

THE EFFECTS OF IMPROVED VEHICLE TECHNOLOGY ON THE DESIGN OF ACCELERATION AND DECELERATION LANES AT FREEWAY ENTRY AND EXIT RAMPS

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ABSTRACT

An important aspect of road geometry design is the provision of safe distances to allow motorists to change speed from low or moderate speed flows to high speed flows, and vice versa.

Design guidelines for determining acceleration and deceleration lane lengths were evaluated to understand the basis for these designs from across the world. It was found that many current guidelines are based on data collected over 40 years ago. Vehicle acceleration and deceleration characteristics have changed over this period and the majority of the Australian vehicle fleet is less than 10 years old.

Data was collected from a number of sites in the Newcastle and Central Coast regions of New South Wales using a combination of video and GPS to measure the performance of passenger vehicles and an associated driver characteristic. The GPS recorded real position at regular time intervals which was used to calculate acceleration or deceleration rates of passenger vehicles. The results were used to determine a driver characteristic which indicated how much of the acceleration and deceleration vehicle performance the average driver was willing to use.

An acceleration model and a deceleration model were developed based on vehicle dynamics. The models output distance and time required to reach target speeds. The parameters for each model to reproduce the guidelines used in the Austroads *Guide to Road Design* were derived. Preliminary results indicated that most drivers tend to use all of the acceleration or deceleration lane length currently provided, rather than to utilise the increased vehicle performance available to them. An important feature of the models is that they allow for the use of actual vertical geometry instead of average grades used in former models.

INTRODUCTION

Road design guidelines vary across the globe and generally seek to provide designs that are safe and efficient. Most design guidelines use the same principles of engineering knowledge but vary the parameters they use depending on factors such as cost, traffic, intended users and level of safety. Published guidelines were available from some of the Australian State road authorities in the 1930's, and at this time road traffic and road building showed a substantial increase in Australia and other industrialised economies. Most guidelines have been based on a designated passenger vehicle, either a manufactured model or a fictional average vehicle that represented most of the vehicles in the market.

Acceleration and deceleration lanes allow drivers to join or depart from major traffic flows without significantly affecting the through flow. Guidelines for determining acceleration and deceleration lane lengths vary between countries and have changed several times from when they were first used in the 1930's. Most guidelines use a table which recommends a length for vehicles to change from an initial speed to a target final speed. Many of these guidelines also incorporate adjustment provisions which account for the average grade of the road.

The performance characteristics of vehicles have been changing as new technical developments have occurred in vehicle engines, brakes and other components. The aim of this investigation was to consider if these changes warranted changes to the currently used Australian guidelines for the design of acceleration and deceleration lanes for freeways. The investigation was limited to passenger vehicles only. The investigation was also limited to a consideration of the acceleration and deceleration lengths required and did not consider the merge and diverge components of the ramp length guidelines.

An acceleration model and deceleration model were created which are based on vehicle dynamics. These models utilise published vehicle data with the combination of a driver characteristic to estimate the acceleration and deceleration lengths required. The driver characteristic factor represents how much of the available acceleration or available deceleration the driver usually uses. The models are compared to current acceleration and deceleration lengths used by modern vehicles and also the lengths used in present guidelines. An assessment is made of the need for further investigations and the need for amendments to current guidelines for acceleration and deceleration lanes.

BACKGROUND

A background literature review was undertaken to determine the changes in guidelines which have occurred over time, the vehicle design characteristics on which guidelines were based, and the acceleration and deceleration technology changes which have occurred.

Design guidelines for acceleration and deceleration lanes

Acceleration and deceleration lanes (also known as speed change lanes) may be provided at intersections and interchanges. In freeway design they are used to allow exiting or entering vehicles to diverge or merge freely with the through traffic on the freeway. This aids in maintaining good traffic flow and also increases road safety. In early road design, freeways were uncommon but speed change lanes were still used at some intersections at grade. Again the purpose of these was to minimise the impact of turning traffic on through traffic and to improve road safety, especially when poor sight distance may have existed. The engineering principles in both situations are similar.

New South Wales

It appears that acceleration and deceleration lanes were first introduced into design guidelines in New South Wales in Department of Main Roads Standard Specifications and Technical Directions (Department of Main Roads NSW 1941), which included the design of intersections at grade. The following three criteria were required for a speed change lane to be designed:

- design speed of the through road of 40 mph (64 km/h) or more
- traffic volume greater than 1000 vehicles per day
- turning traffic an important factor.

