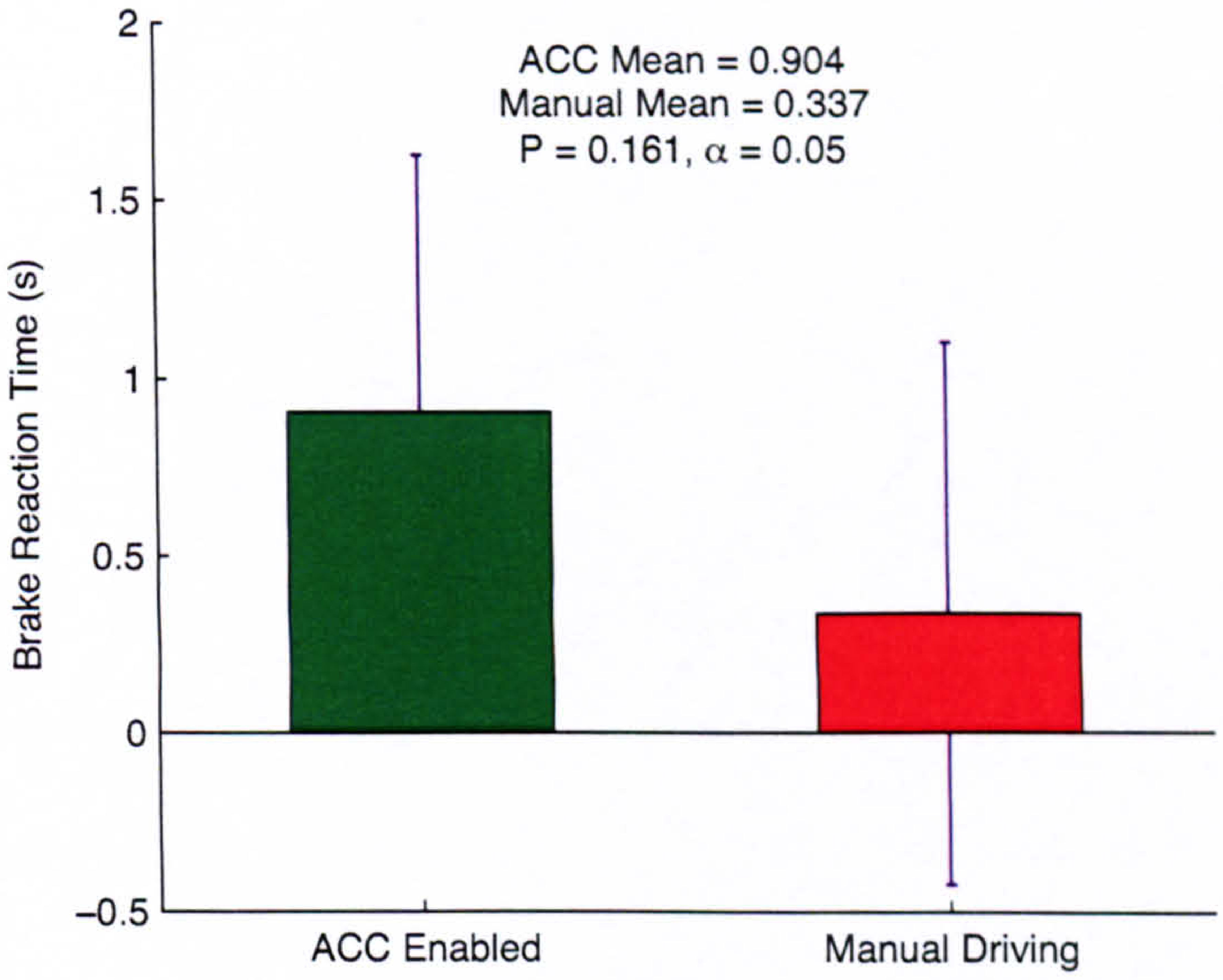


Figure 6.8: Brake reaction time data for CCI scenario

The results from the BRT metric (Figure 6.8) seem to tie in with both of the above findings. BRT was slightly higher in the ACC event. Again the variance is high in both manual and controlled driving. The result can again be explained by the driver's reaction time to the danger warning. While this was not the case in manual driving, the delay of 1s from the start of the event may be due to the expectations that intervention was not necessary.

Acceleration in Bend (AIB)

The AIB event was designed to see if the driver could adjust the steering appropriately, whilst being caused to accelerate by the ACC during cornering. Results show that drivers could perform as expected. In all instances of this event, subjects chose to steer to counteract the effects of the acceleration, rather than using the brakes to disengage the system.

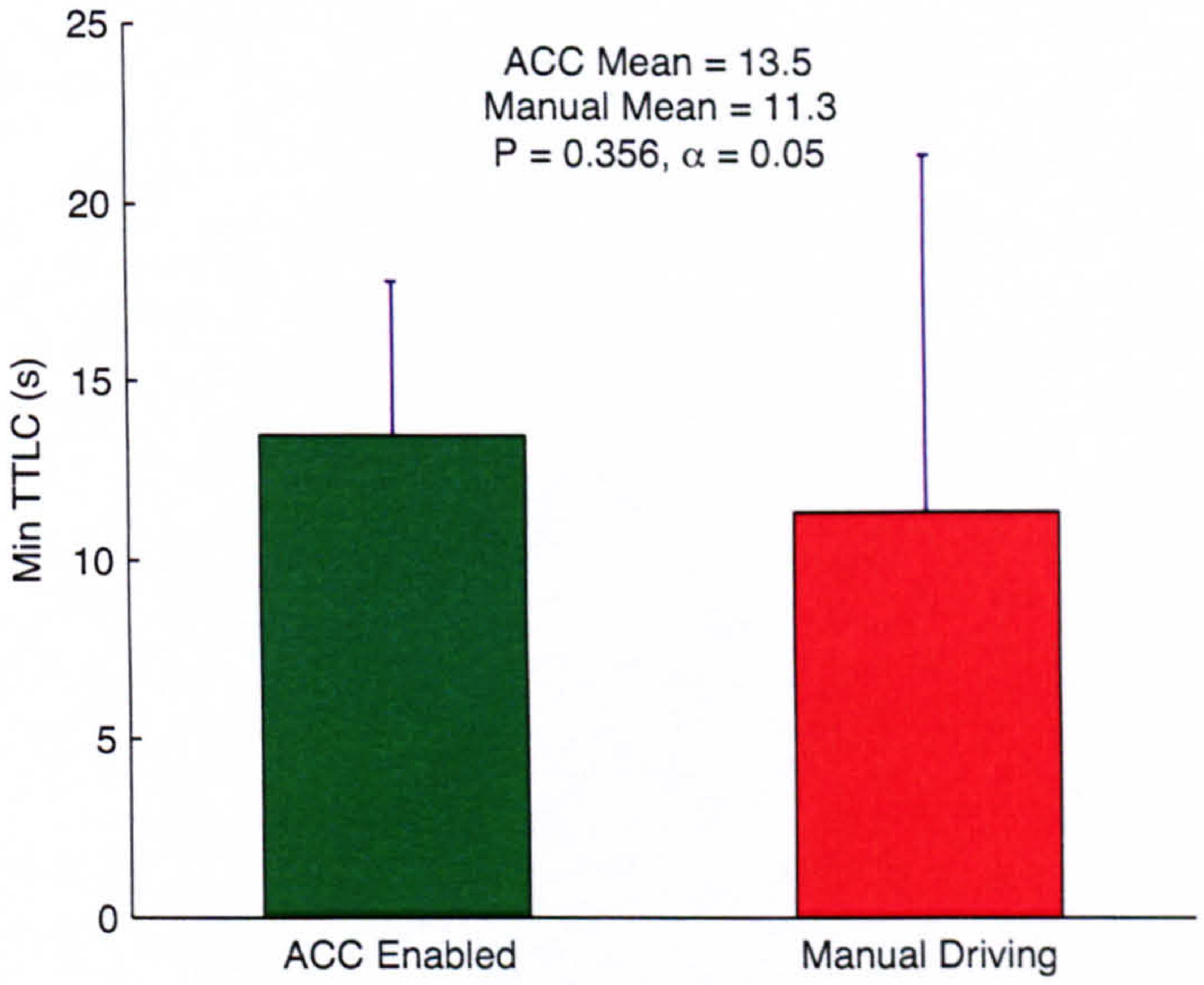


Figure 6.9: Time to lane crossing data for AIB scenario

Time To Lane Crossing (TTLC) is a measure of how long it would take the vehicle to cross the lane given its current heading and position vectors (Lin and Ulsoy 1995). Looking at Figure 6.9, it can be seen that this was actually slightly increased under ACC. While this was surprising, it may have been due to an increased awareness of other aspects of driving, that was reported by drivers using the ACC system (Section 6.2.3).

Both the Cumulative Lane position Error (CLE) (Figure 6.10), a measure of the total deviation from the centreline during the manoeuvre, and Maximum Lateral Error (MLE) (Figure 6.11) were reduced when using the ACC, which validates the TTLC findings. While there appears to be a large change in CLE, it should be remembered that the event lasted for 250m. Average MLE was only slightly reduced (0.2m).

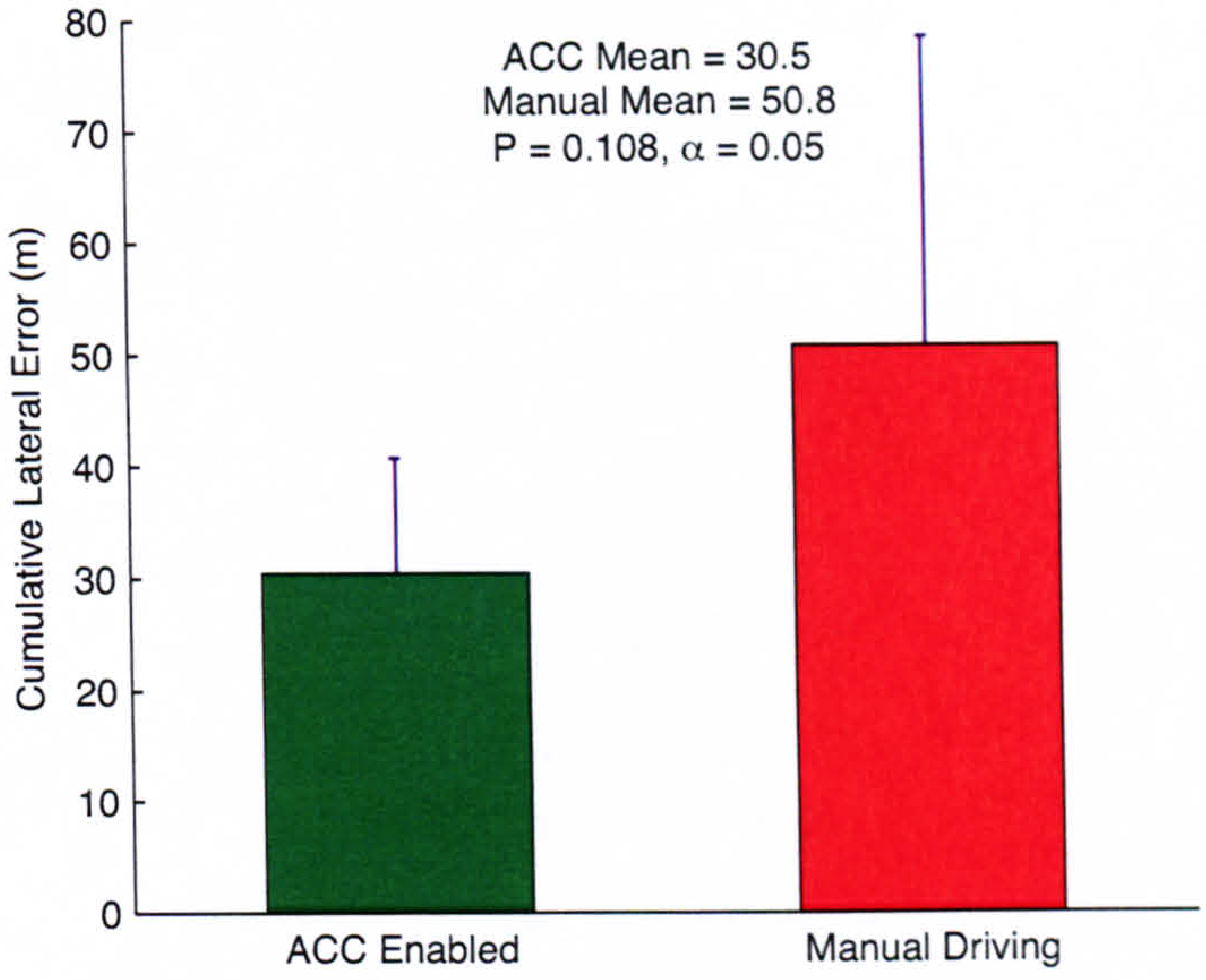


Figure 6.10: Cumulative lateral error data for AIB scenario

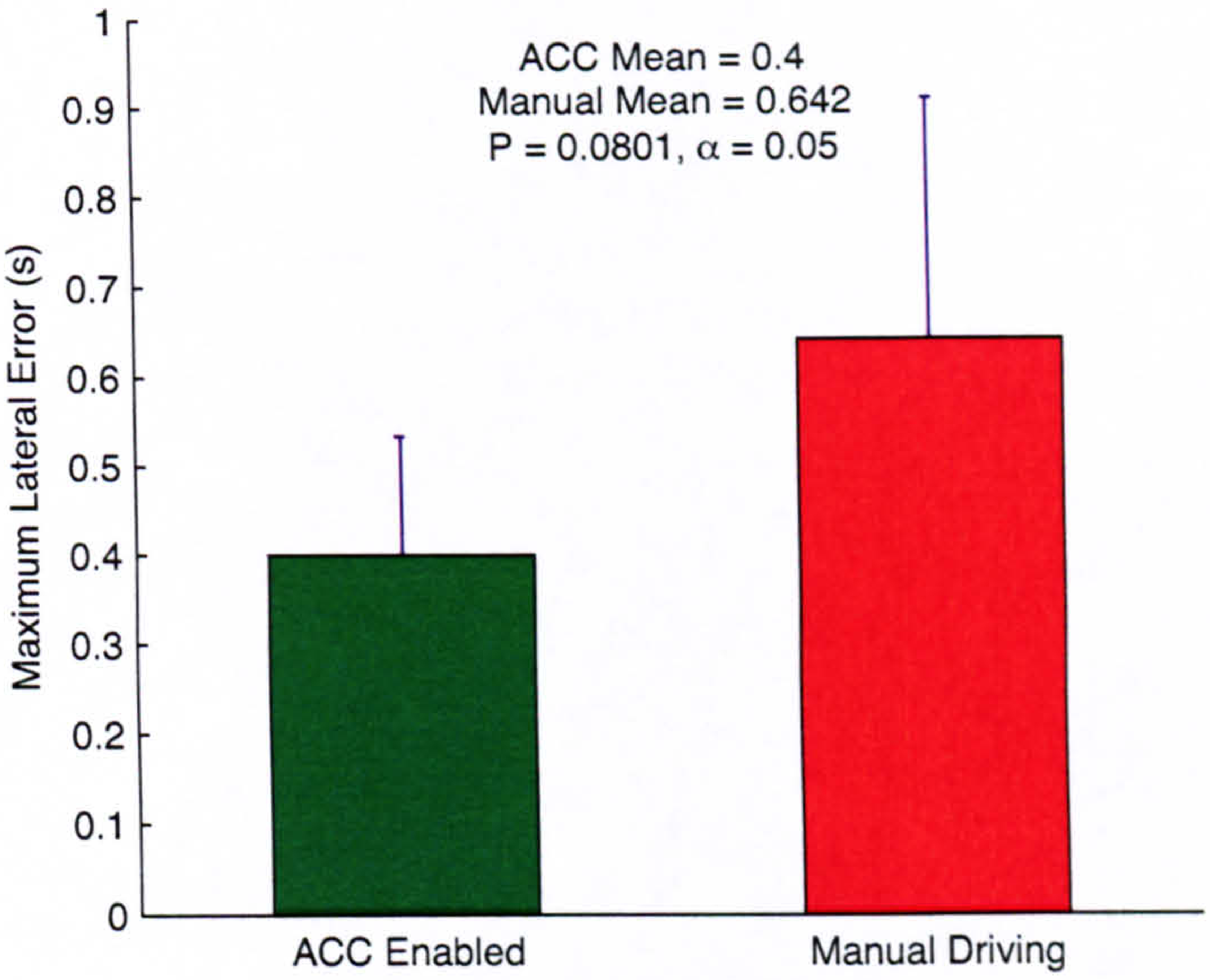


Figure 6.11: Maximum lateral error data for AIB scenario

6.2.2 LKS Scenarios

Narrow Lanes

This scenario was designed to highlight the problems caused when the LKS becomes unavailable, due to poor lane markings. It was suggested that passing control back to the driver suddenly may cause difficulty in regaining control, and may reduce the stability of the vehicle.