If these three criteria were satisfied there were two design tables to use, one for especially heavy routes on arterial roads in outer metropolitan areas and the other table for all other routes.

The Department of Main Roads Training Manual for Road Design Draftsmen (Department of Main Roads NSW 1978) included Interchange Design on freeways in Chapter 38. The recommended minimum deceleration lane length for an off ramp was 275 m regardless of the freeway speed or the design speed of the exit curve on the ramp, and a table indicated the absolute minimum distances allowed for deceleration on exit ramps.

The Roads and Traffic Authority (RTA) *Road Design Guide* (Roads and Traffic Authority NSW 1999) states that deceleration lanes should be provided to separate turning traffic from through traffic and they should consist of a length of parallel lane preceded by a diverge taper. The total lane length is made up of diverge length, plus length required for deceleration, plus any length required for storage. The deceleration length should equal the distance required to decelerate from the approach speed of the through road, to the design speed of the turn, or to stop a vehicle if required. A comfortable deceleration rate (2.5 m/s^2) is used for most of the table but a maximum deceleration rate (3.5 m/s^2) is used in some cases.

Australia

Speed change lanes are mentioned in numerous NAASRA and Austroads Guides and there is some variance depending on which era the guide is from. In the early *Guide Policy for Geometric Design of Major Urban Roads* (National Association of Australian State Road Authorities 1976) mention is made that acceleration lanes are not usually provided as they are not required on most urban roads, however deceleration lanes are common at major intersections.

In the *Guide to Traffic Engineering Practice* (National Association of Australian State Road Authorities 1982) speed change lanes may be provided for the acceleration or deceleration of vehicles entering or leaving the through traffic lanes, however lanes longer than 130 m should be critically examined as they can encourage drivers to use them as through lanes. In the *Guide to Traffic Engineering Practice Part 5 – Intersections at Grade* (Austroads 1988) deceleration lane lengths are generally based on deceleration considerations, except in urban areas where they may be depicted by storage length. Where a full deceleration length cannot be provided a short 30 m parallel lane plus 30 m taper can provide significant benefits. Deceleration lane lengths for level grades from this document are the same as from the *Guide Policy for Geometric Design of Major Urban Roads* (National Association of Australian State Road Authorities 1979). Acceleration lane lengths are based on the speed of the turn or entering speed and the speed of the through road where the merge occurs. Acceleration lane lengths are significantly longer than the previous *Guide Policy for Geometric Design of Major Urban Roads* (National Association of Australian State Road Authorities 1979). Some values used are the minimum length required by 4 seconds of travel time to merge, whereas other figures are based on acceleration requirements identified by Samuels and Jarvis (1978). In the *Guide to Traffic Engineering Practice – Part 5 – Intersections at Grade* (Austroads 2005) and the *Guide to Road Design – Part 4A – Unsignalised and Signalised Intersections* (Austroads 2010), deceleration and acceleration lane lengths recommended are based on the same principles and values as the RTA *Road Design Guide* (Roads and Traffic Authority NSW 1999).

Adjustments for grade were usually provided for in most NAASRA, Austroads and RTA guides. All adjustments were based on an average upgrade or downgrade of 0-2%, 3-4% or 5-6%. Acceleration and deceleration ramps can have complicated vertical geometry and therefore the use of an average grade is likely to decrease confidence in the final recommendation.

United Kingdom

United Kingdom road design standards are produced by the Department for Transport which is a collection of the Highways Agency, The Scottish Office Development Department, The Welsh Office and The Department of the Environment for Northern Ireland. The major design guide for road and highway design is the *Design Manual for Roads and Bridges*, which has 16 volumes. The geometric design standards such as deceleration and acceleration lane lengths for exit and entry ramps are located in *Volume 6 TD 22/06* (Department for Transport 2006). Entry and exit ramp layouts are determined from all purpose merging and diverging diagrams. Preferred layouts are tapered entry and exit ramps with ghost islands and additional lanes in high traffic areas. There is no indication that entry and exit ramp lengths are based on acceleration and deceleration distances required by vehicles. The distances shown in tables and the method described in designing entry and exit ramp lengths indicates that they are based entirely on traffic volumes of the through road and diverging/merging traffic.

United States of America

Road design guidelines in USA are produced by the American Association of State Highway and Transportation Officials (AASHTO), formerly known as the American Association of State Highway Officials (AASHO). The guidelines of these organisations have had a lot of influence on Australian road design guidelines in the past. In *A Policy on Geometric Design of Highways and Streets* (AASHTO 1994) speed change lanes are provided for the deceleration and acceleration of vehicles leaving or entering the through lanes. The lengths are based on the estimated average running speed of the exit curve and through carriageway, which varies from the use of design speed in Australian publications. In the 2004 edition of this policy the lengths for deceleration lanes are unchanged but the acceleration lane lengths have been updated. The figures used have been questioned by Fitzpatrick and Zimmerman (2007) who suggest that additional research should be done to determine whether longer acceleration lane lengths are required. Their recommendation is based on Canadian research reported by Hassan et al. (2006), who suggest a constant acceleration rate of 0.8 m/s² should be used to determine acceleration lane lengths.

Comparison of values

In order to analyse the development of guidelines and to compare recommendations from different jurisdictions, Table 1 has been prepared. Historically, acceleration lane length recommendations have increased whereas deceleration lane lengths have not changed much in Australia. In regard to Australian guidelines, Department of Transport and Main Roads, Queensland (2005), have recommended lower length for acceleration lanes than those recommended by RTA and Austroads, however the lengths for deceleration lanes are marginally longer. In comparing Australian practice with that in the USA, AASHTO policy recommends lengths for acceleration lanes significantly less than those used in Australia but deceleration lane lengths are comparable.

Table 1: History of acceleration and deceleration lane length guidelines (m)

	Acceleration		Deceleration	
	Entry speed: 40 km/h Target speed: 100 km/h	Entry speed: 60 km/h Target speed: 100 km/h	Through speed: 100 km/h Exit speed: 40 km/h	Through speed: 100 km/h Exit speed: 60 km/h
DMR, NSW (1941)	230	230	140	140
<i>AASHO (1957)</i>	280	170	110	80
NAASRA (1979)	275	205	144	118
Austrroads (1988)	410	360	144	118
<i>AASHTO (1994)</i>	300	220	145	120
<i>AASHTO (2004)</i>	285	205	145	120
Qld TMR (2005)	300	240	155	135
Austrroads (2010)	410	340	130	100

Analysis of Table 1 shows that there was a major change for acceleration lane lengths between 1979 and 1988 in Australia. Acceleration lane lengths increased by roughly 50% during this time and the reason for such a substantial change has not been able to be discerned in this investigation. Deceleration lane lengths did not change over the same period. The AASHTO standards have changed over time with slight increases in acceleration and deceleration lane

lengths, until in 2004 there was a decrease in acceleration lane lengths. It is interesting that current AASHTO standards are almost identical to the 1979 Australian standards.

Vehicle design characteristics

Vehicle acceleration and deceleration performance plays a large role in the design of roadway elements such as entry and exit ramps on freeways. A motor vehicle's performance is determined by the engine and braking power available for acceleration and deceleration along the roadway. The power for a motor vehicle is provided by its engine, however not all this power is useable and there are external opposing forces such as air, gravity, rolling and inertia resistances.

Vehicle acceleration performance is dependent on power/weight ratio. Weight is a rough indicator of resistance to motion as the higher the power/weight ratio the better the acceleration performance. Vehicle acceleration rates also decrease as speed increases. Vehicle deceleration performance is generally measured by the braking power available. This relates to the mass of the vehicle and the coefficient of static friction between vehicle tyres and the pavement.

Early design guidelines utilising vehicle acceleration and deceleration were based on USA data reported by (Loutzenheiser 1938) and (Beakey 1938). Australian data was produced in the 1970's (Samuels & Jarvis 1978) but this data is now more than 30 years old and does not appear to have been updated to take account of improvements in vehicle technology.

METHODOLOGY

In order to examine the appropriateness of current standards, a method was needed to measure the acceleration and deceleration lengths being used by modern cars when accelerating onto and decelerating from freeway ramps. Once the method was proven it was used to collect field data from a number of selected sites. It was also considered desirable to develop a theoretical model to calculate acceleration and deceleration lengths, based on published performance characteristics of modern cars, so that a comparison could be made between the outputs of the theoretical model and the field data.