Heading Recovery Time (HRT) is a measure of how quickly the heading angle of the

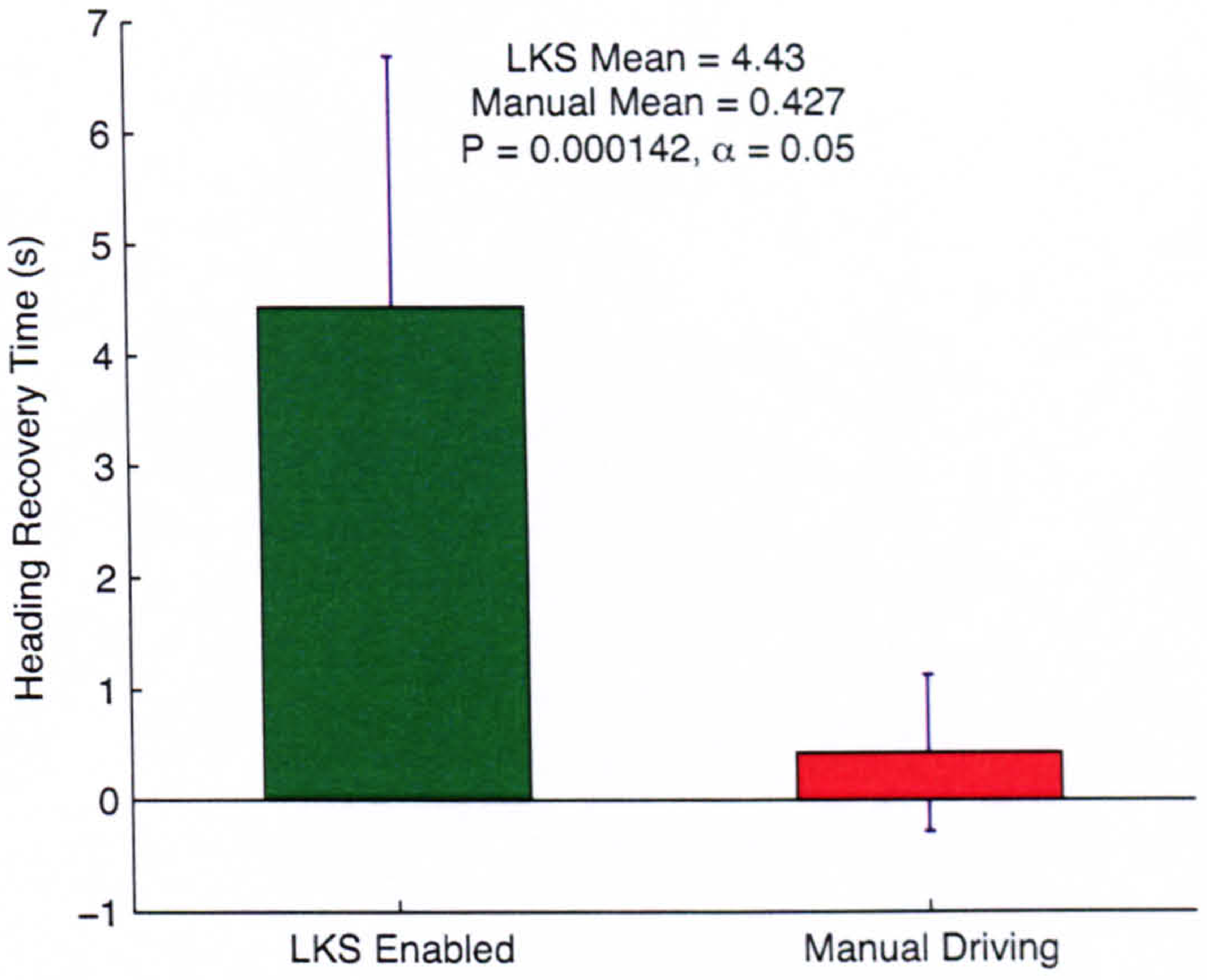


Figure 6.12: Heading recovery time data for narrow lanes scenario

vehicle is brought back to be within 1° of the desired road heading when returning to a straight section of road after a curved section (or after completion of an event). For this narrow lanes scenario this corresponds to the the time taken from the point where the lanes become most narrow. As the narrowing of lanes will cause some deviation in heading, it is a valid measure for both controlled and uncontrolled driving, which gives an indication of the degree of awareness of the driver, and their ability to navigate the roadworks effectively. Results show that the average HRT was significantly increased when driving with the LKS (Figure 6.12).This was in line with expectation, but it is surprising to notice such a difference between controlled and manual driving. Upon regaining control from the LKS, drivers tended to put a large steering input into the system to regain lane position. This overshot the desired level and the driver then had to counteract this input. Under manual driving the driver was used to the steering effort demanded, and was able to apply the desired steering input easily.

The Cumulative Lateral Error (CLE) was also increased by a large amount under the LKS. This substantiates the explanation of the HRT response, in that the increased error could be caused while the driver was trying to regain control, after applying an unnecessary large steering input when the LKS became unavailable. This, like the HRT is statistically significant.

The Cumulative Steering Effort (CSE) metric shown in Figure 6.14 is a measure of the distance spent travelling where the steering input is not zero. This is the integral of the steering wheel angle with respect to distance covered, for the duration of the event. The significantly larger value experienced in the LKS case suggests that; although the system

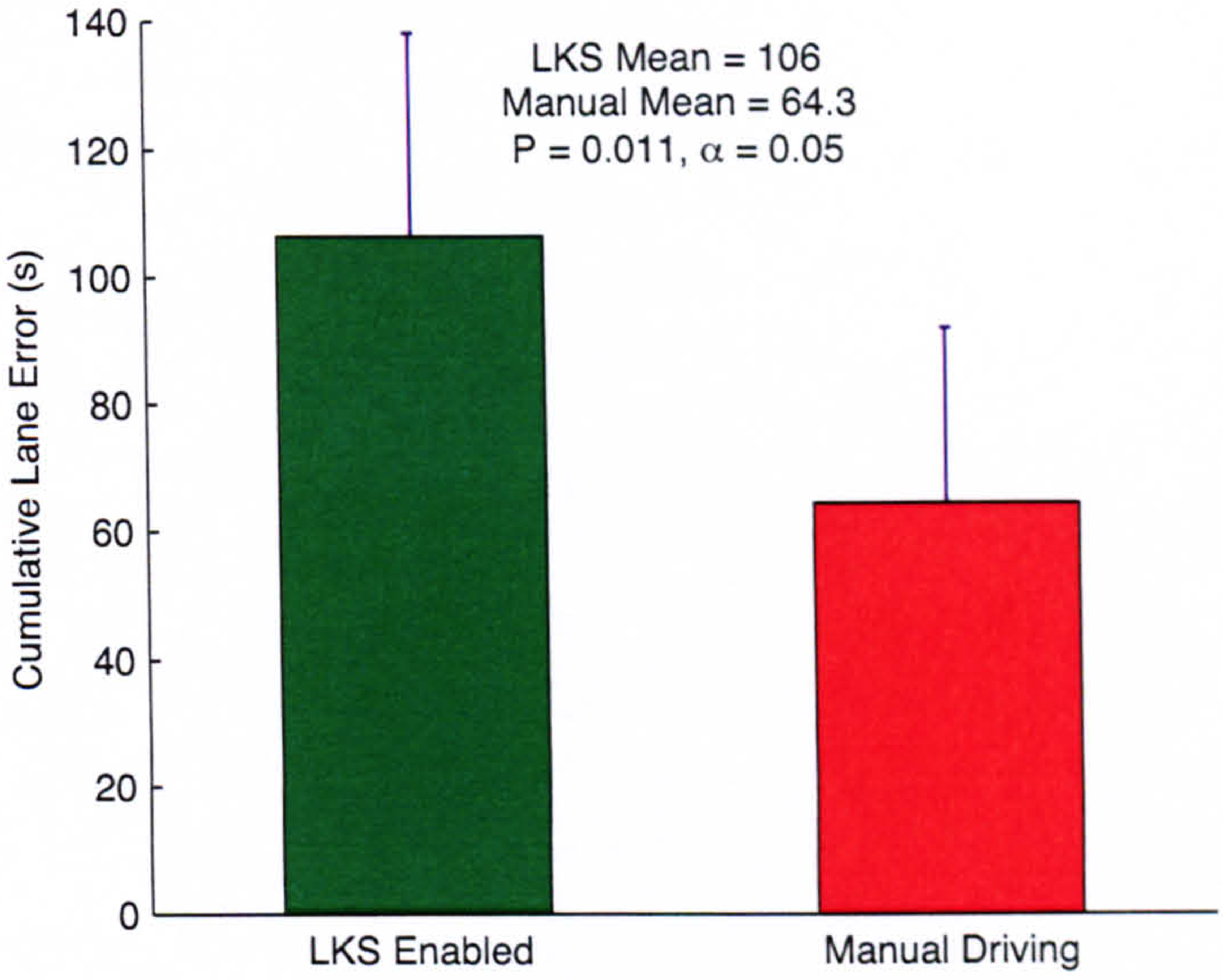


Figure 6.13: Cumulative lateral error data for narrow lanes scenario

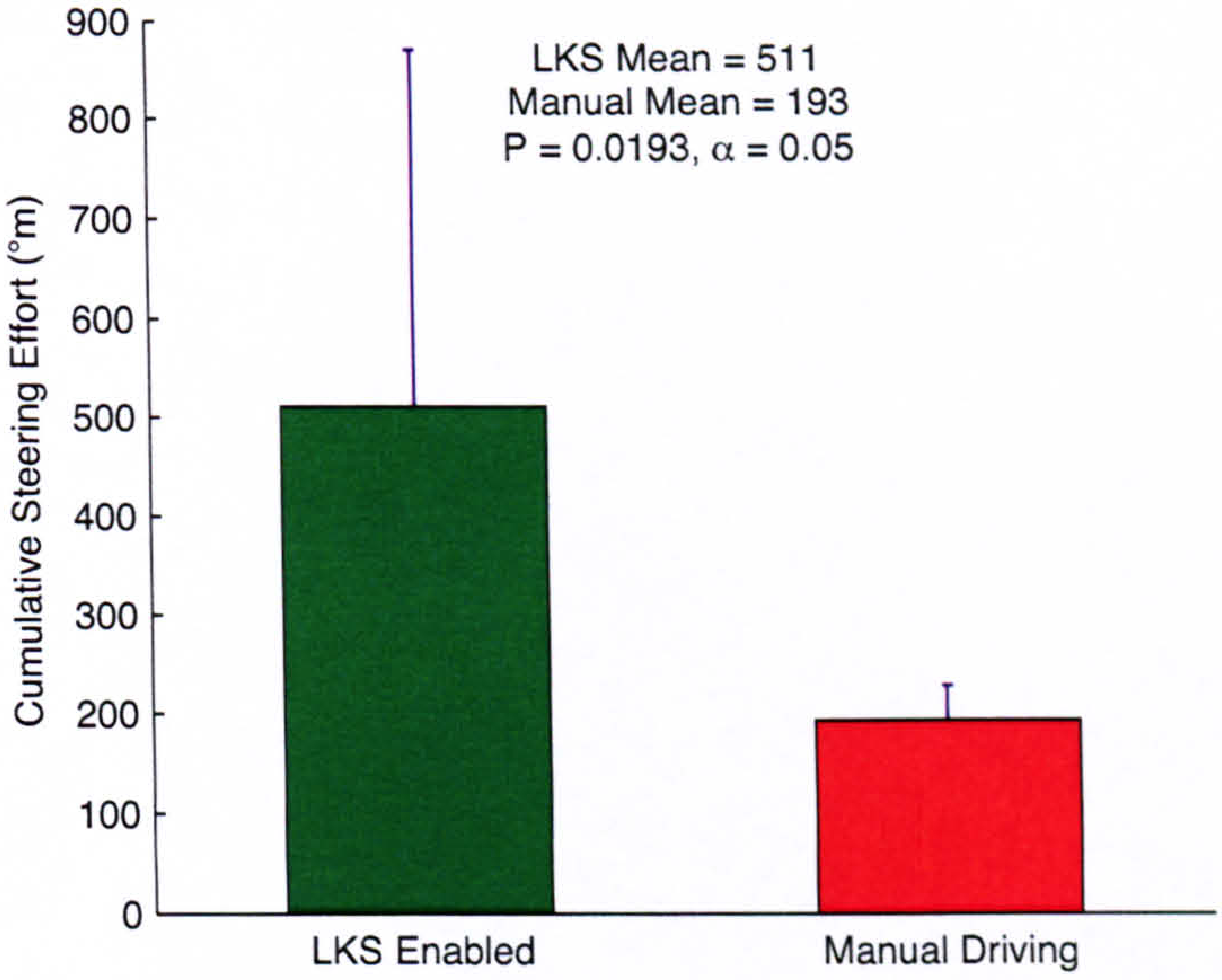


Figure 6.14: Cumulative steering effort data for narrow lanes scenario

is designed to reduce the steering effort required by the driver, upon failure the steer input required is much larger than that experienced under manual driving.