A typical vehicle needed to be chosen to represent the Australian road fleet. Several different class vehicles needed to be tested (cf. Samuels & Jarvis 1978). This was done in order to determine which vehicle was best suited for the design of lane length.

Data collection

Several different methods of data collection have been used in previous studies. Early studies (e.g. Beakey 1938, Loutzenheiser 1938) measured travel times between multiple locations along a stretch of road but only used low sample rates. The method experienced difficulties in estimating where acceleration and deceleration started and finished. Another method used the vehicle speedometer to record speeds at regular time intervals allowing acceleration to be calculated (e.g. Samuels & Jarvis 1978). Recent studies (e.g. Boonsiripant et al. 2010; Rakha et al. 2004; Wang et al. 2004) have adopted Global Positioning System (GPS) technology to collect speed data. These studies have found that GPS data can achieve a relatively high sample rate appropriate for determining acceleration and deceleration rates.

In this study the acceleration rate or deceleration rate of random vehicles was determined by vehicle following and GPS data collection. The method involved a monitoring car containing GPS equipment locked into the NSW Department of Lands CORSnet system (Department of Lands NSW 2010) and following a constant distance behind a vehicle travelling through an acceleration or deceleration zone. The monitoring car also contained a video camera (Blackvue 2011) mounted to the windscreen which allowed determination of vehicle type, accuracy of tracking, and any unusual features in the following action.

Data collection was carried out in two different areas. The first was an area near Charlestown, NSW and the second in the vicinity of Wyong, NSW. In total, the two areas covered a total of eight acceleration lanes and eight deceleration lanes in the Newcastle and Central Coast regions. The Charlestown investigation was performed on the Newcastle Inner City Bypass, a dual carriageway, concrete paved, urban freeway. The freeway has a speed limit of 90 km/h and connects to several main collector roads in the area which have a speed limit of 60 km/h. The freeway generally had a lot of local traffic travelling between residential and commercial areas and is also used by through traffic. The Wyong investigation was performed on the F3 freeway, a dual carriageway, concrete paved, road. The freeway has a speed limit of 110 km/h and connects to several main arterial roads between Sydney and Newcastle. The freeway had some local traffic travelling between residential and commercial areas in the busy Wyong and Tuggerah regions and is also used by through traffic travelling between Sydney, Central Coast, Newcastle and beyond.

Not all sites provided clear data as there was interference from vegetation and structures such as retaining walls and bridges. This interference caused a poor precision signal between the GPS receiver and the satellites and hence provided unreliable data. Such data was omitted, and sites with less than five reliable strings were eliminated from the investigation.

Data was collected in string form. Each string contained a number of points with the easting, northing, reduced level (R.L.) and a timestamp. A new string was started each time a new site was entered. Each string needed the application of an adjustment to allow for different commencing points for the data, so that speed and acceleration/deceleration rates could be related to a chainage, instead of just distance along the string. A Microsoft Excel spreadsheet was developed to import the data and reduce it to provide either acceleration or deceleration rates based on the collected data.

MODEL DEVELOPMENT

Vehicle dynamics models were developed for calculating acceleration and deceleration, based largely on the work of Rakha and associates (Rakha et al. 2001; Rakha et al. 2004).

Acceleration model

The acceleration model is based on Newtons second law of motion which states that the acceleration (a) of a body is parallel and directly proportional to the net force (F) and inversely proportional to the mass (m). The net force acting on an accelerating vehicle is the tractive force developed by the vehicle minus the total resisting force. Based on vehicle mass, engine power and reasonable assumptions on losses in the power transmission system, plus information on air drag resistance, rolling resistance and grade resistance, the theoretical acceleration can be calculated. In practice however, drivers do not generally utilise the full power potential of their vehicles during acceleration. A driver characteristic factor (D_c) is therefore needed to account for this less than full power utilisation, and the factor is applied to the tractive force.

The acceleration model was tested against data collected from NRMA (NRMA Motoring & Services 2010) and an online vehicle database (Profess 2011). NRMA provides published data for 0-100 km/h and 0-80 km/h vehicle tests. The online vehicle database provides published data for 0-60 km/h, 0-80 km/h, 0-100 km/h and 0-120 km/h vehicle tests. Several vehicles were selected to compare the acceleration model created against the published data vehicle tests. The vertical grading was set to zero in the acceleration model during the calibration, as it was unclear on what grade the vehicles had been tested. It was assumed that testing had been on relatively flat level grades. It was assumed that all available engine power was utilised for vehicle acceleration in the tests and the driver characteristic was therefore assumed to be 1. Results were varied, and one reason for this was that the data published by the two sources for a particular vehicle had significant variations (up to 20% in some cases). The acceleration model tended to fit closely to either data set most times and a sample comparison graph is shown in Figure 1.

Deceleration model

The deceleration model is very similar to the acceleration model and is also based on vehicle dynamics. Vehicle dynamics can be complicated for deceleration. There are a number of losses and variables that relate to the braking power of a vehicle, including the type and condition of brakes and the pressure applied by the driver to the brake pedal. Again a driver characteristic factor (D_c) needed to be incorporated to account for the variation between drivers and their driving actions. Other factors such as the tyre type and condition, pavement type and condition and weather also affect the dynamics of a vehicle. The major difference between the deceleration model and the acceleration model is that instead of a tractive force which accelerates the vehicle, there is a braking force that decelerates the vehicle. Another difference is that air drag resistance and rolling resistance help to decelerate the vehicle.

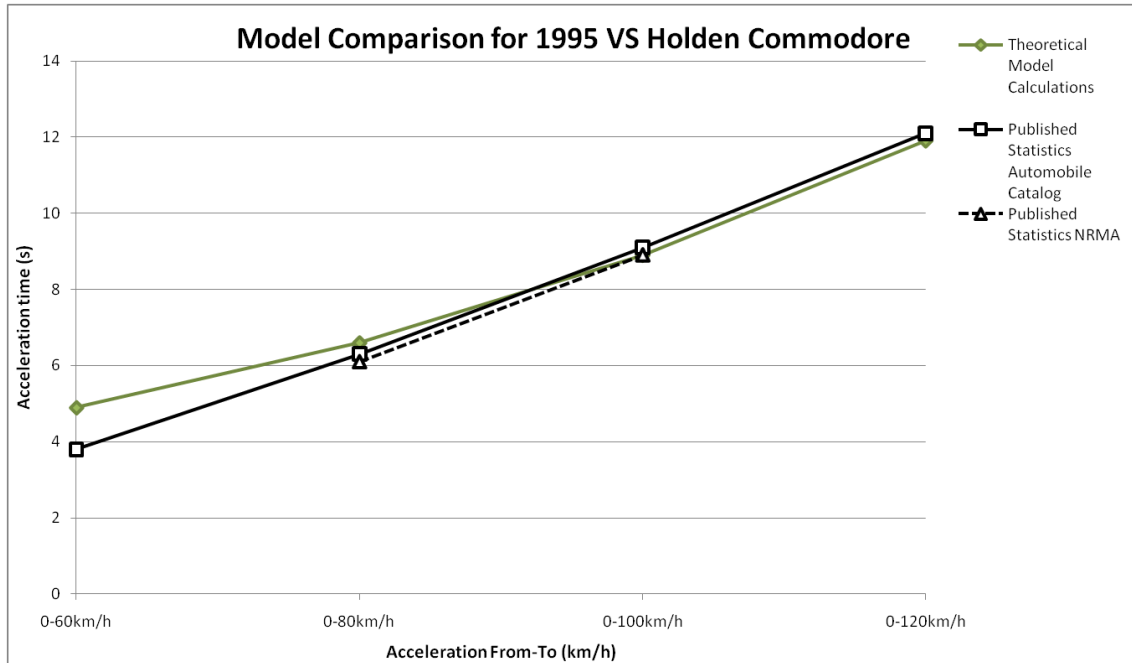


Figure 1: Acceleration model comparison for 1995 VS Commodore

RESULTS

Driver characteristics

A preliminary driver characteristic was determined from the data collected at 12 of the 16 sites as four sites were found to yield unreliable data. As an example, the data and analysis are presented for Site 1 in Figure 2. For the data from this site a 5th order polynomial line with an R^2 value of 0.9168 proved to be the line of best fit.

This collected data was placed against the modelled data. Using typical vehicle parameters, initial and target speeds and vertical grading of the site as inputs for the acceleration model, the model was manipulated to find the driver characteristic which provided the best fit between the trend line and the model. A driver characteristic of 0.43 was determined and the comparison between the trend line and the model is shown in Figure 3.