It should be noted that the drivers display a high degree of trust in the LKS, as none of them chose to disable the system before the event.

Lane Drop

The lane drop scenario was developed to see how the driver would react to a road works event for which the LKS would not become unavailable; instead it would continue to keep to the lane until the driver disabled it.

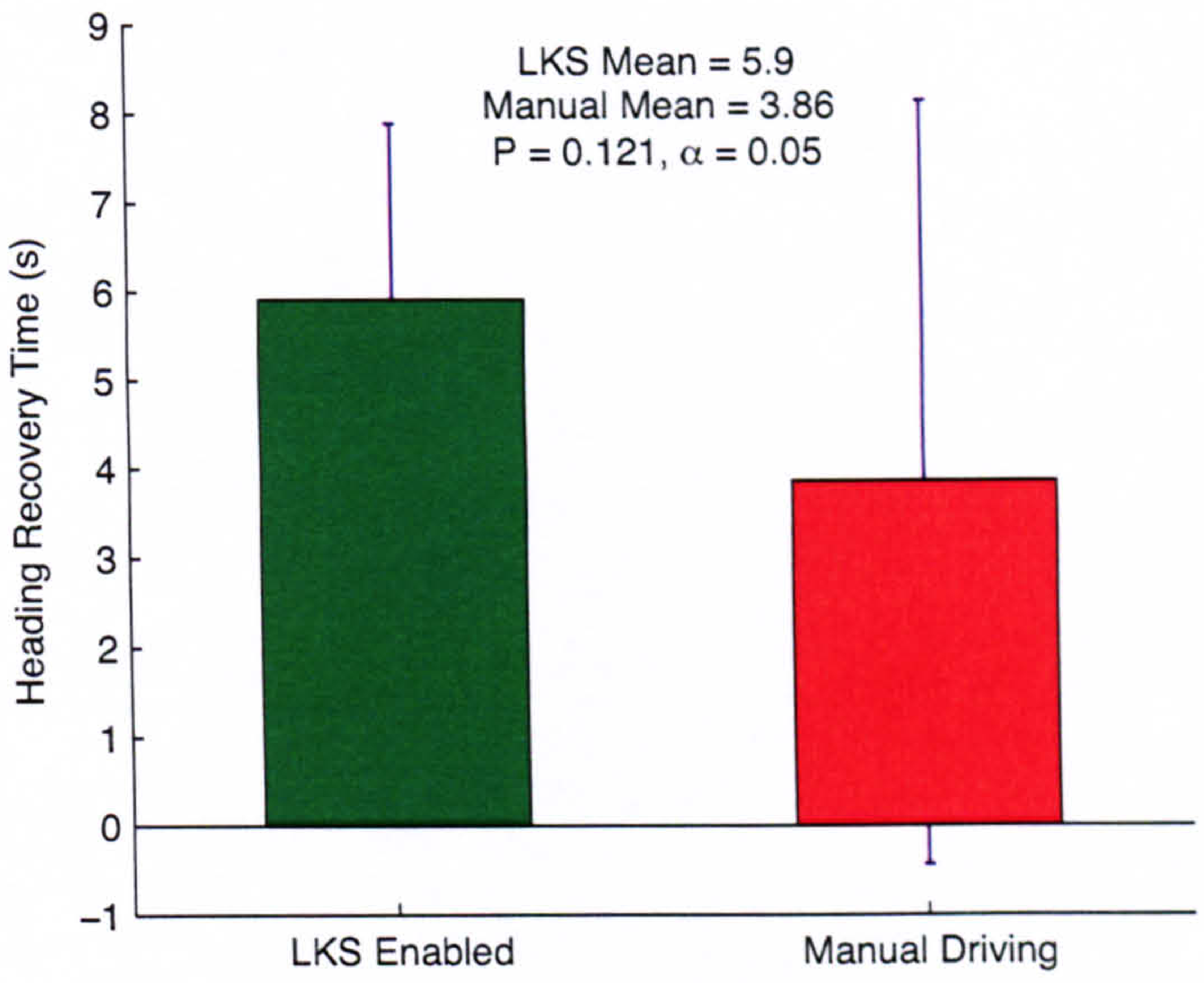


Figure 6.15: Heading recovery time data for lane drop scenario

The mean HRT is shown in Figure 6.15. In this situation HRT was the measure of time taken to regain heading once the subject vehicle had entered the desired lane. As changing lane caused an obvious variation in heading from that of the road this is again a valid measure for both controlled and uncontrolled driving. The increased deviation in heading meant that HRT values were increased from those noticed in the narrow lanes scenario. It can also be seen that in the lane drop event the driver took longer to recover the heading of the vehicle once into the correct lane, when LKS was enabled. This could be due to a number of factors. Sometimes drivers forgot to disable the system before applying the necessary steering input. Once drivers had disabled the system the steering input was too large, and the desired lane was overshot. In other cases, the driver was merely not used to the steering level that was required to change lane. It should be noted that these results were less significant than the narrow lanes scenario. In some cases the driver struggled with the event even in manual driving - hence the high variance shown in both conditions.

While the lane drop scenario was a lateral control event, it is also interesting to look at the impact of it on driver's control of the vehicle. BRT shown in Figure 6.16 suggests that when assisted, the driver took longer to brake for this scenario. This opposes the trend

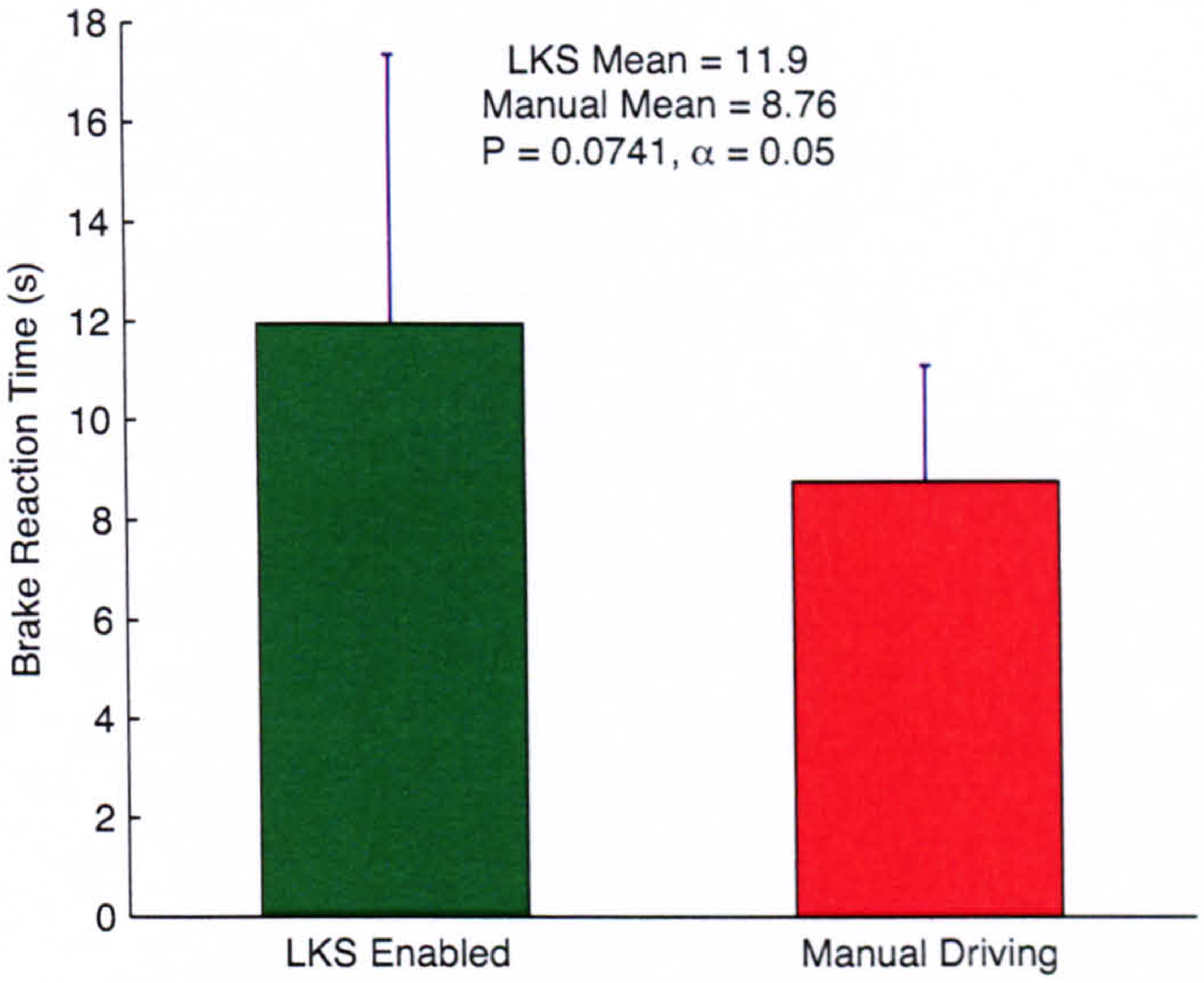


Figure 6.16: Brake response time data for lane drop scenario

that drivers reported, in stating the systems made them more aware of other aspects of driving. It may also suggest that the drivers did not fully understand the capabilities of the system, and thought that it may change lane for them.

6.2.3 Subjective Evaluation

Subjective evaluation of the results was conducted using short questionnaires, completed by every driver after driving with each ADAS. While there was only a small sample size of participants, it was still possible to find some interesting trends in subjects' responses. For each question the driver was asked to compare their experience with the ADAS to manual driving in the simulator. The results are shown as means from all participants on a bar chart, where the magenta bar corresponds to the ACC and cyan bar the LKS. The error bars display the standard deviation of the results from the given mean.

Acceptability

Figure 6.17 displays the mean usefulness and satisfaction perceived by the subjects, when using ACC or LKS. This is assessed using the Van Der Laan et al. (1997) method discussed in Section 6.1.4. The fact that all four bars are positive is promising. Drivers were more accepting of the ACC than the LKS; yet the LKS was still accepted by most of the drivers. The high variance in the results may be due to the small sample size and also the large range of experiences and scenarios that drivers were subject to during the study.

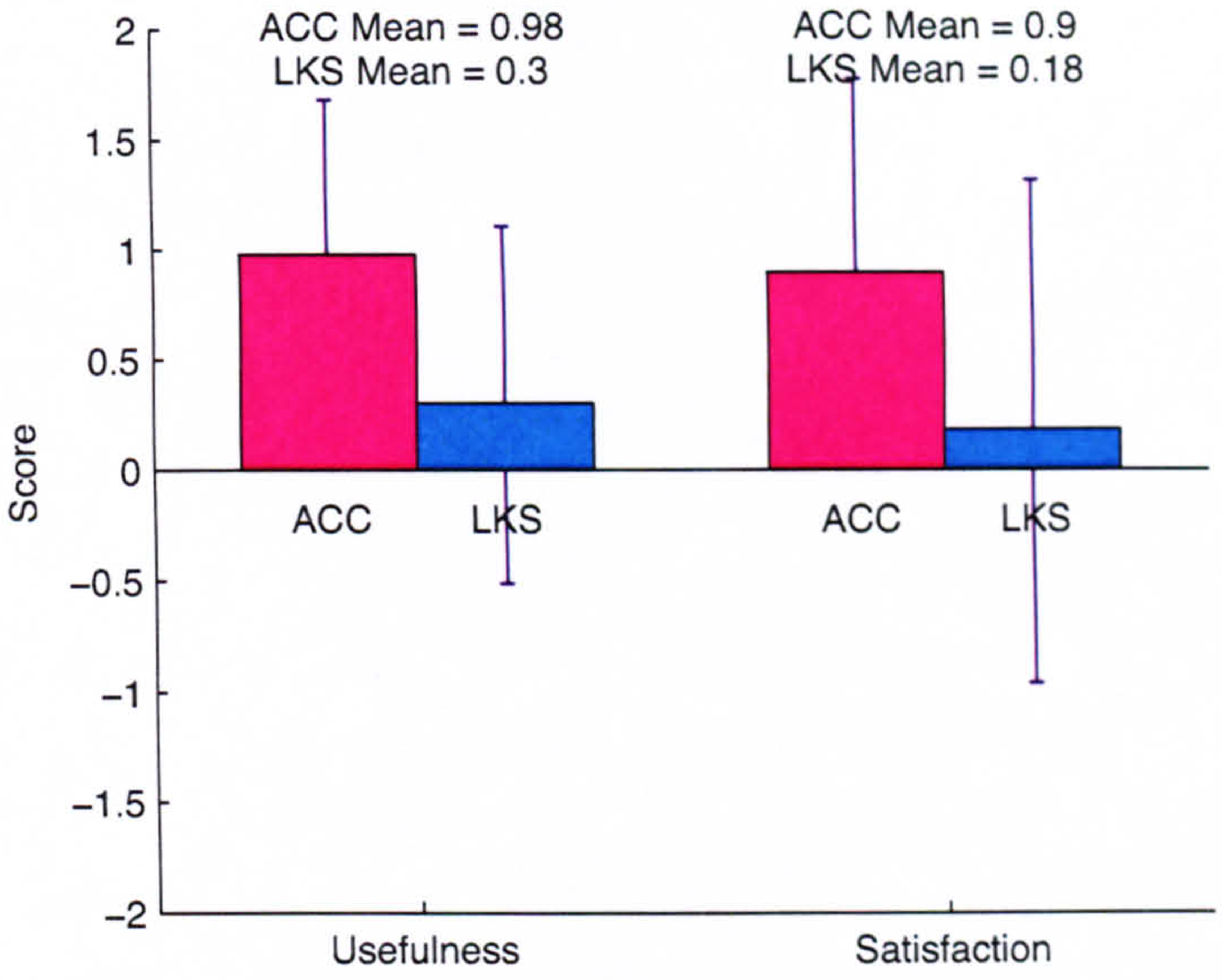


Figure 6.17: Acceptability of ADAS

Drivers also seemed to find both systems satisfying (again both results are positive). These results were similar to the usefulness score, although the means of each were slightly lower than the usefulness case, and the variance was slightly higher.

Concentration

One interesting trend shown in the questionnaire responses was a perceived increased level of attention to other aspects of driving when using the LKS system (Figure 6.18). While this value was not highly significant (still close to zero) it was more positive than that noticed for the same question about ACC. This was especially surprising given the driver's increased reaction time noticed in the lane drop event.

Drivers also reported an increased anticipation of potential conflicts when using both systems (Figure 6.18). In this case the ACC scored higher than the LKS. While this opposes the trend shown in the previous question, it may substantiate some of the positive results seen in the objective ACC results. While the variance of these anticipation results are high, the magnitude of the means is enough to suggest some validity in the trends.

Experience

To assess the driver's experience of the ADAS, they were asked to compare both the level of comfort and enjoyment perceived when using the system compared to manual driving.