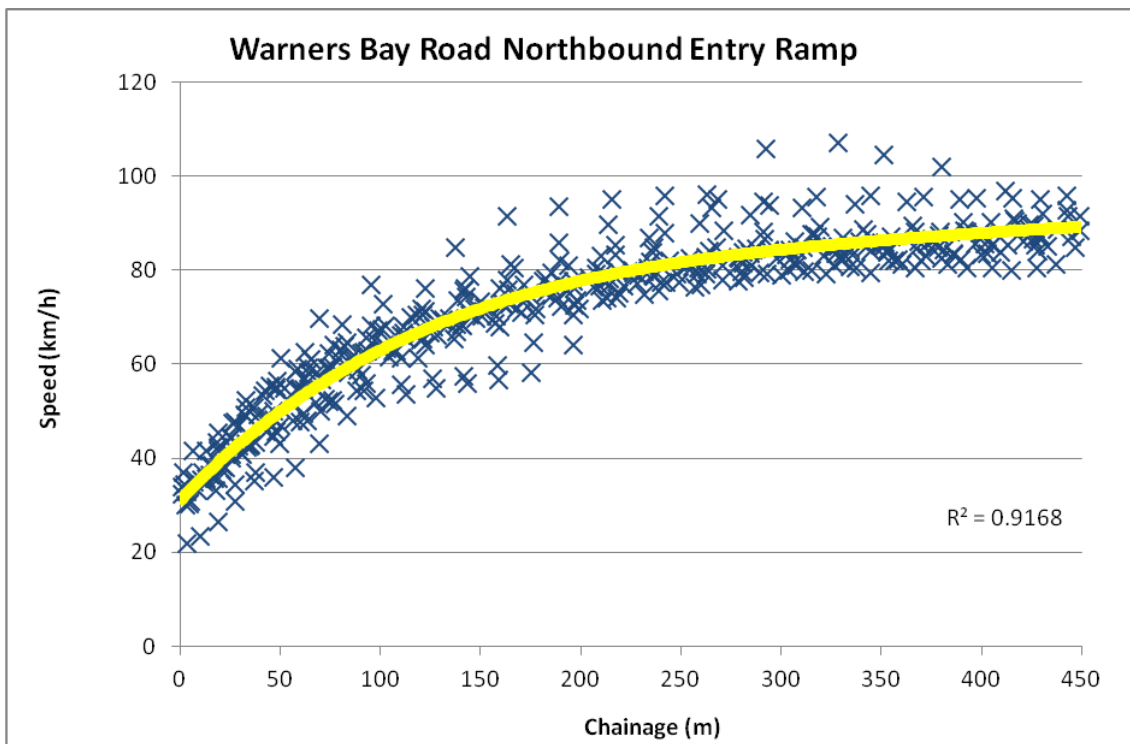


Figure 2: Trend line for Site 1 – Warners Bay Road northbound entry ramp

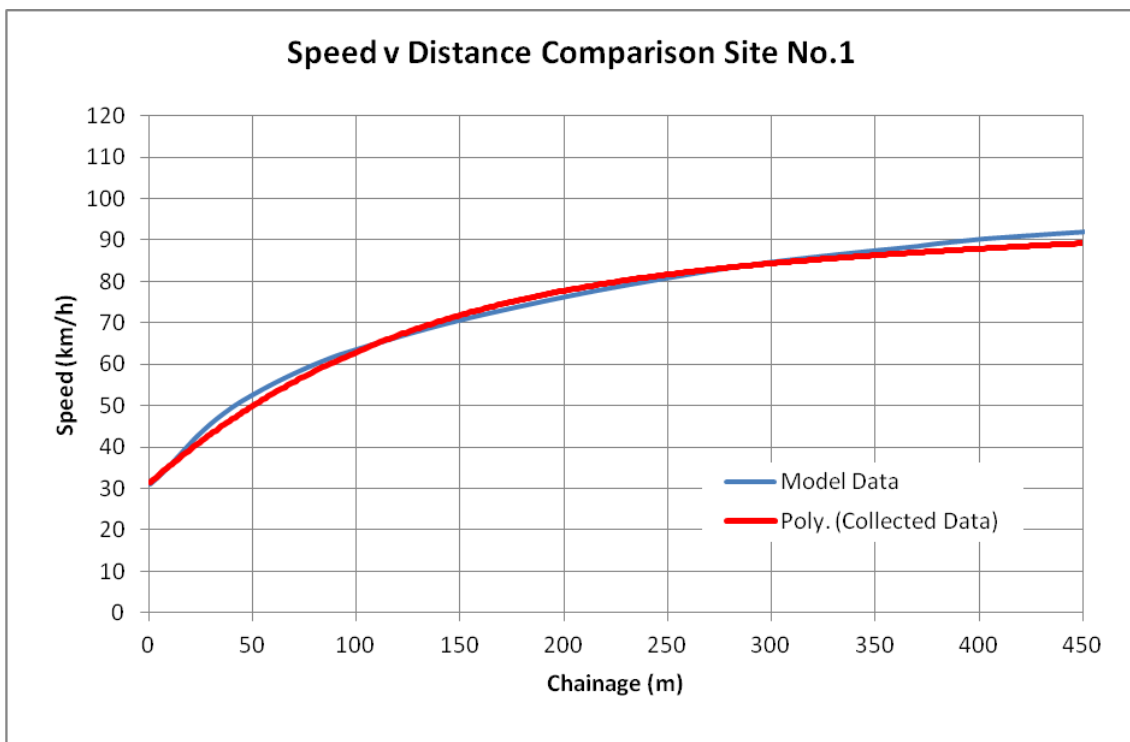


Figure 3: Comparison between collected data and modelled data for Site 1 – Warners Bay Road northbound entry ramp

The preliminary driver characteristics for the sites are shown in Table 2. The 'Model Fit' columns represent a qualitative assessment of how well the modelled data fits against the collected data. The modelled data for acceleration is generally a better fit than for deceleration. One major

reason for the deceleration data not fitting as well as the acceleration data could be that it was frequently observed that two types of deceleration existed. The two types can be classified as:

- engine only or coasting deceleration
- deceleration from applying vehicle brakes.

The deceleration model as currently developed does not differ between these two types of deceleration.

Table 2: Preliminary driver characteristics

Acceleration lanes			Deceleration lanes		
Site	Driver characteristic	Model fit	Site	Driver characteristic	Model fit
1	0.43	Good	2	0.115	Poor
3	0.70	Acceptable	6	0.20	Acceptable
7	0.40	Good	8	0.084	Poor
11	0.75	Good	10	0.143	Acceptable
13	0.41	Acceptable	12	0.075	Acceptable
			14	0.18	Good
			16	0.089	Acceptable

Comparison to current guidelines

Using the typical vehicle parameters in the acceleration and deceleration models and the driver characteristics as determined from the sites tested some comparisons to existing guidelines were compiled.

Acceleration lanes

From the results above it is clear that to get a good fit to the current Austroads guidelines across the whole table different values for the driver characteristic must be used in the acceleration model depending on the desired target speed. Table 3 shows the driver characteristics that need to be used to replicate the guidelines in Austroads *Guide to Road Design Part 4C – Interchanges* (Austroads 2009).

Table 3: Driver characteristics for acceleration model to replicate Austroads guidelines

Target speed (km/h)	80	90	100	110	120
Driver characteristic	0.630	0.673	0.715	0.758	0.832

The driver characteristics as determined from the above table are in a similar range to those obtained in the field data collection. The field data has slightly lower driver characteristic values indicating that drivers utilise longer lane lengths, probably to increase comfort.

Deceleration lanes

A driver characteristic value of 0.285 was found to give an excellent match between the model and the Austroads *Guide to Road Design Part 4C – Interchanges* (Austroads 2009) as shown in Figure 4. This value is again higher than the values found in the field investigation and it was observed that many drivers will tend to coast for most of the deceleration phase and only apply their brakes when needed as they approach the exiting intersection or roundabout.