The results shown in Figure 6.19 illustrate a perceived increase in comfort when using each system. This is more noticeable in the ACC system, but is still apparent with the

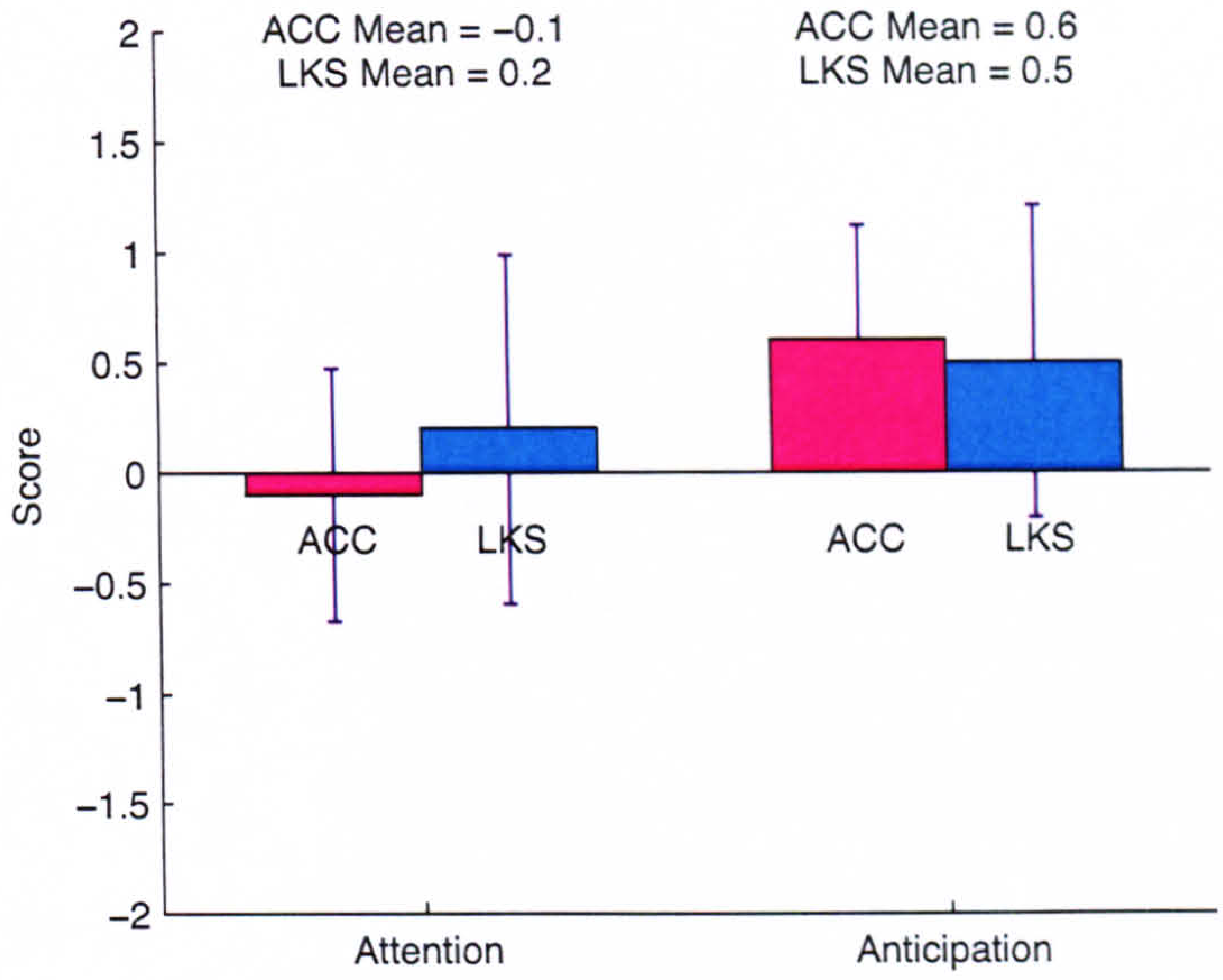


Figure 6.18: Perceived attention and anticipation levels with ADAS

LKS system, suggesting there is promise with both systems. As the ACC is currently marketed as a comfort device, it is arguable that it delivers on its main selling point.

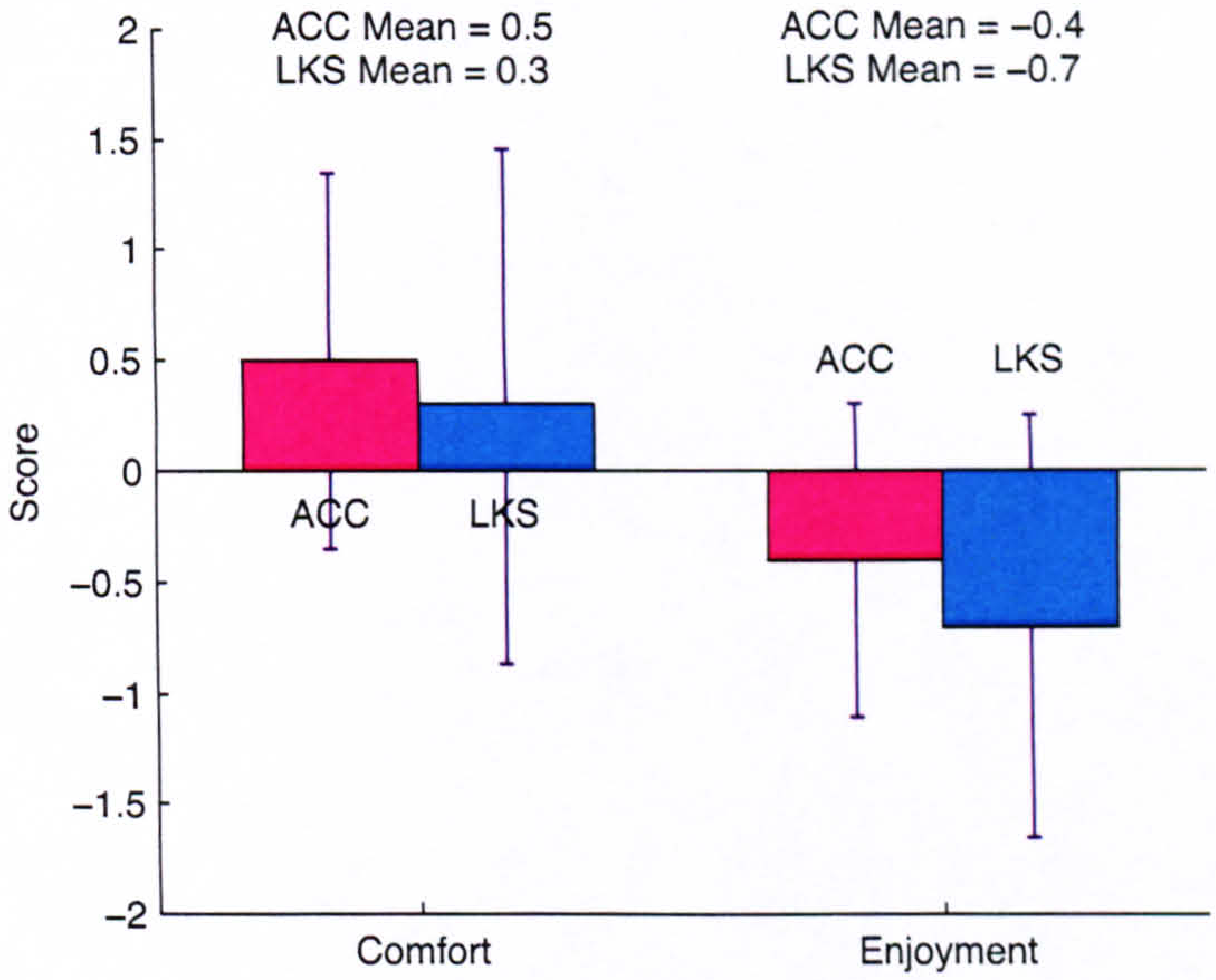


Figure 6.19: Perceived comfort and enjoyment levels with ADAS

While both systems generated an improved feeling of comfort in the drivers, they also seemed to remove some of the enjoyment from the driving experience. This is especially noticeable in the LKS, suggesting that the drivers believed that the enjoyment of driving was more linked to the lateral control task than the longitudinal.

6.2.4 Summary of Results

The simulator experiments conducted as part of this research have generated a lot of results and trends which are summarised in the list below:

- The ACC system actually slightly reduced the overall safety of the vehicle during lead vehicle deceleration events.
- However the same system improved the level of safety for the car cutting in event.
- When under ACC, drivers were able to react to a lead vehicle acceleration during cornering without compromising lane position.
- The LKS caused serious problems for the driver when it was disabled either through driver intervention or poor lane markings.
- The drivers were accepting of both systems.
- Drivers reported an increased level of anticipation of potential conflicts when using both systems.
- The experience of both systems improved the comfort of driving, but reduced the enjoyment.

In order to improve the design and use of ADAS the following suggestions are proposed as a direct result of this study:

- Driver training should be mandatory when the ACC is purchased to ensure the driver understands the capabilities and limitations of the systems; Although this may be difficult to implement.
- Additional methods are required to keep the driver in the loop when using an LKS, to reduce the unsafe large steer angles caused when disabling the system.

Chapter 7

Discussion and Conclusions

Chapter 7 summarises the findings of this research with reference to the new and novel ideas discovered. Recommendations for future work in the field are also discussed.

7.1 Work Covered

Advanced Driver Assistance Systems are generally marketed as a comfort aid, and could also help to reduce accidents caused by excessive speed or inadequate distance headway (Bosch 2004). This body of work has demonstrated successful longitudinal and lateral control systems and investigated their impact on both the vehicle dynamics and the driver.

7.1.1 Longitudinal Control

Off-line simulations have been conducted to develop human centred ADAS and investigate their effects on the vehicle dynamics. An Adaptive Cruise Control (ACC) system was developed at a detailed level and employed on a 9dof vehicle model with all necessary accelerations considered. The system was tested in a range of environmental conditions, as previous research had focused on the sensor's performance rather than the vehicle's. Results were positive, in that the system was capable of all deceleration manoeuvres in dry and wet conditions. In icy conditions the system displayed limited performance. This could be improved with the addition of an Antilock Braking System (ABS).

While ACC may improve the safety of the vehicle it is generally marketed as a comfort aid. With this in mind, tests were performed to monitor comfort levels when the system was subject to a deceleration outside its range of operation. While the headway of the system fell below the desired level, there were no adverse effects on the accelerations, that would be perceived by the driver (longitudinal and pitch). This suggests that the secondary ride of the vehicle and comfort levels of the occupants would be unaffected by a system of this type.

A concern was raised over the effects of the system when cornering. It was possible that a lead vehicle acceleration could cause the vehicle to veer away from the centreline of the lane, depending on the radius of curvature of the bend and the operational parameters of the ACC. Further testing was required using the driving simulator to investigate the driver's reaction to this phenomena (Section 7.1.3)

Once the core adaptive control algorithm was integrated with a conventional cruise control system it became clear that further tuning methods which had previously been avoided in the literature were required. The influence of the two control systems (speed and headway), were varied using a range switch (control bound) and the gains of both systems were tuned to ensure a driver centred response, where the accelerations transmitted to the driver were low, and the system maintained the desired level of headway performance. The following points of interest were noticed during this development, which should be considered in future development of similar ADAS.

- Depending on the powertrain and braking systems, the gains, and control bound selected, it is possible to cause an uncomfortable oscillatory acceleration; attempts should be made to tune this out of the system at the earliest opportunity.

- Care should be taken to ensure that the gains and control bound selected prevent the subject vehicle accelerating to 'catch up' with the leader upon entry of the control bound.

- Currently there are no guidelines on the rate of acceleration of the subject vehicle as the lead vehicle exits the control bound. Systems will therefore accelerate at their maximum limit until they attain the desired set speed. It is suggested that it could be an option for the driver to set a desired level of acceleration depending on their driving style (low value for increased comfort or high for quicker response).

7.1.2 Lateral Control

Although it has previously been under researched compared to longitudinal ADAS, lateral control of passenger vehicles is now receiving more research attention. With this lack of research in mind, a set of test scenarios have been developed to capture the full range of the lateral control tasks that the vehicle will be subject to during motorway driving, including, straight line operation, flat and banked cornering, lane changes (standard and evasive), split μ scenarios, and side winds. Parameters for these scenarios are included in the hope that future research will base lateral control appraisal on the same set of manoeuvres, to increase coherence throughout the field.

Two types of lateral control system have been developed, both showing interesting results. Firstly a simple 'look down' approach from Ackermann (1993) was extended with the addition of an internal model controller for improved yaw stability during severe manoeuvres. This showed acceptable results for low lateral acceleration events, which was impressive given the lack of future road information. The system remained stable for the full range of scenarios in dry conditions, although it was affected by poor weather conditions, and unable to perform high g evasive lane changes in wet and icy conditions. This was due to the vehicle's limits rather than those of the controller, but it is important that drivers are made aware of the systems capabilities. While the tracking results were impressive (low lateral errors), the system failed to consider the driver's steering control behaviour. Generally drivers base their lateral control on the upcoming road layout, rather than solely on their current position. To replicate this control action in a lateral control system, a second algorithm was employed based on the 'look ahead' technique described in Sharp et al. (2000). This system exceeded the performance of the 'look down' controller developed previously. While the tracking was not as accurate as the first system, the system was capable of a wider range of manoeuvres. The accelerations transmitted to the occupants were reduced suggesting a more comfortable experience, although further investigation was necessary to assess the direct impact of the system on the driver.

7.1.3 Driving Simulator Development and Experimentation

Both types of system were tested in isolation using the University of Leeds driving simulator. A range of simulation scenarios were developed which were aimed to investigate the driver's interaction with the systems in critical situations. These scenarios allowed repeatable measures of the subject driver's reactions to an event, both with the assistance system, and in unassisted driving. A range of objective measures and subjective questionnaires were used to assess the impact of these systems on the driver.

Objective Evaluation

For the ACC system, the Lead Vehicle Deceleration (LVD) and Car Cutting In (CCI) scenarios looked at the drivers reaction to lead vehicle braking. In the LVD, drivers were able to react more quickly to critical lead vehicle deceleration, and maintain a larger time to collision, without the assistance of the ACC system. While this may appear initially surprising (it may be expected that the ACC would provide a safer response), there are many factors which may result in this 'less safe' response. Firstly, the driver's trust in the system may mean that they expected the system to handle this deceleration. Secondly, although the driver reported an increased anticipation of potential conflicts, they may not concentrate on the lead vehicle's brake lights as much as during unassisted driving. Finally the setting of the danger warning may result in a system which performs closer to the limit than the unassisted driver would. These issues impact directly on the design of ACC systems. Without sufficient experience of the system, drivers will be unaware of its limits. Depending on the type of driver, the 'danger' state may never be entered. The driver may often intervene, reducing their trust in the system, and its usefulness, and therefore the driver's willingness to invest in the technology in future. Other drivers may expect more of the system, and may wait for the danger state before applying additional braking. Until this type of driver is used to the system, collisions may be more possible than unassisted driving, and the higher accelerations involved may reduce the comfort of driving. The system designer must take care when setting the conditions for the danger state. Adjustable settings may be possible for different driving styles. But this may cause problems as systems become more common, and drivers swap between vehicles with different settings. It is suggested that all drivers should undergo some simple training with the system before using it on the road, to understand the limits of the system and its operation.

The AIB event was set up to investigate the drivers reactions to the lead vehicle accelerations whilst cornering. Off-line simulations had shown that lane departure was possible unless the driver intervened with additional steering/braking. This event proved difficult to trigger given the number of conditions required for the phenomena to occur. But of the successful tests, all remained within the desired lane. The steering efforts involved actually seemed to fall with the ACC system, compared with unassisted driving. It can therefore be concluded that this issue does not compromise the safety of the vehicle.

The Lane Keeping System (LKS) was also investigated using the driving simulator. These tests were slightly different; as this was a relatively new type of system, we were more concerned with the fundamental performance of the LKS and the driver's opinions, rather than complex issues caused by other traffic. To assess how the driver performed in conjunction with LKS, two different types of roadwork scenarios were used where the driver was required to intervene. In the narrow lanes scenario the system becomes unavailable and the driver has to steer to maintain desired lane position. Even with the small sample size, statistically significant results proved that the driver takes longer to recover the heading, and deviates further from the centre line of the lane when equipped with LKS. Similar, if less significant results are noticed in the lane drop event, where the driver must manually disable the system before changing lane. These trends suggest that more effort must be made to keep the driver in the loop, so that they are aware of the level of steering input required in these types of event. While a system of this type will undergo much refinement before it is put to market, it is suggested that drivers undergo a limited amount of training to demonstrate the limits of such a system, and understand its operation.

Benefits of the system noted by drivers, were the relative smooth transition from assisted driving to the LKS system, and the use of the indicators to disable the system. That said, some drivers felt it would have been more natural to disable the system using the steering system alone. A minimum speed criteria may also be necessary for successful control as some drivers had problems using the system at low speeds.

Subjective Evaluation

Drivers responded well to both systems. The responses were monitored through a range of structured questions. Given the small sample size, few of the results were statistically significant, but trends in the responses were noticed. Drivers were generally accepting of both systems, the ACC system scored higher than the LKS, and both were slightly more useful than satisfying. These results are especially promising given the type of driving scenario that the drivers were subjected to during the experiment, with a much higher proportion of dangerous and evasive scenarios than would have been expected in normal motorway driving.

Drivers reported that the experience of driving with both systems was generally more comfortable than normal driving, while this was hoped to be the outcome for the ACC system, it may also mean that the LKS can be marketed as a comfort device, rather than a safety aid. The enjoyment of driving was reduced with both systems, when compared to normal driving, suggesting that the control tasks involved in unassisted driving generate a level of enjoyment, which is reduced as they are taken away from the driver. This is more evident with the LKS which may suggest that this enjoyment is linked more to the steering operation rather than throttle/brake control.

7.2 Conclusions

- Through the use of an advanced vehicle model, the effects of ADAS on the vehicle dynamic performance have been fully captured, improving the understanding of the systems.
- The vehicle's performance under longitudinal and lateral control is not adversely affected in wet conditions. ACC performance is compromised in icy conditions. Lateral control systems are capable of good performance in icy conditions, although this performance deteriorates for more severe evasive manoeuvres.
- The impact of the systems on the levels of driver comfort have been assessed. Drivers have reported an improved level of comfort when driving with both systems, thanks to low translational and rotational accelerations attained through driver centred tuning of the systems.
- A range of lateral control motorway test events have been developed which can be used in future investigations to assess the comparative performance of other full lateral control systems.
- Objective results from the simulator studies have shown little or no significant safety benefit from ACC in evasive scenarios where driver intervention is required.
- Drivers took much longer to regain desired lane position and control of the vehicle when driving with the LKS in the two safety critical LKS simulator scenarios.
- Driving simulator studies have shown drivers acceptance of both ACC And LKS systems, even when used in a mixture of standard and evasive scenarios.

7.3 Future Work

While research into ACC has been fairly extensive, further work is recommended to address issues discovered in this body of work, that that may reduce the comfort levels experienced with the system, and compromise the safety of its operation:

- Investigation into the use of the system in conjunction with ABS and other assistance systems.
- There are further questions over the interaction of the driver with the system, should they be allowed to set the desired level of acceleration, or will this additional control lessen their understanding of the system?

- A short driving training exercise should be developed to ensure driver's understand the limits and operation of the system before use on the open road.

Lateral control systems are still in a relative infancy with many aspects of the development still undecided or uninvestigated. The main issues revealed by this study that require further work are:

- Methods to ensure the driver is kept in the loop, ensuring a simple transition from assisted to unassisted driving if the system should fail.
- Use of the steering system to disable the controller. A torque threshold or other condition needs to be developed to allow the driver to disable the system without additional thought processing, this should allow quick and safe switching of control when necessary.

References

Abou-Jaoude, R. (2003). ACC Radar Sensor Technology, Test Requirements, and Test Solutions. *IEEE Transactions on Intelligent Transportation Systems*, 4(3):115 – 122.

Ackermann, J. (1993). *Robust Control - Systems with Uncertain Physical Parameters*. Springer-Verlag.

Auckland, R. A., Manning, W. J., and Carsten, O. M. J. (2006). Dynamic Analysis of Lateral Control Systems. In *Proceedings of AVEC '06: The 8th International Symposium on Advanced Vehicle Control*, pages 747 – 752.

Auckland, R. A., Manning, W. J., Carsten, O. M. J., and Jamson, A. H. (2008). Advanced driver assistance systems: Objective and subjective performance evaluation. *Vehicle System Dynamics*, 46(1 supp 1):883 – 897.

Auckland, R. A., Manning, W. J., Carsten, O. M. J., Levesley, M. C., and Crolla, D. A. (2005). Dynamic Performance of Adaptive Cruise Control Vehicles. *SAE 2005 World Congress*.

Audi (2008). Glossary - Adaptive Cruise Control. Available from: `http://www.audi.com/audi/com/en2/tools/glossary/operation_comfort/adaptive_cruise_control.html` [cited 2008].

Bareket, Z., Fancher, P., Peng, H., Kangwon, L., and Assaf, C. A. (2003). Methodology for Assessing Adaptive Cruise Control Behavior. *IEEE Transactions on Intelligent Transportation Systems*, 4(3):123 – 131.

Beji, L. and Bestaoui, Y. (2001). An Adaptive Method of Automated Vehicles with Integrated Longitudinal and Lateral Dynamics in Road Following. *Second Workshop on Robot Motion and Control*, pages 201 – 206.

Bernard, J. E. and Clover, C. L. (1995). Tire Modeling for Low-Speed and High Speed Applications. *SAE Transactions*, 104(6):474–483.

Bertozzi, M., Broggi, A., and Fascioli, A. (2000). Vision-based intelligent vehicles: State of the art and perspectives. *Robotics and Autonomous Systems*, 32(1):1–16.

Bosch, R. (2004). *Bosch Automotive Handbook.* Robert Bosch GmbH, 6 edition.

Chan, C. Y., Bougler, B., Nelson, D., Kretz, P., Tan, H.-S., and Zhang, W.-B. (2000). Characterization of Magnetic Tape and Magnetic Markers as a Position Sensing System for Vehicle Guidance and Control. In *Proceedings of the 2000 American Control Conference*, volume 1, pages 95 – 99.

Chee, W. and Tomizuka, M. (1994). Vehicle Lane Change Maneuver in Automated Highway Systems. Technical Report UCB-ITS-PRR-94-22, California PATH.

Chen, C. and Tan, H.-S. (1998). Steering Control of High Speed Vehicles: Dynamic Look Ahead and Yaw Rate Feedback. In *Proceedings of the 37th IEEE Conference on Decision and Control*, volume 1, pages 1025 – 1030.

Cheng, B., Hashimoto, M., and Suetomi, T. (2002). Analysis of Driver Response to Collision Warning during Car Following. *JSAE Review*, 23(2):231 – 237.

Citroën (2008). Citroën UK Technology - Safety - LDWS. Available from: `http://www.citroen.co.uk/technology/safety/ldws/` [cited 2008].

Darbha, S. and Rajagopal, K. R. (1999). Intelligent Cruise Control Systems and Traffic Flow Stability. *Transportation Research Part C: Emerging Technologies*, 7:329 – 352.

Delphi (2003). Delphi Forewarn Adaptive Cruise Control with Driver Alert -Specification Sheet.

Dugoff, H. and Brown, B. J. (1970). Measurement of Tire Shear Forces. *SAE Transactions.*

Fancher, P., Bareket, Z., and Ervin, R. (2000). Human-Centered Design of an ACC-with-Braking and Forward-Crash-Warning System. In *Proceedings of the 5th International Symposium on Advanced Vehicle Control.*

Fancher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., and Haugen, J. (1998). Intelligent Cruise Control Field Operational Test. Technical report, The University of Michigan Transportation Research Institute, Ann Arbor, Michigan 48109-2150 USA.

Francis, B. A. and Wonham, W. M. (1976). The Internal Model Principle of Control Theory. *Automatica*, 12(5):457–465.

Furukawa, Y., Abe, M., and Wang, B. (2002). Possibility of a Driver-Assist-System during Evasive Lane Change. In *Proceedings of the 6th International Symposium on Advanced Vehicle Control.*

Genta, G. (1997). *Motor Vehicle Dynamics: Modeling and Simulation.* World Scientific.

Gern, A., Franke, U., and Levi, P. (2000). Advanced Lane Recognition-Fusing Vision and Radar. In *Proceedings of the IEEE Intelligent Vehicles Symposium*, pages 45–51.

Gietelink, O., De Schutter, B., and Verhaegen, M. (2006). Adaptive Importance Sampling for Probabilistic Validation of Advanced Driver Assistance Systems. In *American Control Conference*, page 6.

Griffin, M. J. (2007). Discomfort from Feeling Vehicle Vibration. *Vehicle System Dynamics*, 45(7):679–698.

Groen, E. L. and Bles, W. (2004). How to Use Body Tilt for the Simulation of Linear Self Motion. *Journal of Vestibular Research*, 14(5):375–385.

Guldner, J., Tan, H.-S., and Patwardhan, S. (1997). Study of Design Directions for Lateral Vehicle Control. In *IEEE Conference on Decision and Control*, volume 5, pages 4732 – 4737.

Guldner, J., Utkin, V., and Ackermann, J. (1994). A Sliding Mode Control Approach to Automatic Car Steering. In *Proceedings of the 1994 American Control Conference*, volume 2, pages 1969 – 1973.

Guvenc, B. and Guvenc, L. (2002). Robust Two Degree-of-Freedom Add-on Controller Design for Automatic Steering. *IEEE Transactions on Control Systems Technology*, 10(1):137–148.

Hatipoglu, C., Ozguner, U., and Redmill, K. (2003). Automated Lane Change Controller Design. *IEEE Transactions on Intelligent Transportation Systems*, 4(1):13 – 22.

Hernandez, J. I. and Kuo, C.-Y. (2003). Steering Control of Automated Vehicles Using Absolute Positioning Gps and Magnetic Markers. *IEEE Transactions on Vehicular Technology*, 52(1):150 – 161.

Hernandez, J. I. and Kuo, C. Y. (2004). Lateral Control of Higher Order Nonlinear Vehicle Model in Emergency Maneuvers Using Absolute Positioning Gps and Magnetic Markers. *IEEE Transactions on Vehicular Technology*, 53(2):372 – 384.

Heydinger, G. J., Salaani, M. K., Garrott, W. R., and Grygier, P. A. (2002). Vehicle Dynamics Modelling for the National Advanced Driving Simulator. In *Proceedings of the IMechE Part D Journal of Automobile Engineering*, volume 216.

Highways-Agency (1993). *Design Manual for Roads and Bridges*, volume 6.

Hoedemaeker, M. (2000). Driving Behaviour with Acc and the Acceptance by Individual Drivers. *IEEE Transactions on Intelligent Transportation Systems*, pages 506 – 509.

Hoedemaeker, M. and Brookhuis, K. A. (1998). Behavioural Adaptation to Driving with an Adaptive Cruise Control (ACC). *Transportation Research Part F: Traffic Psychology and Behaviour*, 1(2):95–106.

Hong, S. J., Choi, J. Y., Jeong, Y. I., Jeong, K. Y., Lee, M. H., Park, K. T., Yoon, K. S., and Hur, N. S. (2001). Lateral Control of Autonomous Vehicle by Yaw Rate Feedback. *IEEE International Symposium on Industrial Electronics, 2001*, 3:1472 – 1476.

Iijima, T., Higashimata, A., Tange, S., Mizoguchi, K., Kamiyama, H., Iwasaki, K., and Egawa, K. (2000). Development of an Adaptive Cruise Control System with Brake Actuation. *SAE 2000 World Congress - Journal of Passenger Car - Electronic and Electrical Systems*.

Ioannou, P., Xu, Z., Eckert, S., Clemons, D., and Sieja, T. (1993). Intelligent Cruise Control: Theory and Experiment. In *IEEE Conference on Decision and Control*, volume 2, pages 1885 – 1890.

Ishida, S. and Gayko, J. (2004). Development, Evaluation and Introduction of a Lane Keeping Assistance System. In *Proceedings of the IEEE Intelligent Vehicles Symposium*, pages 943–944.

ISO/FDIS (2002). Transport Information and Control Systems - Adaptive Cruise Control Systems - Performance Requirements and Test Procedures. Technical report, International Standards Organisation, Geneva.

Jamson, A. H., Horrobin, A. J., and Auckland, R. A. (2007). Whatever Happened to the Lads? Design and Development of the New University of Leeds Driving Simulator. In *Driving Simulator Conference*.

Kanaris, A., Kosmatopoulos, E., and Loannou, P. (2001). Strategies and Spacing Requirements for Lane Changing and Merging in Automated Highway Systems. *IEEE Transactions on Vehicular Technology*, 50(6):1568 – 1581.

Kelley, C. (2003). *Solving Nonlinear Equations with Newton's Method*. SIAM.

Kesting, A., Treiber, M., Schönhof, M., and Helbing, D. (2007). Extending Adaptive Cruise Control to Adaptive Driving Strategies. *Transportation Research Record*, 2000(1):16–24.

Khatun, P., Bingham, C., Schofield, N., and Mellor, P. (2002). An Experimental Laboratory Bench Setup to Study Electric Vehicle Antilock Braking/Traction Systems and Their Control. *IEEE Transactions on Vehicular Technology*, 3:1490–1494 vol.3.

Kosecka, J., Blasi, R., Taylor, C., and Malik, J. (1998). A Comparative Study of Vision-Based Lateral Control Strategies for Autonomous Highway Driving. In *IEEE International Conference on Robotics and Automation*, volume 3, pages 1903 – 1908.

Lee, J. and Moray, N. (1992). Trust, Control Strategies and Allocation of Function in Human-Machine Systems. *Ergonomics*, 35(10):1243–1270.