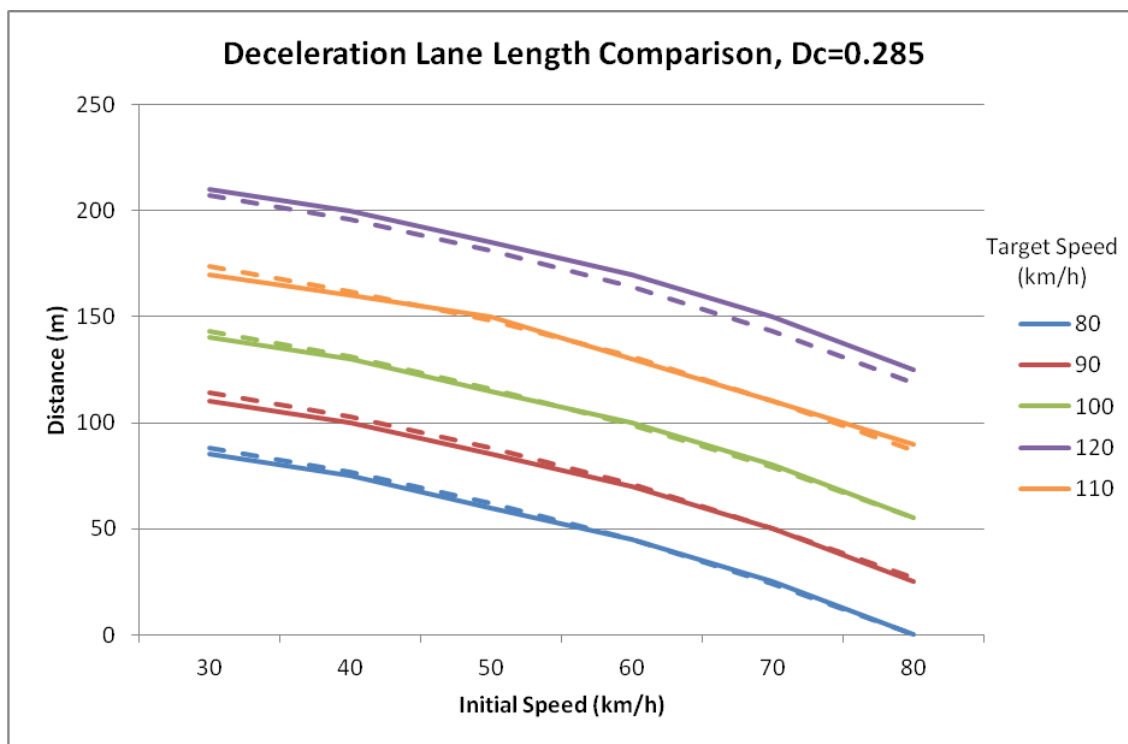


Figure 4: Comparison between Table 2.17 (Austroads 2009) and deceleration model using a driver characteristic of 0.285 {Solid lines = model results; Dashed lines = Austroads Guidelines}

CONCLUSION

The investigation has found that advances in vehicle technology in recent decades have resulted in increased vehicle performance for deceleration and acceleration. As the majority of cars in the Australian vehicle fleet are less than 20 years old, most drivers have vehicles with acceleration and deceleration characteristics which are markedly superior to those in use when previous studies were performed (e.g. Samuels & Jarvis 1978). However the results from the current study show that most drivers are not using this performance increase to accelerate or decelerate faster. The majority of drivers accelerate over the whole length of lane, including the merge or diverge area. Although this could be conjectured to be due to a greater awareness by drivers of energy usage issues, it is considered that the major reason is probably simply one of driver comfort.

The investigation reveals that based on the improved acceleration and deceleration characteristics of modern cars, it would be possible to recommend decreased lengths for freeway entry and exit ramps. Whilst this might lead to a saving in construction costs it would result in increased costs for vehicle energy usage and could also have an adverse impact on driver comfort and road safety. The effect of reduced ramp lengths also needs to be investigated for other vehicle types before consideration is given to changing current guidelines. In some situations (e.g. adjacent to a major industrial area where significant heavy vehicle movements may occur) the acceleration and deceleration characteristics of heavy vehicles may need to be considered and this could be a consideration in any future review of ramp length guidelines.

A further aspect is that in many areas of Australia, older freeways now carry much higher traffic volumes than when they were first developed and this is requiring a transition from a freeway to a managed motorway operation. The effect on entry and exit ramps is that entry ramps require ramp metering and control, and exit ramps are increasingly used for vehicle storage to manage the discharge into the surrounding road network. So while it is possible that the required ramp lengths on lower volume rural freeways may be able to be reduced, freeways experiencing substantially increased traffic flows may find the traditional operation of ramps has changed and the considerations of acceleration and deceleration are no longer relevant.

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