Leelavansuk, P., Shitamitsu, K., Mouri, H., and Nagai, M. (2002). Study on Cooperative Control of Driver and Lane-Keeping Assistance System. In *Proceedings of the 6th International Symposium on Advanced Vehicle Control.*

Liang, C.-Y. and Peng, H. (2000). String Stability Analysis of Adaptive Cruise Controlled Vehicles. *JSME international journal. Series C, Mechanical systems, machine elements and manufacturing*, 43(1):611–761.

Lin, C.-F. and Ulsoy, A. (1995). Calculation of the Time to Lane Crossing and Analysis of Its Frequency Distribution. In *Proceedings of the 1995 American Control Conference*, volume 5, pages 3571–3575.

Liu, A. and Pentland, A. (1997). Towards Real-Time Recognition of Driver Intentions. In *IEEE Conference on Intelligent Transportation System*, pages 236 – 241.

Lu, X., Hendrick, J. K., and M, D. (2002). ACC/CACC - Control Design, Stability and Robust Performance. In *Proceedings of the 2000 American Control Conference*, pages 4327 – 4332.

Macadam, C. (2003). Understanding and Modeling the Human Driver. *Vehicle System Dynamics*, 40(1):101–134.

MacAdam, C. C. (1981). Application of an Optimal Preview Control for Simulation of Closed-Loop Automobile Driving. *IEEE Transactions on Systems, Man and Cybernetics*, 11(6):393–399.

Martinez, J. and Canudas-de-Wit, C. (2007). A Safe Longitudinal Control for Adaptive Cruise Control and Stop-and-Go Scenarios. *IEEE Transactions on Control Systems Technology*, 15(2):246.

Maurel, D., Parent, M., and Donikian, S. (1999). Influence of Acc in Stop&Go Mode on Traffic Flow. *Future Transportation Technology Conference and Exposition*, pages 1999–01–2887.

Mechanical-Simulation (2006). *Carsim Reference Manual*. Mechanical-Simulation, 6.03 edition.

Michon, J. A. (1993). *GIDS Architecture*, pages 147 – 159. Taylor and Francis.

Mourant, R. R. and Thattacherry, T. R. (2000). Simulator Sickness in a Virtual Environments Driving Simulator. In *IEA 2000/HFES 2000: XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society*, pages 534–537.

Muir, B. M. (1989). *Operators' Trust in and Percentage of Time Spent Using the Automatic Controllers in a Supervisory Process Control Task*. PhD thesis, University of Toronto.

Nagiri, S., Amano, Y., Fukui, K., and Doi, S. (2004). Driver Behavior and Active Safety: A Study of Personally Adaptive Driving Support System Using a Driving Simulator. *R&D Review of Toyota CRDL*, 39(2):24–33.

Newton, A. P. and Best, M. C. (2006). The Influence of Motion on Handling Dynamics Analysis in Full Vehicle Simulators. In *Proceedings of the 8th International Symposium on Advanced Vehicle Control*, pages 303–308.

Pacejka, H. B. (2002). *Tyres and Vehicle Dynamics*. Oxford, Butterworth-Heinemann.

Pacejka, H. B. and Besselink, I. J. M. (1997). Magic Formula Tyre Model with Transient Properties. *Vehicle System Dynamics*, 27(S1):234 – 249.

Persson, M., Botling, F., Hesslow, E., and Johansson, R. (1999). Stop and Go Controller for Adaptive Cruise Control. In *Proceedings of the 1999 IEEE International Conference on Control Applications*, volume 2.

Plöchl, M. and Edelmann, J. (2007). Driver models in automobile dynamics application. *Vehicle System Dynamics*, 45(7-8):699–741.

Polychronopoulos, A., Möhler, N., Ghosh, S., and Beutner, A. (2005). System design of a situation adaptive lane keeping support system, the SAFELANE system. *AMAA Handbook.*

Prestl, W., Sauer, T., Steinle, J., and Tschernoster, O. (2000). The BMW Active Cruise Control ACC. *SAE 2000 World Congress - Journal of Passenger Car - Electronic and Electrical Systems.*

Prohaska, R. and Devlin, P. (1998). Combined Brake and Steering Actuator for Automatic Vehicle Control. Technical report, California PATH, 1357 S.46th Street, Bldg. 452 Richmond, CA 94804-4648.

Rajamani, R., Tan, H.-S., Law, B. K., and Zhang, W.-B. (2000). Demonstration of Integrated Longitudinal and Lateral Control for the Operation of Automated Vehicles in Platoons. *IEEE Transactions on Control Systems Technology*, 8(4):695 – 708.

Redmill, K., Upadhya, S., Krishnamurthy, A., and Ozguner, U. (2001). A Lane Tracking System for Intelligent Vehicle Applications. *IEEE Transactions on Intelligent Transportation Systems*, pages 273–279.

Reid, D. and Drewell, N. (1972). A Pilot Model for Tracking with Preview. In *Proceedings of the Eighth Annual Conference on Manual Control.*

Reymond, G., Heidet, A., Canry, M., and Kemeny, A. (2000). Validation of Renault's Dynamic Simulator for Adaptative Cruise Control Experiments. In *DSC2000 Driving Simulation Conference*, pages 181 – 191.

Richardson, M., Corrigan, D., King, P., Smith, I., Barber, P., and Burnham, K. (2000). Application of Control System Simulation in the Automotive Industry. *IEE Seminar on Tools for Simulation and Modelling*, pages 8/1 – 8/13.

Rohling, H., Meinecke, M., Mott, M., and Urs, L. (2001). Research Activities in Automotive Radar. In *The Fourth International Kharkov Symposium on Physics and Engineering of Millimeter and Sub-Millimeter Waves*, volume 1, pages 48 – 51.

Rudin-Brown, C. M. and Parker, H. A. (2004). Behavioural Adaptation to Adaptive Cruise Control (Acc): Implications for Preventive Strategies. *Transportation Research Part F: Traffic Psychology and Behaviour*, 7(2):59–76.

Russell, M., Crain, A., Curran, A., Campbell, R., Drubin, C., and Miccioli, W. (1997). Millimeter-Wave Radar Sensor for Automotive Intelligent Cruise Control (ICC). *IEEE Transactions on Intelligent Transportation Systems*, 45(12):2444 – 2453.

SAE (1976). *Vehicle Dynamics Terminology.*

Sakai, S. and Hori, Y. (2000). Advanced Vehicle Motion Control of Electric Vehicle Based on the Fast Motor Torque Response. In *Proceedings of the 5th International Symposium on Advanced Vehicle Control.*

Salvucci, D. D. and Liu, A. (2002). The Time Course of a Lane Change: Driver Control and Eye-Movement Behavior. *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(2):123 – 132.

Sebastian, R., Kaufmann, T., Bolourchi, F., and Tan, H.-S. (1997). Design of an Automated Highway Systems Steering Actuator Control System. In *IEEE Conference on Intelligent Transportation System*, pages 254 – 259.

Sharp, R. S., Casanova, D., and Symonds, P. (2000). A Mathematical Model for Driver Steering Control, with Design, Tuning and Performance Results. *Vehicle System Dynamics*, 33(5):289–326.

Stanton, N. and Young, M. (2005). Driver Behaviour with Adaptive Cruise Control. *Ergonomics*, 48(10):1294–1313.

Szostak, H. T., Allen, W. R., and Rosenthal, T. J. (1988). Analytical Modeling of Driver Response in Crash Avoidance Maneuvering Volume II: An Interactive Model for Driver/Vehicle Simulation. Technical report, U.S Department of Transportation.

Takahashi, A. and Asanuma, N. (2000). Introduction of Honda ASV2 (Advanced Safety Vehicle-Phase 2). In *Proceedings of the IEEE Intelligent Vehicles Symposium*, pages 694–701.

Tanigawa, K., Masuda, J., Nakamura, K., and Hayashi, K. (1984). Cruise Control System for Automotive Vehicle. United States Patent.

Ungoren, A. and Peng, H. (2005). An Adaptive Lateral Preview Driver Model. *Vehicle System Dynamics*, 43(4):245–259.

Vahidi, A. and Eskandarian, A. (2003). Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control. *IEEE Transactions on Intelligent Transportation Systems*, 4(3):143 – 153.

Vakil, S. and Hansman-Jr, R. (2002). Approaches to Mitigating Complexity-Driven Issues in Commercial Autoflight Systems. *Reliability Engineering and System Safety*, 75(2):133–145.

Van Der Laan, J. D., Heino, A., and De Waard, D. (1997). A Simple Procedure for the Assessment of Acceptance of Advanced Transport Telematics. *Transportation Research Part C: Emerging Technologies*, 5(1):1–10.

Visteon (2004). Driver Awareness - Adaptive Cruise Control. Available from: `http://www.visteon.com/technology/automotive/media/adaptive_cruise_spec.htm` [cited 2004].

Wegner, J. (1998). Automotive Mm-Wave Radar: Status and Trends in System Design and Technology. In *Proceedings Inst. Elect. Eng. Colloquium Automotive Radar and Navigation Techniques*, pages 1 – 7.

Weinberger, M., Winner, H., and Bubb, H. (2000). Adaptive Cruise Control Long-Term Field Operational Test. In *Proceedings of the 5th International Symposium on Advanced Vehicle Control.*

Yuhara, N. and Tajima, J. (2000). Advanced Steering System Adaptable to Lateral Control Task and Driver's Intention. In *Proceedings of the 5th International Symposium on Advanced Vehicle Control.*

Zheng, P. and McDonald, M. (2005). Manual Vs. Adaptive Cruise Control - Can Driver's Expectation be Matched? *Transportation Research Part C: Emerging Technologies*, 13(5-6):421–431.

Zhou, J. and Peng, H. (2005). Range Policy of Adaptive Cruise Control Vehicles for Improved Flow Stability and String Stability. *IEEE Transactions on Intelligent Transportation Systems*, 6(2):229–237.

Zwaneweld, P., Van Arem, B., Bastianensen, E., Soeteman, J., Fremont, G., and Belarbi, F. (1999). Development Scenarios for Advanced Driver Assistance Systems. Technical report, TNO - Department of Traffic, 97 Schoemakerstraat 2628 VK Delft.

Appendix A

Modelling Parameters

A.1 Vehicle Parameters

```
mf   = 100;         %total front unsprung mass (kg)
mr   = 80;          %total rear unsprung mass (kg)
mb   = 1370;        %sprung vehicle mass (kg)
Izz  = 3038;        %vehicle yaw inertia (kgm2)
Ixx  = 388;         %vehicle roll inertia (kgm2)
Iyy  = 2620;        %vehicle pitch inertia (kgm2)
a    = 1.08871;     %distance from CG to front axle (m)
b    = 1.61129;     %distance from CG to rear axle (m)
tw   = 0.75;        %track width (m)
hcg  = 0.55;        %CG height (m)
hgr  = 0.285;       %height of ref roll axis above ground (m)
hgp  = 0;           %height of ref pitch axis above ground (m)
Bf   = 30000;       %front spring stiffness (N/m)
Cf   = 2750;        %front corner damping (Ns/m)
Cr   = 750;         %rear corner damping (Ns/m)
Bw   = 200000;      %front spring stiffness (N/m)
Baf  = 0;           %front ARB stiffness (N/m)
Bar  = 20053;       %rear ARB stiffness (N/m)
Rr   = 0.3;         %tyre rolling radius (m)
Iw   = 1.1;         %wheel inertia (kgm2)
Ls   = 1.6;         %dist from CG to look down sensor (m)
BF   = 0.714;       %front brake split
```

A.2 Look Ahead Control Parameters

```
dp = 30;        %look ahead distance
np = 7;         %number of look ahead points
K_0 = 2;        %look ahead initial gain
K_yaw = 0.5;    %look ahead yaw gain
```

A.3 Tyre Parameters

```
%% Pacejka tyre model
% Equations from Pacejka, H. B. and I. J. M. Besselink (1997).
% "Magic Formula Tyre Model with Transient Properties."
% Vehicle System Dynamics 27(Suppl): pp234-249.
% Parameter values from Pacejka, H. B. (2002).
% Tyres and Vehicle Dynamics. Oxford, Butterworth-Heinemann.
```

```
% parameter def
Ro = 0.313;   % m
Fzo = 4000;   % N
mo = 9.3;     % kg
Vo = 16.67;   % m/s

Pcx1 = 1.685;
Pdx1 = 1.210;
Pdx2 = -0.037;
Pex1 = 0.344;
Pex2 = 0.095;
Pex3 = -0.020;
Pex4 = 0;
Pkx1 = 21.51;
Pkx2 = -0.163;
Pkx3 = 0.245;
Phx1 = -0.002;
Phx2 = 0.002;
Pvx1 = 0;
Pvx2 = 0;

rbx1 = 12.35;

rbx2 = -10.77;
rcx1 = 1.092;
rhx1 = 0.007;

qsx1 = 0;
qsx2 = 0;
qsx3 = 0;

Pcy1 = 1.193;
Pdy1 = -0.990;
Pdy2 = 0.145;
Pdy3 = -11.23;
Pey1 = -1.003;
Pey2 = -0.537;
Pey3 = -0.083;
Pey4 = -4.787;
Pky1 = -14.95;
Pky2 = 2.130;
Pky3 = -0.028;
Phy1 = 0.003;
Phy2 = -0.001;
Phy3 = 0.075;

Pvy1 = 0.045;
Pvy2 = -0.024;
Pvy3 = -0.532;
Pvy4 = 0.039;

rby1 = 6.461;
rby2 = 4.196;
rby3 = -0.015;
rcy1 = 1.081;
rhy1 = 0.009;
rvy1 = 0.053;
rvy2 = -0.073;
rvy3 = 0.517;
rvy4 = 35.44;
rvy5 = 1.9;
rvy6 = -10.71;
qbz1 = 8.964;
qbz2 = -1.106;
qbz3 = -0.842;
qbz4 = -0.227;
qbz5 = 0;
qbz9 = 18.47;
```

```
qbz10 = 0;            qIaxz = 0.071;        qFcx1 = 0.1;
qcz1 = 1.180;         qIby = 0.696;         qFcy1 = 0.3;
qdz1 = 0.100;         qIbxz = 0.357;        qFcx2 = 0;
qdz2 = -0.001;        qIc = 0.055;          qFcy2 = 0;
qdz3 = 0.007;
qdz4 = 13.05;         qma = 0.237;          qV1 = 7.1e-5;
qdz6 = -0.008;        qmb = 0.763;          qV2 = 2.489;
qdz7 = 0.000;         qmc = 0.108;          qFz1 = 13.37;
qdz8 = -0.296;                              qFz2 = 14.35;
qdz9 = -0.009;        qcbx0z = 121.4;
qez1 = -1.609;        qcby = 40.05;         qsy1 = 0.01;
qez2 = -0.359;        qccx = 391.9;         qsy3 = 0;
qez3 = 0;             qccy = 62.7;          qsy4 = 0;
qez4 = 0.174;
qez5 = -0.896;        qkbxz = 0.228;        qa1 = 0.135;
qhz1 = 0.007;         qkby = 0.284;         qa2 = 0.035;
qhz2 = -0.002;        qkcx = 0.910;         qbvxz = 3.957;
qhz3 = 0.147;         qkcy = 0.910;         qbvT = 3.957;
qhz4 = 0.004;
                      qcbT0 = 61.96;        Breff = 9;
Ssz1 = 0.043;         qcbGP = 20.33;        Dreff = 0.23;
Ssz2 = 0.001;         qccP = 55.82;         Freff = 0.01;
Ssz3 = 0.731;         qkbT = 0.080;
Ssz4 = -0.238;        qkbGP = 0.038;
qIay = 0.109;         qkcP = 0.834;
```

Appendix B

Simulator Experiment Documentation

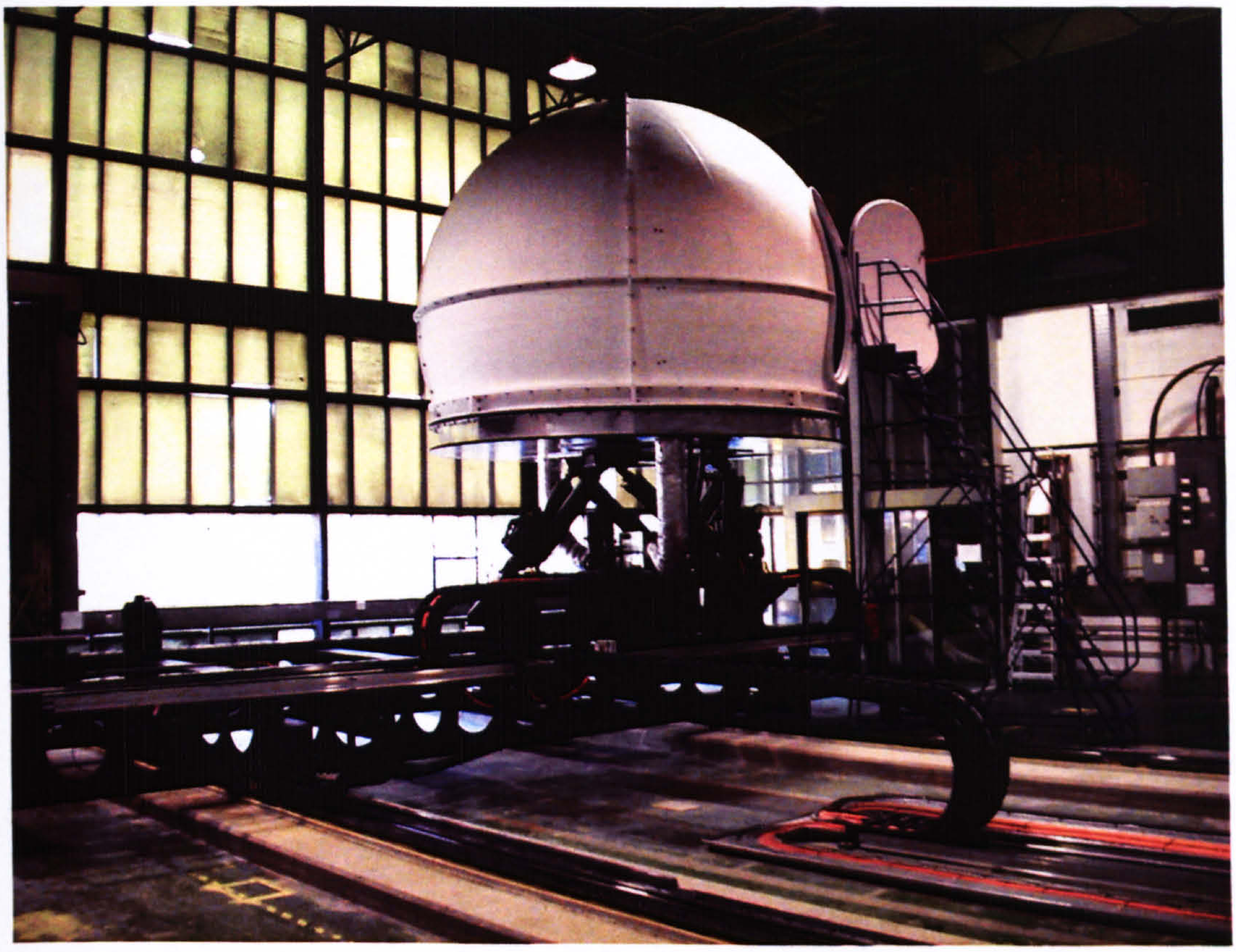
Participant Briefing (Easy Pilot)

Background

The study in which you have been invited to participate, seeks to investigate how drivers' behave when their vehicle is equipped with Advanced Driver Assistance Systems (ADAS). The project is funded by the EPSRC and will aid us in more fully understanding the interaction between the driver and these ADAS, helping to improve their design.

The Simulator

Today you will be driving in the Leeds Driving Simulator (LDS). The LDS offers us a controlled and safe environment in which to study driver behaviour. From the outside, the two major items that can be seen are the motion system and the large, white projection dome. Inside the dome is a Jaguar S-type vehicle cab. All the controls in the simulator work as expected and the instrument panel also operates displaying speed, engine revs and various warning lights.



As can be seen in the image, entry to the simulator dome is currently via some access steps from the lab area up to the dome door. You will be accompanied up the steps by the researcher and will enter the dome via the top platform. Please inform the researcher if you have any problems with the access steps or entering the dome. Please do not feel pressurised: if you do not want to enter the dome, then you are perfectly at liberty to withdraw from the study. The access steps are a temporary solution until our boarding platform is completed.

Practice drives

Before beginning the experimental drive, you will be accompanied on a practice drive by the researcher. The first session is designed to allow you to become familiar with driving the simulator and the ADAS. Only when you feel comfortable will you be asked to continue. Please feel free to ask any questions that you have.

The LDS now includes a large amplitude motion system. The motion system attempts to recreate the dynamic forces we feel as we drive a vehicle. Even with full motion, your first drive may feel a little odd, especially when accelerating, braking or negotiating a curve. However, don't worry, as this is true for everybody who drives the simulator for the first time. These "odd" feelings usually subside after a few minutes of driving.

Experience has shown us that new drivers tend to set off too quickly, making control of the car difficult. Please start slowly and gradually increase your speed during the drive. You may also have the impression that the steering is over-sensitive and tend to over-steer at first. To prevent this, our major form of feedback to drivers is through the normal "self-centring" felt at the steering wheel. Please use this to help keep the car straight. You may find that is easier to straighten the simulator after a curve by letting the steering wheel slip through you hands. Apply only small inputs to the steering wheel.

For a small percentage of people, the initial "odd" or "unsteady" feelings do not subside and they begin to feel a little unwell. This usually manifests itself in the form of a feeling of motion sickness. If you do feel unwell or nauseous, please do not be embarrassed to withdraw from the study. We would rather this than make you feel ill! Simply inform the researcher that are not feeling well and we will stop the simulation. The researcher will take you back to the briefing area.

The researcher will explain all of the driving controls of the Jaguar prior to your practice drive.

Study description

The study is investigating the interaction between the driver and the ADAS. We ask is that you drive the simulator as you would if it were a real vehicle. The scenario that we want to imagine yourself in is as though you are driving to a meeting during the morning peak traffic.

The researcher will remain with you in the vehicle during the study just in case of any problems. Please try as much as possible to ignore their presence. During the study there will be certain times when we require you to drive with the controller and certain time when we require you to switch it off and drive as you normally would. You will be informed of this at the relevant time by the researcher.

Ethics, safety and confidentiality

It is important that you understand that we are **not** looking at your individual driving style or judging your ability as a driver. We are solely interested in the behaviour of a group of drivers to draw conclusions about drivers in general.

As with all our research, this study is subject to the strict ethical guidelines of the British Psychological Society and the requirements of the Data Protection Act. In particular please note that:

- At no time now, nor in the future, will any information you provide be published that allows you as an individual to be identified.
- You are free to withdraw from the study at any time without having to give any reason for your decision.
- Video footage, which may include images of your face, may be used during the dissemination of this research project to the scientific community and research sponsors only. We will **not** make such footage available to other organisations, such as the broadcast media.

Prior knowledge

In order to achieve meaningful results from this study, it is **extremely** important to us that you have no prior knowledge of the study itself. If anyone, whom you know, has taken part in this study and has since discussed the details of study with you, please let the researcher know.

Other details

Should you need the toilets, they are located through the double doors along the corridor from the simulator offices. Please help yourself to the refreshments provided.

Contacts

If you have any questions on this research project please feel free to speak to Hamish Jamson at the University of Leeds (0113 343 5730).

Finally, thank you very much for expressing an interest in this work and we hope that you enjoy you time at the LDS. Your contribution towards the science of road safety is appreciated.

UNIVERSITY OF LEEDS
DRIVING SIMULATOR
INVESTIGATING DRIVER BEHAVIOUR IN A SAFE AND CONTROLLABLE RESEARCH ENVIRONMENT

ADAS Information Adaptive Cruise Control (ACC)

Advanced Driver Assistance Systems, or ADAS, are systems designed to help the driver in the driving process. When designed correctly they should remove some workload from the driver, making driving an easier experience and also improving safety.

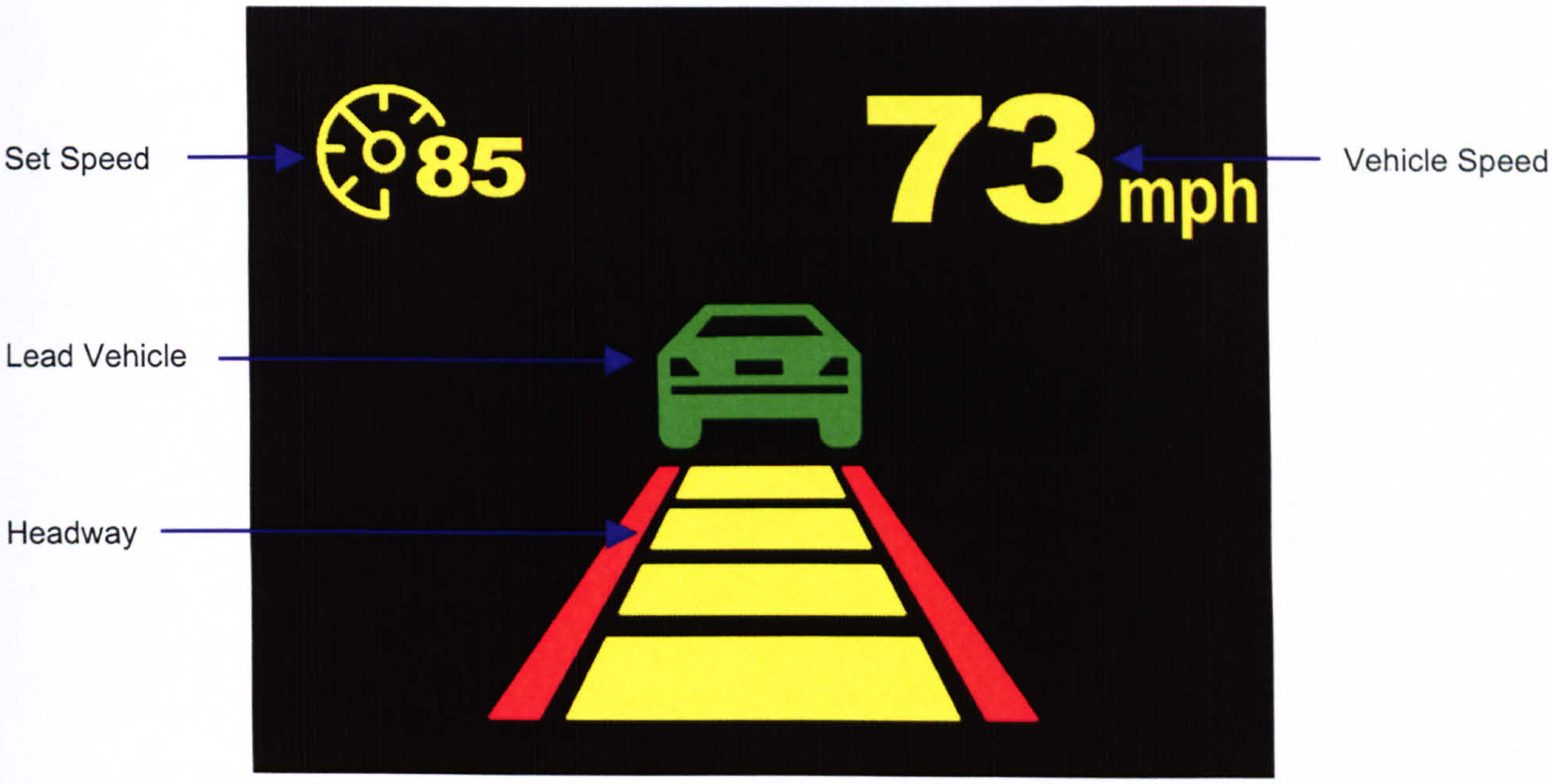
Adaptive Cruise Control (ACC)

An ACC system maintains a desired speed specified by the driver; in addition, ACC can adapt vehicle speed to changing traffic conditions by means of automatic acceleration or braking. This removes the need for the driver to adjust his/her following gap (headway) to the lead vehicle.

To enable the system simply press either the **SET +** or **SET –** buttons on the steering wheel. The vehicle will then continue to travel at its current speed (**Set Speed**). To disable the system press either the **CANCEL** button or apply the brakes.

During operation use of the accelerator pedal is disabled, steering control of the vehicle must be performed by the driver.

Information on the system is provided through the Graphical User Interface (GUI) in the centre console of the vehicle. This is shown below:



Set Speed - When the controller is **Enabled** it tries to maintain a speed. This is called the set speed. It can be adjusted (in 2 mph increments) using the **SET +** and **SET –** buttons on the steering wheel.

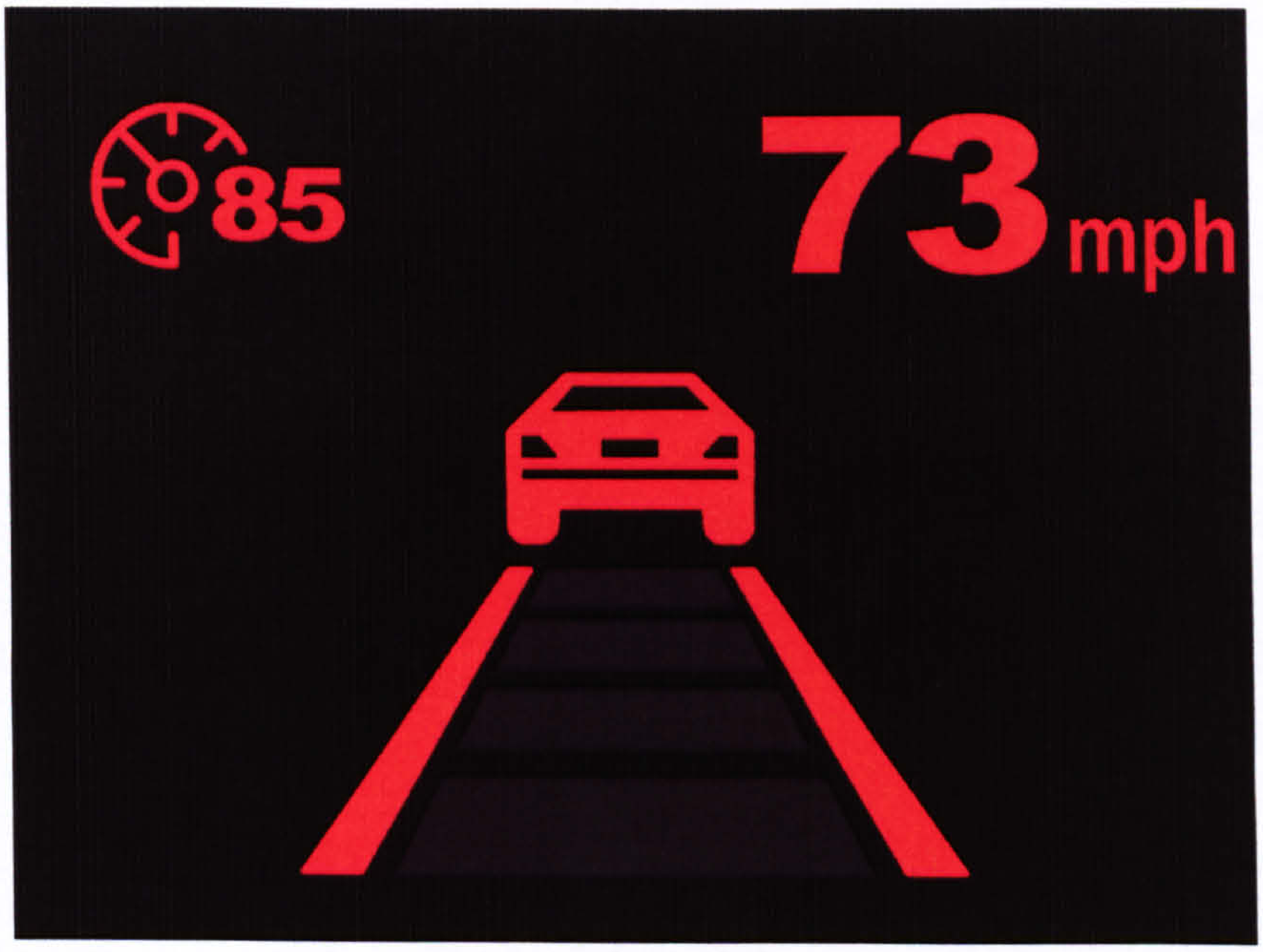
Vehicle Speed - This shows the actual speed of the vehicle.

Lead Vehicle - When there is a vehicle within the range of the system this will appear green showing that the system is trying to maintain a gap to that vehicle rather than the **Set Speed**. When there is no **Lead Vehicle** the car will be grey.

Headway - The time gap to the lead vehicle is called headway. This is initially set to level 2, but again it can be adjusted using the buttons on the back of the steering wheel.

System Limits

ACC is designed to brake and accelerate the vehicle, but 'panic braking' and coming to rest are **NOT** possible with the current system. For this reason there may be occasions when the braking required is too large for the system. In these scenarios the system will inform the driver by an audible warning and all elements of the GUI become red (shown below). **The DRIVER should then apply the brakes, disabling the system and then regain control of the vehicle.**
For the purpose of this study the controller will be re-enabled automatically after 10 seconds of manual driving.



We will now go to the simulator to have a practice drive with the system. During this practice please feel free to ask any questions about the ACC or simulator.

UNIVERSITY OF LEEDS
DRIVING SIMULATOR
INVESTIGATING DRIVER BEHAVIOUR IN A SAFE AND CONTROLLABLE RESEARCH ENVIRONMENT

ADAS Information Lane Keeping System (LKS)

Advanced Driver Assistance Systems, or ADAS, are systems designed to help the driver in the driving process. When designed correctly they should remove some workload from the driver, making driving an easier experience and also improving safety.

Lane Keeping System (LKS)

Lane Keeping Control is a lateral control system that maintains the vehicle's position in the lane without the need for constant steering by the driver. It uses a camera to pick up the white lane markings on the road and controls the steering system to ensure the desired path is followed. Feedback of the system is provided using a GUI located in the centre console of the vehicle. The three possible states are shown below.

Enabled

Disabled

Unavailable

Enabled – When under lane keeping control this image will be displayed. The system can be enabled using the button on the steering wheel. As the controller becomes enabled there will be an audible beep to inform the driver.

Disabled – When changing lane the LKS needs to be disabled to allow the driver to perform the desired manoeuvre. This can be achieved by pushing the indicator stalk in the desired direction. Once the driver has completed the manoeuvre the LKS will be automatically **enabled** after a short pause.

Unavailable – Due to the nature of the vision system on which the LKS is based there are certain scenarios where the system cannot perform adequately. When this happens control is transferred back the driver. They are informed of this by an audible warning and the display of the red steering wheel.
When the LKS becomes available again it will automatically be **enabled** (green steering wheel)

When in operation the LKS disconnects the steering wheel from the rest of the steering system. This means that the steering wheel will not move when the LKS is enabled.
We will now go to the simulator to have a practice drive with the system. During this practice please feel free to ask any questions about the LKS or simulator.

ACC Questionnaire

ACCEPTABILITY

1. During the last drive you have been driving a car that is fitted with an Adaptive Cruise Control (ACC) that will maintain your speed or the headway to the lead vehicle.
Having had some experience of the system, please indicate how acceptable you find the system by ticking the box that most accurately expresses your feelings on each line.

useful	☐	☐	☐	☐	☐	useless
pleasant	☐	☐	☐	☐	☐	unpleasant
bad	☐	☐	☐	☐	☐	good
nice	☐	☐	☐	☐	☐	annoying
effective	☐	☐	☐	☐	☐	superfluous
irritating	☐	☐	☐	☐	☐	likeable
assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

CONCENTRATION

2. Having driven the simulator with and without ACC, the following questions ask you to compare certain aspects of the driving task

Compared to 'normal' driving' within the simulator, when driving under the control of ACC…	**Increased**		**Stayed the same**		**Decreased**
my attention to other road users was	1	2	3	4	5
my attention to speed limit signs was	1	2	3	4	5
my awareness of the speed limit was	1	2	3	4	5
my attention to other aspects of driving (e.g. scanning the road ahead) was	1	2	3	4	5
the number of times I check my speedometer was	1	2	3	4	5
my tendency to brake was	1	2	3	4	5
my tendency to accelerate was	1	2	3	4	5
my anticipation of potential conflicts was	1	2	3	4	5

Subject ID:

EXPERIENCE OF THE SYSTEM

3. When driving with ACC, I find it

easier	1	2	3	4	5	**more difficult**

to keep to the speed limit of the road.

4. The ACC

increased	1	2	3	4	5	**decreased**

my enjoyment of driving

5. The ACC

increased	1	2	3	4	5	**decreased**

the comfort of driving

6. Compared to 'normal' driving, when driving under ACC, I felt:

more secure	1	2	3	4	5	**less secure**
***'in'* control**	1	2	3	4	5	***'under'* control (i.e. controlled by system)**
more confident	1	2	3	4	5	**more apprehensive**
at a greater risk of becoming accident involved	1	2	3	4	5	**at a lower risk of becoming accident involved**

7. Compared to 'normal' driving, how has ACC affected your frustration experienced in the following situations?

overtaking	**decreased frustration**	1	2	3	4	5	**increased frustration**
fast moving traffic	**decreased frustration**	1	2	3	4	5	**increased frustration**

8.	Please read each statement carefully, and then circle the appropriate response that describes you. **I view the Adaptive Cruise Control system as:**	**Strongly disagree**				**Strongly agree**
	A safety system	1	2	3	4	5
	A driving aid	1	2	3	4	5
	An interference to driving	1	2	3	4	5
	A source of frustration for myself	1	2	3	4	5
	Increasing driver comfort	1	2	3	4	5
	Creating difficulties when overtaking	1	2	3	4	5
	Making the driver less vigilant (i.e. less observant)	1	2	3	4	5
	Taking the fun out of driving	1	2	3	4	5
	Unnecessary driving aid	1	2	3	4	5

SYSTEM SAFETY

9. Generally, which of the following did you rely on to inform you of:
(tick ONE box only)

ACC Warnings:

visual LCD display	☒	auditory cue	☒	visual and audio cue equally	☒	neither	☒

ACC engaged

visual LCD display	☒	auditory cue	☒	visual and audio cue equally	☒	neither	☒

The LCD display was:

too big	1	2	3	4	5	**too small**
appropriately positioned	1	2	3	4	5	**inappropriately positioned**
easy to understand	1	2	3	4	5	**confusing**
useful	1	2	3	4	5	**unnecessary**
focusing	1	2	3	4	5	**distracting**

10. The auditory cue was:

likeable	1	2	3	4	5	**irritating**
easy to understand	1	2	3	4	5	**confusing**
focusing	1	2	3	4	5	**distracting**
useful	1	2	3	4	5	**unnecessary**

11. When driving under ACC, do you now feel more, less or at the same amount of risk when driving in these situations <u>compared to 'normal' driving</u>?

overtaking	**decreased risk**	1	2	3	4	5	**increased risk**
fast moving traffic	**decreased risk**	1	2	3	4	5	**increased risk**

ACC Questionnaire

SYSTEM TRUST

This section asks you to rate your trust in the ACC system. Please rate the extent to which you agree with the following statements by placing a line along the line provided.

12. **The performance of the system enhanced my driving safety**

0 Strongly Disagree	100 Strongly Agree

13. **I am familiar with the operation of the system**

0 Strongly Disagree	100 Strongly Agree

14. **I trust the system**

0 Strongly Disagree	100 Strongly Agree

15. **The system is reliable**

0 Strongly Disagree	100 Strongly Agree

16. **The system is dependable**

0 Strongly Disagree	100 Strongly Agree

17. **I have confidence in the system**

0 Strongly Disagree	100 Strongly Agree

How much would you be willing to pay to have ACC installed in your vehicle? **£__________ approx**

Subject ID:

LKS Questionnaire

ACCEPTABILITY

1. During the last drive you have been driving a car that is fitted with a Lane Keep System LKS that will maintain your lane position unless you momentarily disable it.

   Having had some experience of the system, please indicate how acceptable you find the system by ticking the box that most accurately expresses your feelings on each line.

useful	☐	☐	☐	☐	☐	useless
pleasant	☐	☐	☐	☐	☐	unpleasant
bad	☐	☐	☐	☐	☐	good
nice	☐	☐	☐	☐	☐	annoying
effective	☐	☐	☐	☐	☐	superfluous
irritating	☐	☐	☐	☐	☐	likeable
assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

CONCENTRATION

2. Having driven the simulator with and without LKS, the following questions ask you to compare certain aspects of the driving task

Compared to 'normal' driving within the simulator, when driving under the control of LKS…	**Increased**		**Stayed the same**		**Decreased**
my attention to other road users was	1	2	3	4	5
my attention to speed limit signs was	1	2	3	4	5
my awareness of the speed limit was	1	2	3	4	5
my attention to other aspects of driving (e.g. scanning the road ahead) was	1	2	3	4	5
the number of times I check my speedometer was	1	2	3	4	5
my tendency to brake was	1	2	3	4	5
my tendency to accelerate was	1	2	3	4	5
my anticipation of potential conflicts was	1	2	3	4	5

Subject ID:

LKS Questionnaire

EXPERIENCE OF THE SYSTEM

3. When driving with LKS, I find it

easier	1	2	3	4	5	**more difficult**

to keep to the speed limit of the road.

4. The LKS

increased	1	2	3	4	5	**decreased**

my enjoyment of driving

5. The LKS

increased	1	2	3	4	5	**decreased**

the comfort of driving

6. Compared to 'normal' driving, when driving under LKS, I felt:

more secure	1	2	3	4	5	**less secure**
***'in'* control**	1	2	3	4	5	***'under'* control (i.e. controlled by system)**
more confident	1	2	3	4	5	**more apprehensive**
at a greater risk of becoming accident involved	1	2	3	4	5	**at a lower risk of becoming accident involved**

7. Compared to 'normal' driving, how has LKS affected your frustration experienced in the following situations?

overtaking	**decreased frustration**	1	2	3	4	5	**increased frustration**
through roadworks	**decreased frustration**	1	2	3	4	5	**increased frustration**
fast moving traffic	**decreased frustration**	1	2	3	4	5	**increased frustration**

8. The LKS system relies upon visual system to track lane markings of the road . There are likely to be times when the visual system fails and steering control is handed back to the driver.

If this has happened to you, did you…

feel frustration	1	2	3	4	5	**feel relief**

Subject ID:

9.	Please read each statement carefully, and then circle the appropriate response that describes you. **I view the Lane Keeping System as:**	**Strongly disagree**				**Strongly agree**
	A safety system	1	2	3	4	5
	A driving aid	1	2	3	4	5
	An interference to driving	1	2	3	4	5
	A source of frustration for myself	1	2	3	4	5
	Increasing driver comfort	1	2	3	4	5
	Creating difficulties when overtaking	1	2	3	4	5
	Making the driver less vigilant (i.e. less observant)	1	2	3	4	5
	Taking the fun out of driving	1	2	3	4	5
	Unnecessary driving aid	1	2	3	4	5

SYSTEM SAFETY

10. Generally, which of the following did you rely on to inform you of:
(tick ONE box only)

LKS unavilable:

visual LCD display	☒	auditory cue	☒	visual and audio cue equally	☒	neither	☒

LKS system engaged

visual LCD display	☒	auditory cue	☒	visual and audio cue equally	☒	neither	☒

The LCD display was:

too big	1	2	3	4	5	**too small**
appropriately positioned	1	2	3	4	5	**inappropriately positioned**
easy to understand	1	2	3	4	5	**confusing**
useful	1	2	3	4	5	**unnecessary**
focusing	1	2	3	4	5	**distracting**

11. The auditory cue was:

likeable	1	2	3	4	5	**irritating**
easy to understand	1	2	3	4	5	**confusing**
focusing	1	2	3	4	5	**distracting**
useful	1	2	3	4	5	**unnecessary**

LKS Questionnaire

UNIVERSITY OF LEEDS
DRIVING SIMULATOR

SYSTEM TRUST

This section asks you to rate your trust in the LKS system. Please rate the extent to which you agree with the following statements by placing a line along the line provided.

12. The performance of the system enhanced my driving safety

0 Strongly Disagree	100 Strongly Agree

13. I am familiar with the operation of the system

0 Strongly Disagree	100 Strongly Agree

14. I trust the system

0 Strongly Disagree	100 Strongly Agree

15. The system is reliable

0 Strongly Disagree	100 Strongly Agree

16. The system is dependable

0 Strongly Disagree	100 Strongly Agree

17. I have confidence in the system

0 Strongly Disagree	100 Strongly Agree

18. How much would you be willing to pay to have LKS installed in your vehicle? **£__________ approx**

Subject ID: