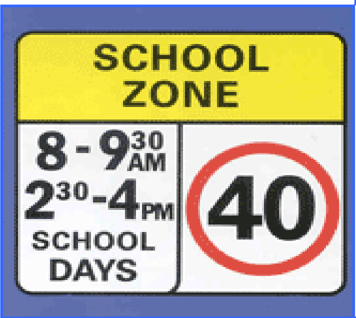
AP-T229-13

AUSTROADS TECHNICAL REPORT

Expanded Operating Speed Model



Austroads

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Expanded Operating Speed Model

Austroads

Sydney 2013

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SUMMARY

Austroads Project TS1456 (Expanded Operating Speed Model) was established to update and expand road design operating speed models used in Australia. In particular, the project has reviewed the current validity of the existing operating speed model for rural roads and, as necessary, identified adjustments to the model that reflect changes in driver speed behaviour. This included the deceleration of cars and heavy vehicles on horizontal curves and the influence of horizontal curves in sequence.

The project method consisted of a series of tasks that identified appropriate curve sites and collected speed measurement data for cars and heavy vehicles at 12 curve sites. Speed data was analysed in order to validate and consider potential modifications to the existing deceleration on horizontal curves model and curves in sequence. Additionally, the deceleration of articulated trucks on horizontal curves was analysed.

The speed measurement data obtained for cars was used to validate the existing deceleration on horizontal curves models and to develop revised models. Differences were observed between the revised and existing models particularly for medium radius curves, where the revised models predicted faster curve departure speeds than indicated by the existing models.

Articulated trucks were generally found to travel slower than cars on the approach to and at the midpoint of curves. However, the speed reduction due to horizontal curves was found to be similar to that for cars. This was reflected in the deceleration on horizontal curves models developed which predicted similar results to the models developed for cars.

Analysis of curves in sequence found that one grouping of curves was generally in line with the operating speed model procedures. For the second grouping of curves, the section operating speed and acceleration behaviour between curves differed from the operating speed model predictions. However, the superelevation for these curves exceeded the Austroads (2010a) recommended maximum values, which may have influenced the results. Differing speed environments upstream and downstream of the curves in sequence may also have been a factor.

The revised deceleration on horizontal curves models for cars developed as part of the project are presented for consideration in updating the existing Austroads model. Prior to updating the existing models, further research may consider investigating curve radii greater than 250 m to confirm the results of the project, as the greatest differences in model predictions occurred in this range of curve radii.

The deceleration on horizontal curves models for articulated trucks generally produced similar results to the revised models developed for cars. All curve sites included in the study were on level grades. Further research would be of benefit to examine the influence of gradients on trucks or other factors that may influence their behaviour.

Further research may also further examine curves in sequence, to consider whether the results that deviated from the existing operating speed model practices extend to a larger number of curves, or are influenced by factors such as superelevation or the speed environment upstream of the curves.

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1 INTRODUCTION

1.1 Background

Austroads Project TS1456 (Expanded Operating Speed Model) was established to update and expand road design operating speed models used in Australia. In particular, the project has reviewed the current validity of the existing operating speed model for rural roads and, as necessary, identified adjustments to the model that reflect changes in driver speed behaviour. This included the deceleration of cars and heavy vehicles on horizontal curves and the influence of horizontal curves in sequence.

The current operating speed model for rural roads was adopted by Austroads in the early 1980s, and validated again by VicRoads in 1994. No further refinement or developments to the model have been undertaken since then. In the absence of actual operating speed data for a road, current design practice for most new or upgraded roads is to add 10 km/h to the posted speed limit and adopt that speed as the operating speed and hence the design speed. Without having evidence based operating speeds for design vehicles and a method for estimating changes, designs can potentially become overly conservative leading to unnecessary additional construction costs or not provide the necessary geometric requirements resulting in a road that is unsafe.

This project seeks to test the validity the existing model for rural conditions and expand it to consider the operating speed of trucks on rural roads.

1.1.1 Deceleration on Horizontal Curves Model for Rural Roads

The project focussed on reviewing the existing model for deceleration on horizontal curves on rural roads currently included in the Austroads *Guide to Road Design - Part 3: Geometric Design* (Austroads 2010a). This model provides designers with a tool to estimate the changes in vehicular speed as they travel through a horizontal curve of a given radius and approach speed.

Definitions of terminology related to the operating speed model are included in Appendix A. A background to the development of the deceleration on horizontal curves graph is provided in Appendix B.

1.1.2 Operating Speed Model for Articulated Trucks on Rural Roads

Austroads (2010a) currently does not include an operating speed model for trucks on rural roads. As part of this project, speed measurements were collected for heavy vehicles for the purposes of developing such a model. The data collection sites were limited to ‘neutral’ feature sites (Section 2.2.1), including sites with gradients of 3% or less. Consequently, it was not possible to investigate all elements of a truck model, such as the influence of gradients.

1.1.3 Curves in Sequence

Austroads (2010a) provides operating speed design practices for curves in sequence. As part of this project, speed data was collected to review the design recommendations related to curves in sequence.

1.2 Purpose of Report

This report documents the process undertaken to collect speed data on horizontal curves, analyse the data and assess the implications that the analysis has in terms of the deceleration on curves for cars and trucks and the influence of curves in sequence. In addition, it outlines potential revisions of the existing operating speed model for horizontal curves.

1.3 Structure of Report

The remainder of this report is structured as follows:

- Section 2 highlights the method used
- Section 3 discusses the results
- Section 4 provides conclusions and further considerations.

The appendices provide information on terminology, the background to the existing operating speed model and details of the method, data collection and analysis.

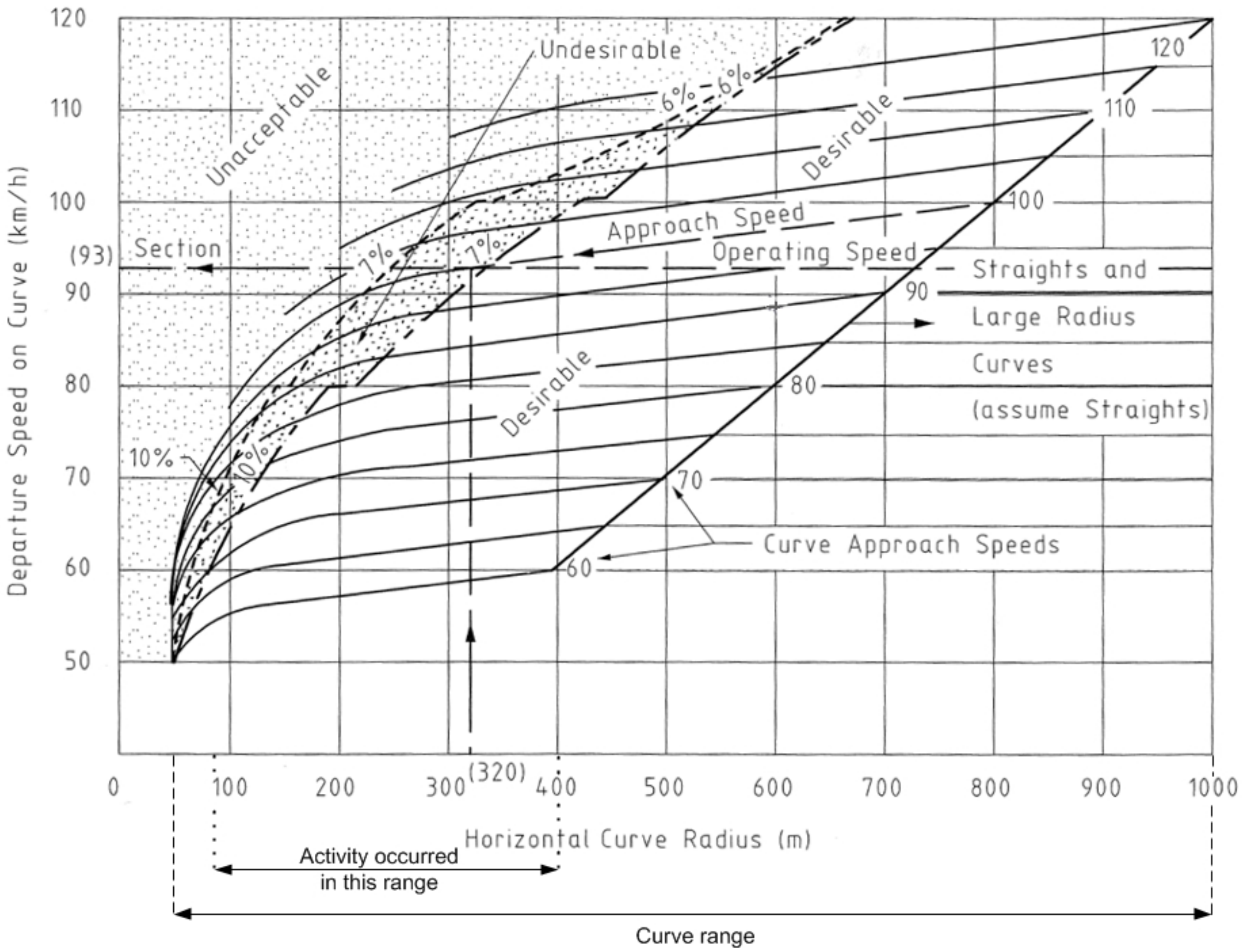
2 METHOD

The project method consisted of a series of tasks including:

- identifying horizontal curve sites for data collection
- collecting speed measurements at sites
- analysing data
- validating the existing Austroads operating speed model
- identifying potential enhancements to the existing operating speed model.

2.1 Identifying Horizontal Curve Sites

Figure 2.1 shows the existing deceleration on horizontal curves graph included in Part 3 of the *Guide to Road Design* (Austroads 2010a). The graph considers curves with radii between 50 and 1000 m. However, the focus of the project was curves with radii in the range of 90 to 400 m. This range of curve radii was identified as the model area where a speed reduction would be most readily observed and hence provided the greatest opportunity for validation.



Source: Austroads (2010a) with annotations.

Figure 2.1: Existing Austroads deceleration on curves graph

2.2 Identifying Curves

2.2.1 Desire Curve Features

A site identification process was required to locate horizontal curves that were suitable for validating the operating speed model. It was desirable to include curves with 'neutral' features including:

- good pavement condition
- flat longitudinal grade (i.e. grades of 3% or less)
- lane widths of at least 3 m
- superelevation in accordance with Austroads (2010a).

Austroads (2010a) recommends maximum values of superelevation for horizontal curves (Table 2.1). All curve sites included in the project were located in rural areas.

Table 2.1: Maximum values of superelevation to be used for different road types

Road type	Speed range (km/h)	Maximum superelevation
Urban	All speeds	5%
High speed rural	Greater than 90	6%
Intermediate speed rural	Between 70 and 89	7%
Low speed rural	Less than 70	10%

Source: Austroads (2010a).

2.2.2 Data Collection Sites

Based on the desired criteria, curves were chosen. The process of identifying curves is further described in Appendix C. Curves were selected to represent a range of curve radii and approach speed groupings (Table 2.2).

The project focused on small radius curves (nine sites) and included medium radius curves (three sites). The definition of a small or medium radius curve varied depending on the approach speed. The table identifies the number of curves included in the project for each approach speed and curve radii combination. No large radius curves (i.e. curves with radii larger than Group B) were included in the study.

As shown in Table 2.2, no sites were available for the two slowest approach speed groupings and limited sites were available for the remaining approach speeds. The approach speed grouping was based on the 85th percentile speed on the approach to a curve for cars, as this measurement forms the basis of the operating speed model.

A summary of the curve site characteristics is provided in Appendix D. The chosen curve sites generally were able to meet the criteria for a neutral feature site. However, the desired curve criteria for superelevation were exceeded at some sites, particularly the curves in sequence on Barkers Lodge Road. At these sites, Austroads (2010a) recommends superelevation of 6%. For this pair of curves, the superelevation was measured as 8% and 10%.

The signing and marking strategies used at the curve sites were not used as specific curve selection criteria (see Appendix D). Most sites had horizontal curve advisory speed warning signs. However, the influence of these signs on driver behaviour or operating speed was not assessed as part of the project.

The speed data obtained at the data collection sites is summarised in Appendix E.

Table 2.2: Operating speed model validation sites (based on speed data for all cars)

Approach speed grouping[(1)] (km/h)	Group A (small radius)			Group B (medium radius)			Total (approach speed grouping)
	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[(2)]	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[(2)]	
55 to less than 65	50 to less than 100	–	–	100 to less than 350	–	–	–
65 to less than 75	50 to less than 100	–	–	100 to less than 450	–	–	–
75 to less than 85	50 to less than 150	1	–	150 to less than 500	–	–	1
85 to less than 95	50 to less than 200	4	1	200 to less than 550	1	1	7
95 to less than 105	50 to less than 250	1	2	250 to less than 600	1	–	4
Total (all sites)							12

1 Approach speed grouping is based on the operating speed for cars, measured on the approaches to a curve.
2 Paired curves in sequence are listed as two separate curves in the table. The approach speed grouping is based on the operating speed (cars) for the exterior approaches to curves in sequence.

2.2.3 *Banded Speed Measurements*

In order to expand the combinations of different approach speeds, a method was developed to band the approach speed data. The method developed is described in Appendix C. Banding speed data provided additional combinations of approach speed and curve radii from which to validate the operating speed model (Table 2.3). In total, using this approach provided 57 speed and curve radii groupings from which to analyse the operating speed model.

Table 2.3: Operating speed validation sites (based on banded speed data)

Banded approach speed grouping (km/h)	Group A (small radius)			Group B (medium radius)			Total (approach speed grouping)
	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[(1)]	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[(1)]	
55 to less than 65	50 to less than 100	1	–	100 to less than 350	6	2	9
65 to less than 75	50 to less than 100	1	–	100 to less than 450	7	4	12
75 to less than 85	50 to less than 150	3	2	150 to less than 500	5	2	12
85 to less than 95	50 to less than 200	6	2	200 to less than 550	2	2	12
95 to less than 105	50 to less than 250	6	3	250 to less than 600	2	1	12
Total (all sites)							57

1 Paired curves are sequence is listed as two separate curves in the table. The approach speed grouping is based on banded approach speed data for the exterior approaches to curves in sequence.

Banded speed considerations

As the existing operating speed model is based on 85th percentile speed measurements, it was necessary to determine changes in speed for the banded speed data equivalent to those for the 85th percentile speed measurements. This process is discussed in Appendix C.

2.3 Validating the Existing Operating Speed Model

The speed data collected at the 12 curve sites was analysed in order to:

- assess the validity of the existing deceleration on horizontal curves graph
- consider the operating speed of trucks on level terrain
- review the method applied by the existing operating speed models to curves in sequence.

2.3.1 Determining Speed Reduction through Curve

In order to validate the existing operating speed model for a specific approach speed, methods of analysing the data included either:

- plotting the actual approach speed and fitting curves
- adjusting the measured approach speed to the approach speed being considered.

The project adopted the latter approach, as a similar approach could be applied to include banded speed measurements in the analysis. Using this approach, measurements within ±5 km/h of the speed of interest were compiled.

For example, if the approach speed of interest was 100 km/h, but the measured operating speed was 103 km/h, then it was desirable to adjust the measured speed. Equivalent speeds were determined by applying the percentage reduction in speed between the approach speed and curve midpoint speed to determine the speed reduction for the desired approach speed.

2.3.2 Comparing Predicted and Measured Speed Reduction on Curves

To validate the existing deceleration on horizontal curves graph, the speeds measured on horizontal curves were compared with the speed reduction predicted by the existing deceleration on horizontal curves model.

2.3.3 Developing Revised Deceleration on Horizontal Curves Models

Regression models were developed based on the speed data obtained from the curve sites. The models developed are discussed in Appendix F. This process was used to consider models for both cars and articulated trucks.

2.4 Curves in Sequence

The current Austroads operating speed model includes a series of procedures to predict changes in speed through curves in sequence. To validate the existing operating speed model, the project examined:

- whether straights (between horizontal curves) shorter than 200 m had an effect on vehicle operating speed
- section operating speeds through the curves in sequence
- deceleration due to horizontal curves.

Two pairings of curves were reviewed:

- Barkers Lodge Road (120 and 140 m radius curves)
- Healesville-Kinglake Road (160 and 250 m radius curves).

For each linkage of curves, the measured operating speeds for cars were compared with the changes in speed as determined by the existing operating speed model in each direction of travel. Operating speed model predictions were based on Section 3 and Appendix C of the *Guide to Road Design Part 3* (Austroads 2010a).

Aspects of the existing operating speed model considered included:

- the predicted curve departure speed, Figure 3.5 of Austroads (2010a)
- the section operating speed, Table 3.3 of Austroads (2010a)
- where applicable, acceleration on straights, Figure 3.4 of Austroads (2010a)
- operating speed model procedures, as detailed in Section 3 and Appendix C of Austroads (2010a).

3 RESULTS

3.1 Introduction

The two aspects of the existing operating speed model were investigated were:

- deceleration on horizontal curves model for cars
- curves in sequence for cars.

In addition, speed measurements for articulated trucks were analysed to investigate development of a deceleration on horizontal curves model for articulated trucks.

3.2 Deceleration on Horizontal Curves Models for Cars

Results of the analysis of speed data were used to develop revised deceleration on horizontal curves models for different approach speeds. Figure 3.1 shows the revised models developed in comparison to the existing Austroads models. The revised models are shown for the range of curve radii included in the study (i.e. 90 to 400 m).

Further figures detailing the revised models are included in Appendix G.

3.2.1 Small Radius Curves

For small radius curves, differences were observed between the existing and revised models. This included:

- For the smallest radius curves (90 and 100 m), the existing model predicted a greater curve departure speed than the revised model for 80 and 90 km/h approach speeds.
- For a 250 m radius, the revised model predicted a greater curve departure speed than the existing model for a 100 km/h approach speed.

3.2.2 Medium Radius Curves

For all approach speed and curve radii combinations, the revised model predicted greater curve departure speeds than the existing model. The differences were greatest for a 400 m radius and the fastest approach speeds (90 and 100 km/h), where differences exceeded 4 km/h. This was influenced by the minimal reduction in curve departure speed at sites with 320 and 400 m radii.

As shown in Figure 3.1, the revised model predicted that the largest curve radius where a reduction in curve departure speed occurred was in the medium radius grouping for all approach speeds, except at 100 km/h approach speeds[1]. For the existing operating speed models, this was predicted to occur in the large radius grouping.

For example, at a 90 km/h approach speed, the existing model predicted that curves with radii less than 700 m would cause a curve departure speed less than 90 km/h. The revised model predicted that this would occur for curve radii less than 400 m.

[1] For the 100 km/h approach speed, the largest curve radius where no reduction in curve speed would occur was greater than the range of curves (90 to 400 m radii) included in the study.

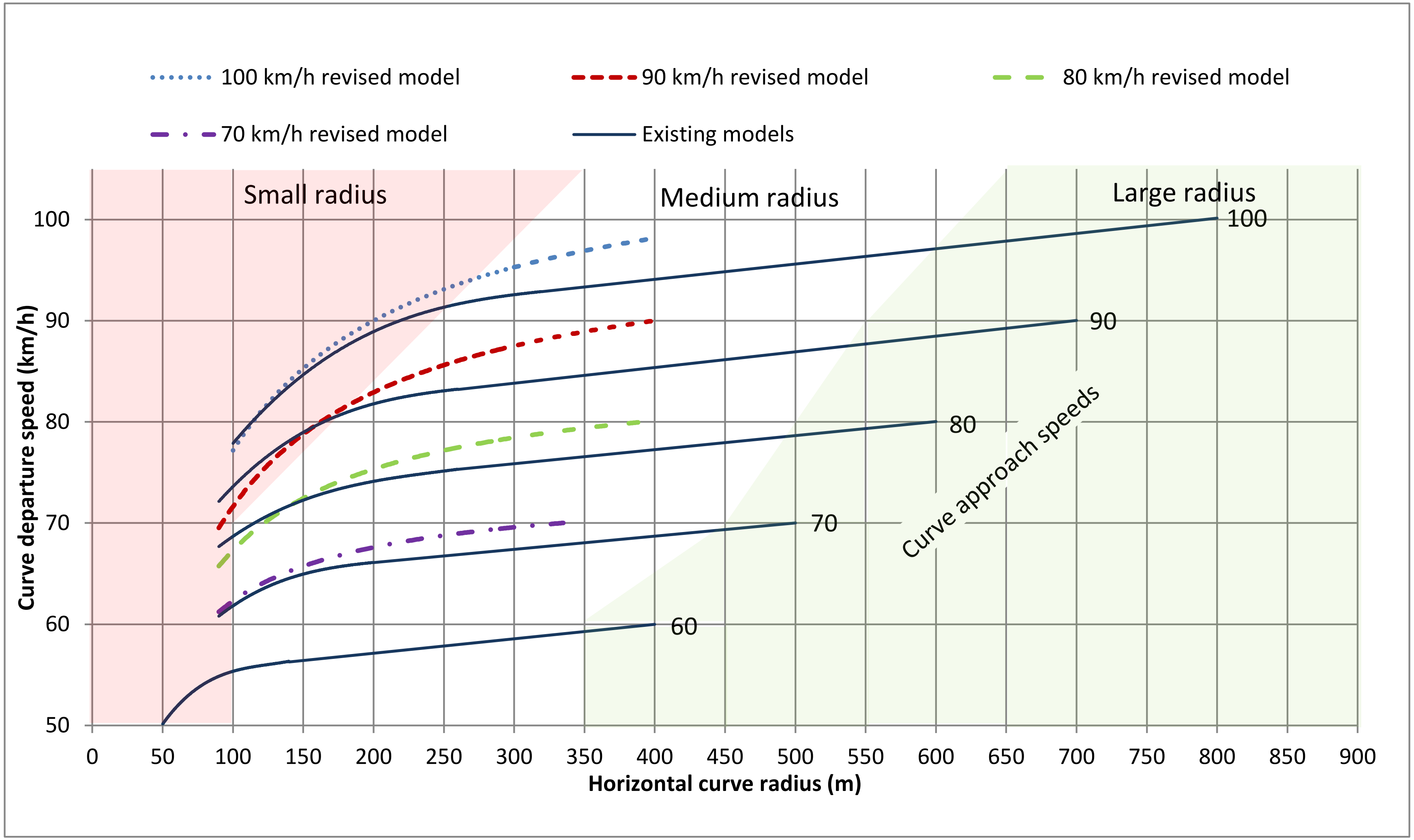


Figure 3.1: Comparison of existing and revised deceleration on curves models for cars

3.2.3 Not Included in the Analysis

It was not possible to validate or develop a revised model for the 60 km/h approach speed, as only two of the curve sites were found to have deceleration on the curves for this approach speed. However, the banded speed measurements for 60 km/h were faster than predicted by the existing operating speed model and generally in line with the trends observed for faster approach speeds.

Speed measurements were not collected at any sites with curve radii greater than 400 m, including the large radius grouping shown in Figure 3.1. Although, based on the results obtained for curve radii between 90 and 400 m, minimal speed reduction was observed for curves with radii of 320 and 400 m, which suggested that minimal reduction in curve departure speed would be expected for curves in the large radius grouping.

3.3 Articulated Trucks

3.3.1 Differences between Articulated Truck and Car Speeds

Articulated trucks were found to travel at slower speeds than cars on the approaches to and at the midpoint of horizontal curves. This result generally aligned with Table 3.4 of Austroads (2010a), which suggests that as an average condition, articulated trucks (defined as a 19 m semi-trailer) travel at speeds 10 km/h slower than cars for speeds between 70 and 100 km/h.

Additionally, at half of the curve sites, the speed reduction for articulated trucks between the approach and midpoint of a curve was found to be similar to that for cars. This is likely to have influenced the similarities between the predicted articulated truck and car curve departure speeds discussed in Section 3.3.2.

Appendix G provides additional details of the relationships between car and truck speeds observed at the curve sites.

3.3.2 Deceleration on Horizontal Curves Model for Articulated Trucks

Due to limited sample sizes and numbers of curve sites with articulated truck speed data, develop deceleration on horizontal curves models were limited to 80 and 90 km/h approach speeds. Figure 3.2 shows the deceleration on horizontal curves model developed for articulated trucks at an 80 km/h approach speed. Included in the diagram are the existing and revised models for cars, as well as the curve midpoint speed data collected as part of the study.

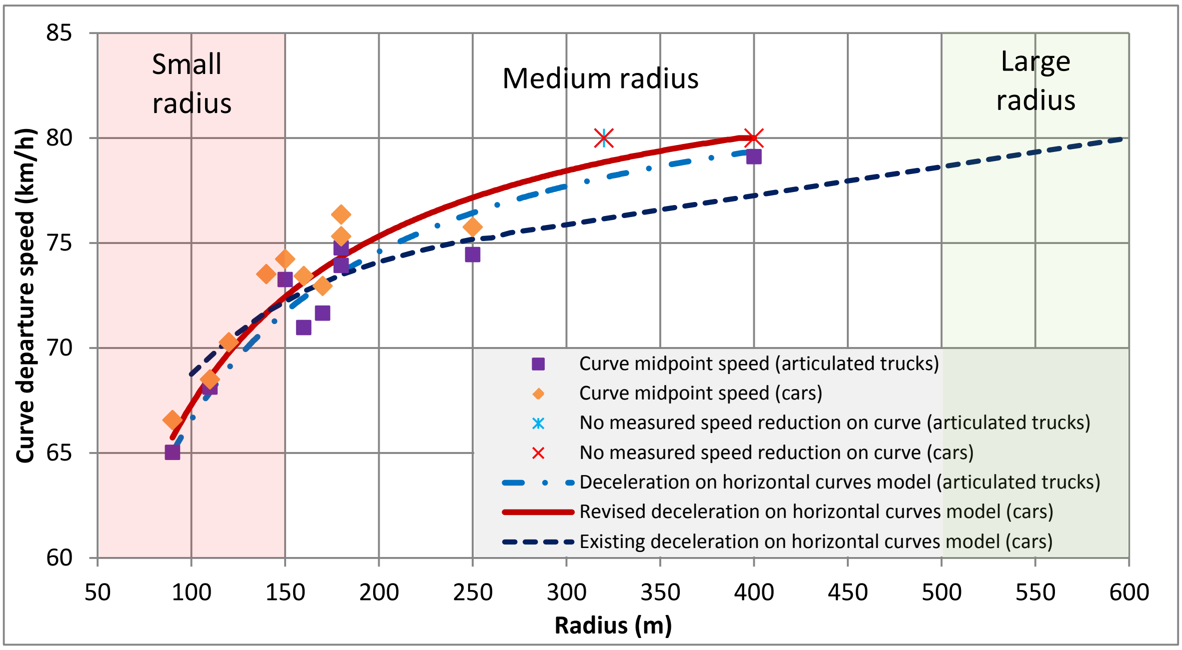


Figure 3.2: 80 km/h approach speed, measured speed on curve (articulated trucks and cars)

Across the entire range of curve radii included in the study, the articulated truck model for 80 km/h approach speeds predicted a curve departure speed approximately 1 km/h less than the revised car model. Similar results were obtained for the articulated truck model developed for 90 km/h approach speeds.

The articulated truck model for 90 km/h approach speeds and other aspects of the articulated truck models are included in Appendix G.

3.4 Curves in Sequence

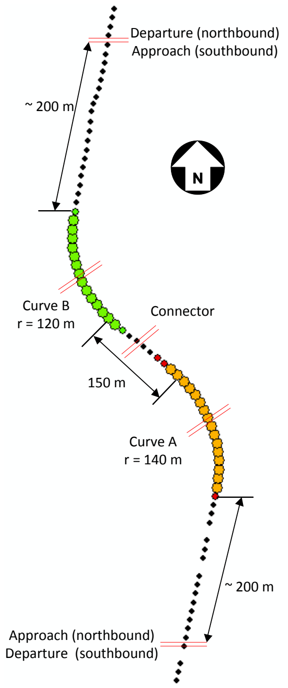
The project analysed both:

- larger radius curve followed by a smaller radius curve
- smaller radius curve followed by a larger radius curve.

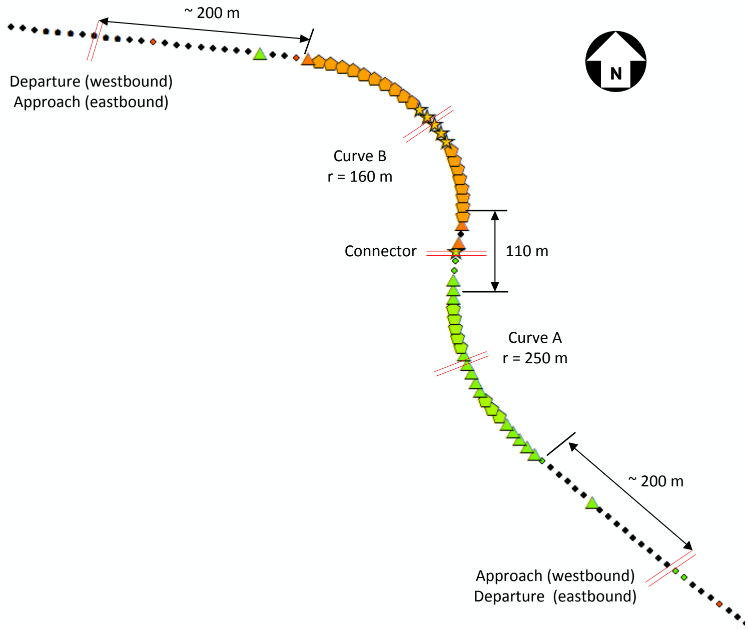
The curves were analysed using the method described in Section 2.4. The results of the analysis are summarised in this section. Supplemental figures are included in Appendix G.

3.4.1 Curve Sites

Both curve sites consisted of a pair of curves of differing radii separated by a connecting straight shorter than 200 m. Diagrams of the curves sites are shown in Figure 3.3.



(a) Barkers Lodge Rd



(b) Healesville-Kinglake Rd

Figure 3.3: Curves in sequence sites

The posted speed limit, range of curve radii and section operating speed for the curves are shown in Table 3.1. Additional characteristics of the curve sites are provided in Appendix D.

Table 3.1: Route characteristics

Route	Posted speed limit (km/h)	Range of curve radii (m)	Section operating speed (km/h)(1)
Barkers Lodge Road	100	120–140	75
Healesville-Kinglake Road	80	160–250	82

1 Determined from Table 3.3 of Part 3 of the *Guide to Road Design* (Austroads 2010a).

3.4.2 Larger Radius Curve Followed by Smaller Radius Curve

Figure 3.4 shows a comparison of the speed measurements and existing operating speed model predictions for the two routes where a larger radius curve was followed by a smaller radius curve.

Healesville-Kinglake Road westbound

The westbound direction of Healesville-Kinglake Road consisted of a 250 m radius curve followed by a 160 m radius curve. Changes in speed on Curves A and B were determined using the existing deceleration on horizontal curves graph (Austroads 2010a). Speed changes generally aligned with the operating speed model predictions including:

- minimal change in speed measured between the midpoint of Curve A (80.9 km/h) and the approach to Curve B (80.1 km/h)
- slightly greater speed measured at the midpoint of Curve B (76.1 km/h) than the predicted departure speed for Curve B (73 km/h).

Barkers Lodge Road northbound

The northbound direction of Barkers Lodge Road consisted of a 140 m radius curve followed by a 120 m radius curve. At the Curve A midpoint, the measured speed (86.4 km/h) was similar to the curve departure speed predicted (85 km/h). However, an increase in speed was observed between the midpoint of Curve A and the approach to Curve B (from 86.4 to 89.3 km/h). This did not align with the procedures recommended by the existing operating speed model, which suggested no change in speed.

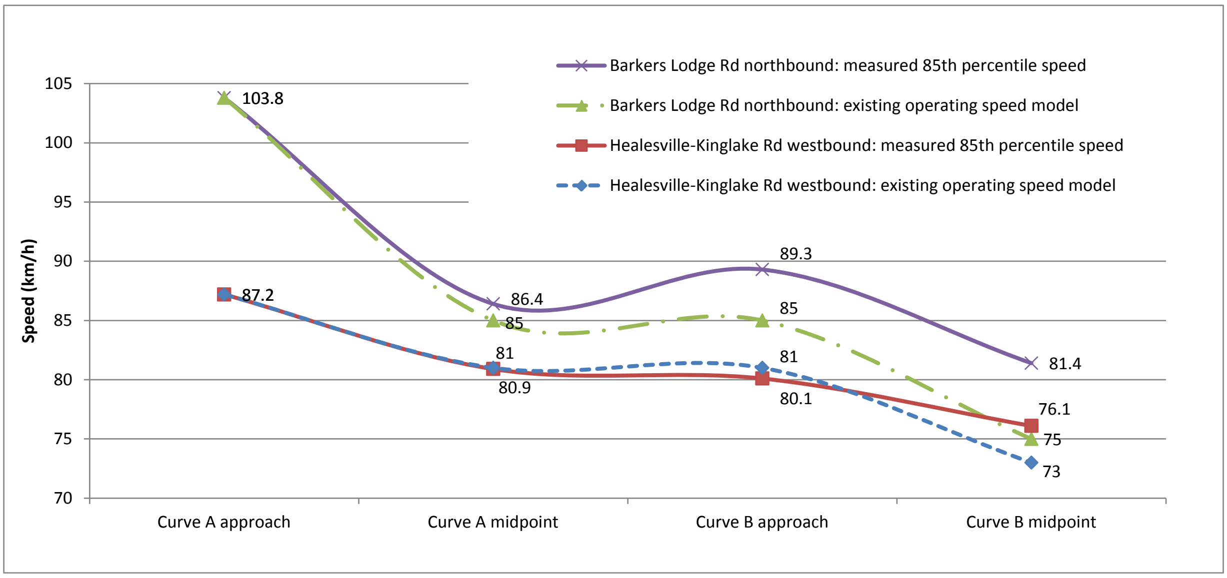


Figure 3.4: Larger radius curve followed by smaller radius curve

3.4.3 *Smaller Radius Curve Followed by Larger Radius Curve*

Figure 3.5 shows a comparison of the speed measurements and existing operating speed model predictions for the two routes where a smaller radius curve was followed by a larger radius curve.

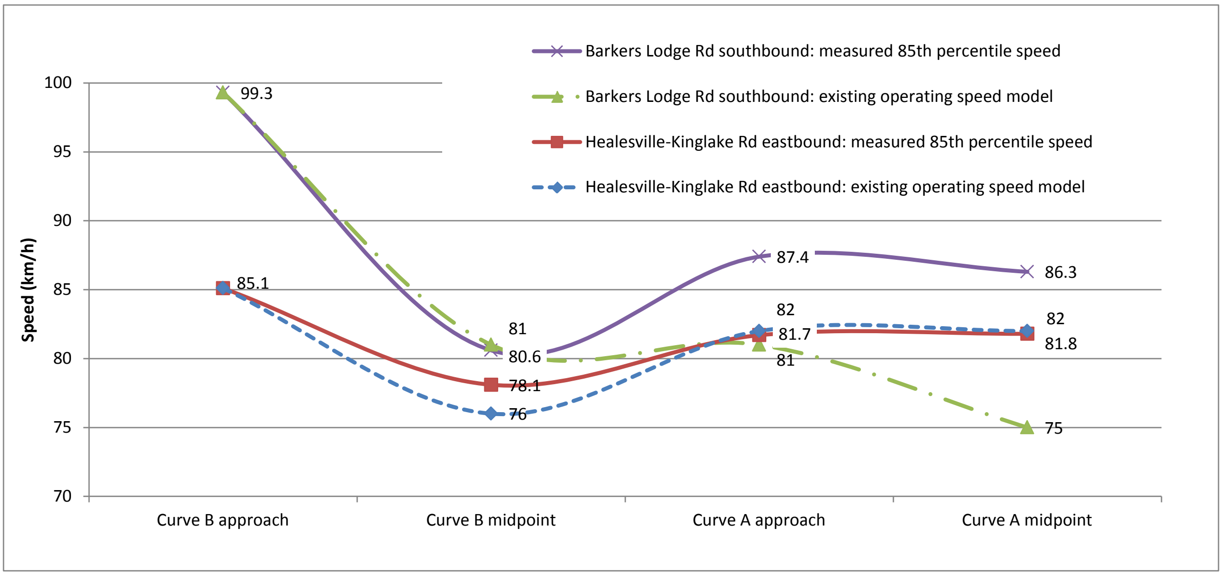


Figure 3.5: Smaller radius curve followed by larger radius curve

Healesville-Kinglake Road eastbound

For the eastbound direction of Healesville-Kinglake Road (160 m radius curve followed by a 250 m radius curve), the results showed a close correlation with the operating speed model predictions.

Using the existing deceleration on horizontal curves graph, the departure speed was determined for Curve B (76 km/h). This value was less than the section operating speed (82 km/h), which suggested that vehicles would accelerate after departing Curve B.

Using the acceleration on straights chart (Figure 3.4 from Austroads 2010a), the speed was predicted to increase to the section operating speed at the approach to Curve A (82 km/h). The section operating speed was similar to the measured speed (81.7 km/h) at the approach to Curve A. The section operating speed was predicted to be maintained through Curve A and was measured as 81.8 km/h at the Curve A midpoint.

Barkers Lodge Road southbound

For the southbound direction of Barkers Lodge Road, a 120 m radius curve was followed by 140 m radius curve. The measured speed at the Curve B midpoint (80.6 km/h) closely aligned with the predicted speed (81 km/h).

An increase in speed was measured between the Curve B midpoint (80.6 km/h) and the approach to Curve A (87.4 km/h). A slightly slower speed was measured at the Curve A midpoint (86.3 km/h). However, as the section operating speed (75 km/h) was slower than the predicted departure speed for Curve B (81 km/h), further slowing was predicted on Curve A. As a result, the Curve A departure speed was predicted to decrease to the section operating speed.

3.5 Discussion of Results

3.5.1 Deceleration of Cars on Horizontal Curves

Based on the analysis of the speed data collected as part of this study, revised deceleration on curves models were developed for a range of different approach speeds.

The results of the analysis generally found that:

- For small radius curves, the revised models predicted speeds that differed from the existing models, particularly for:
  - the smallest radii grouping, where measured speeds where similar to or less than the speed predicted by the existing model
  - the largest radii grouping, where measured speeds were greater than the speeds predicted by the existing model.
- For medium radius curves, the revised models predicted greater curve departure speeds than for the existing models.
- The largest differences in speed deceleration between the existing and revised models were for a 400 m curve radius and faster approach speeds (90 and 100 km/h).
- The largest curve radius at which a reduction in curve departure speed was predicted was smaller for the revised models than for the existing models.

It was not possible to validate or develop a revised model for the 60 km/h approach speed, as only two of the curve sites were found to have deceleration on the curves for this approach speed. However, the speed measurements obtained for 60 km/h generally supported the trends found in the faster approach speeds, including faster curve departure speeds.

For one of the isolated curve sites included in the project, superelevation exceeded the Austroads (2010a) recommended maximum value. This is discussed in Appendix H. However, this was not found to have an observable influence on curve departure speeds.

3.5.2 Articulated Trucks

The speed measurements obtained as part of the study found that articulated trucks approached and travelled through curves at slower speeds than cars. These results generally aligned with the guidance provided in Austroads (2010a).

With regards to the speed reduction due to horizontal curves, at a number of the sites included in the study, the speed reduction was found to be similar for articulated trucks and cars. Consequently, the deceleration on horizontal curves models for articulated trucks at 80 and 90 km/h approach speeds produced similar results to the revised car models.

3.5.3 Curves in Sequence

The results of the analysis suggested that the curves in sequence on Healesville-Kinglake Road were generally in line with the procedures recommended by the operating speed model.

However, differences were observed between the measured speeds and operating speed model predictions on Barkers Lodge Road. These included:

- an increase in speed measured on the connecting straight between curves, where the operating speed model predicted that speeds would remain constant
- speed measured on the downstream curves that was greater than predicted by the existing model.

A contributing factor to the differences observed on Barkers Lodge Road may have been the superelevation on these curves, which exceeded the Austroads (2010a) recommended maximum values. This is further discussed in Appendix H.

Another factor that may have contributed to the differences between the measured speeds and the operating speed model for curves in sequence were differing speed environments upstream and downstream of a site. As shown in Table 3.2, for Healesville-Kingslake Road, the section operating speed for the curves in sequence and the measured speeds upstream and downstream were more closely aligned than for Barkers Lodge. The differing speed environments on Barkers Lodge Road may have contributed to acceleration on the connecting straights between curves.

Table 3.2: Speed parameters for curves in sequence

Route	Direction	Speed parameter (km/h)			
		Posted speed limit	Upstream measured operating speed	Curves in sequence section operating speed	Downstream measured operating speed
Healesville-Kinglake Road	Eastbound	80	85.1	82	86.5
	Westbound	80	87.2	82	85.8
Barkers Lodge Road	Northbound	100	103.8	75	97.8
	Southbound	100	99.3	75	99.0

3.5.4 Data Collection and Analysis Factors

Method of measuring speed

As part of the project, pneumatic tube counts were used to obtain speed measurements. This differed from previous studies (e.g. Botterill 1994), which were based on radar speed measurements. It was desirable to use a method of speed measurement for the project that would not influence a driver's speed.

Tube counts were chosen considering previous studies that had found that the presence or absence of tube detectors did not have an effect on measured mean speeds (Johnston & Fraser 1983, Pitcher 1989). The use of tube counts also allowed speeds to be measured across multiple days and different times of the day.

The pneumatic tube counts recorded vehicle speeds on the approach to a curve, at the curve midpoint and downstream from a curve. However, the existing operating speed model was based on the curve departure speed, which represents the maximum deceleration on a curve. The maximum deceleration on a curve may not occur at the curve midpoint. However, the need for bi-directional counts led to using the curve midpoint as a count location. This issue is further discussed in the data collection procedures described in Appendix C.

Number of curve sites and sample sizes

The project included 12 sites where speed measurements were conducted. Three sites were included with curve radii of 250 m or greater (i.e. 250, 320 and 400 m). The 320 and 400 m radius curves were found to have minimal reduction in speed. However, the 250 m radius curve aligned more closely with the existing operating speed model.

Across all sites, large sample sizes were generally obtained for cars. However, for articulated trucks less data was available. This resulted in smaller sample sizes and limited the approach speeds for which banded speed measurements could be developed for articulated trucks.

Additionally, due to the limited number of sites, it was not possible to independently verify the results of the regression models.

4 CONCLUSIONS AND FURTHER CONSIDERATIONS

4.1 Conclusions

The results of the study suggested that the existing Austroads deceleration on horizontal curves model provides a conservative representation of the operating speeds of vehicles, particularly for medium radius curves (Figure 4.1).

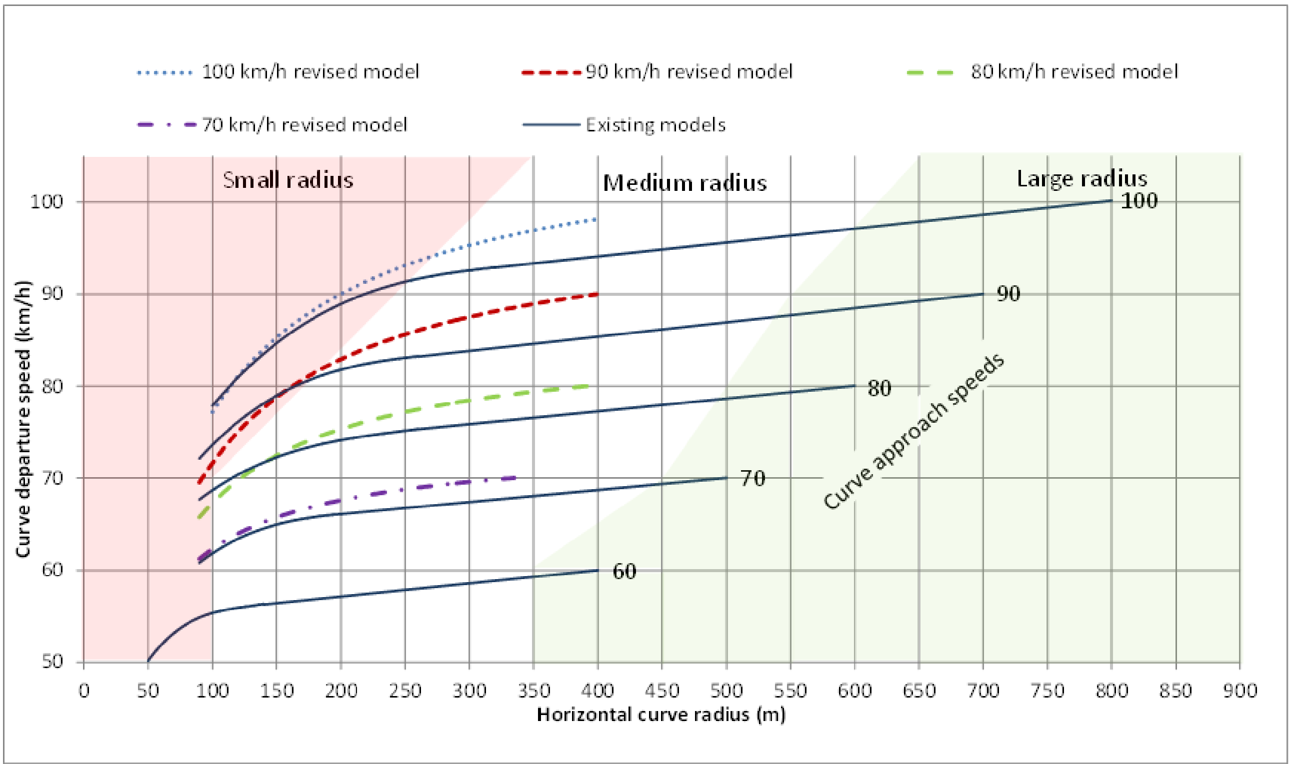


Figure 4.1: Comparison of existing and revised deceleration on curves models for cars

Articulated trucks were generally found to travel slower than cars on the approach to and at the midpoint of curves. However, the speed reduction due to horizontal curves was found to be similar to that for cars. This was reflected in the deceleration on horizontal curves models developed which predicted similar results to the models developed for cars.

Analysis of curves in sequence found that one grouping of curves was generally in line with the operating speed model procedures. For the second grouping of curves, the section operating speed and acceleration behaviour between curves differed from the operating speed model predictions. However, the superelevation for these curves exceeded the Austroads (2010a) recommended maximum values, which may have influenced the results. Differing speed environments upstream and downstream of the curves in sequence may also have been a factor.

4.2 Further Considerations

The revised deceleration on horizontal curves models (Figure 4.1) are presented for consideration for updating the existing Austroads operating speed model. Prior to updating the existing models, further research may consider investigating curve radii greater than 250 m to confirm the results of the project. Between the existing and revised models, the greatest differences in curve departure speed occurred in this range of curve radii. However, the project focussed on small radius curves and included limited sites in the medium range.

The deceleration on horizontal curves models for articulated trucks generally produced similar results to the revised models developed for cars. All curve sites included in the study were on level grades. Further research would be of benefit to examine the influence of gradients on trucks or other factors that may influence their behaviour.

Further research may also further examine curves in sequence, to consider whether the results that deviated from the existing operating speed model practices extend to a larger number of curves, or are influenced by factors such as superelevation or the speed environment upstream of the curves.

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APPENDIX A SPEED PARAMETER TERMINOLOGY

The following terminology is used in the discussion of the operating speed model. The definitions are taken from Part 3 of the *Guide to Road Design* (Austroads 2010a) and are consistent with the *Austroads Glossary of Terms* (Austroads 2010b).

A.1 Operating Speed

The term ‘operating speed’ refers to the 85th percentile speeds of cars at a time when traffic volumes are low, and drivers are free to choose the speed at which they travel.

A.2 Operating Speed of Trucks

The term ‘operating speed of trucks’ refers to the 85th percentile speed of trucks at a time when traffic volumes are low. In many places, the operating speeds of cars and trucks will be different due to their performance characteristics, especially on grades.

A.3 Desired Speed

The term ‘desired speed’ refers to the operating speed that drivers will adopt on the less constrained alignment elements (i.e. longer straights and large radius horizontal curves of a reasonably uniform section of road when not constrained by other vehicles). In other words, it is the operating speed that drivers build up to and are then happy to settle at.

A.4 Section Operating Speed

Vehicle speeds on a series of curves and short straights tend to stabilise at a value related to the range of curve radii. This speed is called the ‘section operating speed’.

A.5 Limiting Curve Speed

The limiting curve speed is the speed at which a vehicle travelling on a curve, of given radius and superelevation, will have a side friction demand equal to the absolute maximum recommended for that speed (see Austroads 2010a).

A.6 Speed Environment

The operating speed that drivers will adopt on the less constrained elements, such as straights and large radius horizontal curves of a more or less uniform section of road when not constrained by other vehicles. It is numerically equivalent to the 85th percentile desired speed.

APPENDIX B DECELERATION ON CURVES MODEL

B.1 VicRoads Deceleration on Curves Model

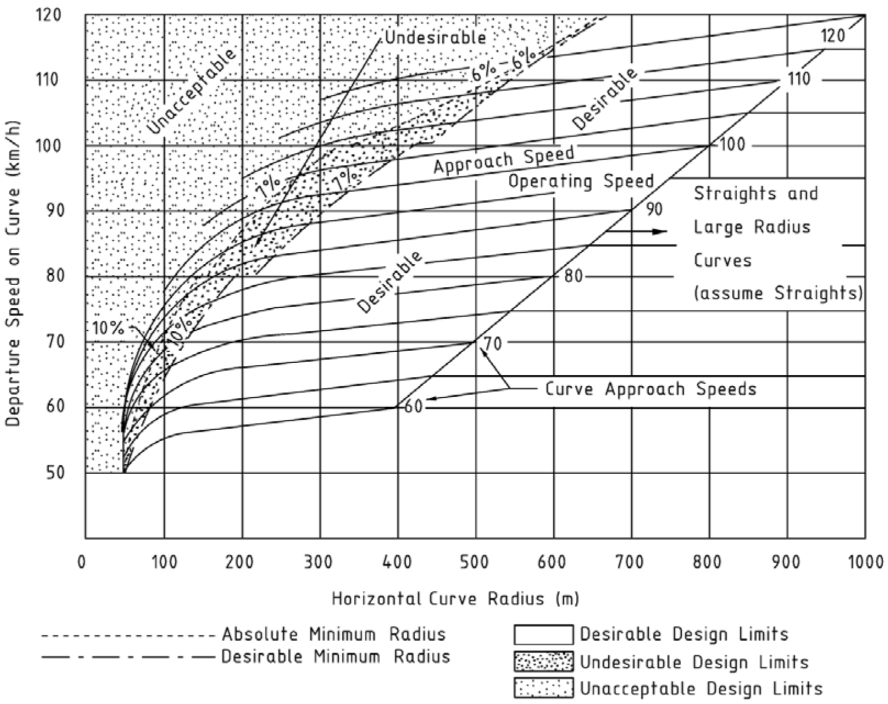
The VicRoads operating speed model for horizontal alignment design was developed to overcome difficulties experienced in applying previous curve speed prediction methods developed by McLean (1979, 1981). The prototype for the model was devised by Pape (1993). The relatively uniform speed which a driver could be expected to adopt through a single curve, or a linked group of curves of similar radius was defined as the section operating speed. Initially this was given by the McLean (1979, 1981) curve speed relations, but based on the approach speed to the curve, or to the first curve for a curve sequence, instead of the speed environment.

Limited observations of speed behaviour on tangents were used to provide relations for predicting curve approach speeds at the end of a tangent as a function of speed at the start of the tangent and the tangent length.

Botterill (1994) undertook field investigations to test the validity of the model. These investigations supported the general structure of the model, but recommended refinements to the forms of the relations for speed-radius and speed changes on tangents. These refinements were adopted in the VicRoads (1994) version of the model. The model was retained, with some minor amendments, in VicRoads (2002).

The VicRoads operating speed model was subsequently adopted for the 2003 Austroads *Rural Road Design Guide* (Austroads 2003, now superseded) and is now contained in the Austroads *Guide to Road Design Part 3: Geometric Design* (Austroads 2010a).

Figure B 1 shows the deceleration on curves graph included in Austroads (2010a).



Source: Austroads (2010a).

Figure B 1: Deceleration on curves graph

APPENDIX C CURVE IDENTIFICATION, DATA COLLECTION AND COLLATION

C.1 Curve Site Identification

The process of identifying curve sites meeting the desired criteria (Section 2.2.1) included a number of steps to determine the geometric features and approach speeds to a particular curve site.

C.1.1 Obtaining Data

Data was obtained from two primary sources to conduct the review:

- Hawkeye network survey vehicle (NSV) data.
- In-vehicle travel runs on candidate routes.

Network survey vehicle data

Horizontal curve features were identified by reviewing Hawkeye NSV data that had been previously collected by ARRB and for which permission was obtained to use as part of the project. NSV data was available for 10 m segments on candidate routes.

To determine the horizontal radius of a curve, the value was based on the NSV data. Data smoothing was necessary to account for differences between the actual centreline design radius and the survey vehicle path of travel. A three point average was used including the measurement of the 10 m interval at a specific location plus the interval immediately prior to and after the measurement. This was based on the procedure used by Turner and Tate (2009) when using similar data to determine curve radii.

In-vehicle data collection

The data review identified candidate routes with potential curves that had the desired curve criteria. To obtain an indication of the speed profiles that would be obtained at candidate sites, in-vehicle data collection was conducted.

Data was collected on the candidate routes using an in-vehicle GPS data logger (Figure C 1). A GPS data logger is a small device that is connected to the vehicle's on-board diagnostics (OBD) system and is able to record key indicators measured by the vehicle's on-board computer and engine management system. The logged speed is the measurement received directly from the engine management system. The unit does not measure speed based on GPS coordinates over time. The speed measured by the GPS logger may also differ from the speed that is displayed on a vehicle's speedometer.

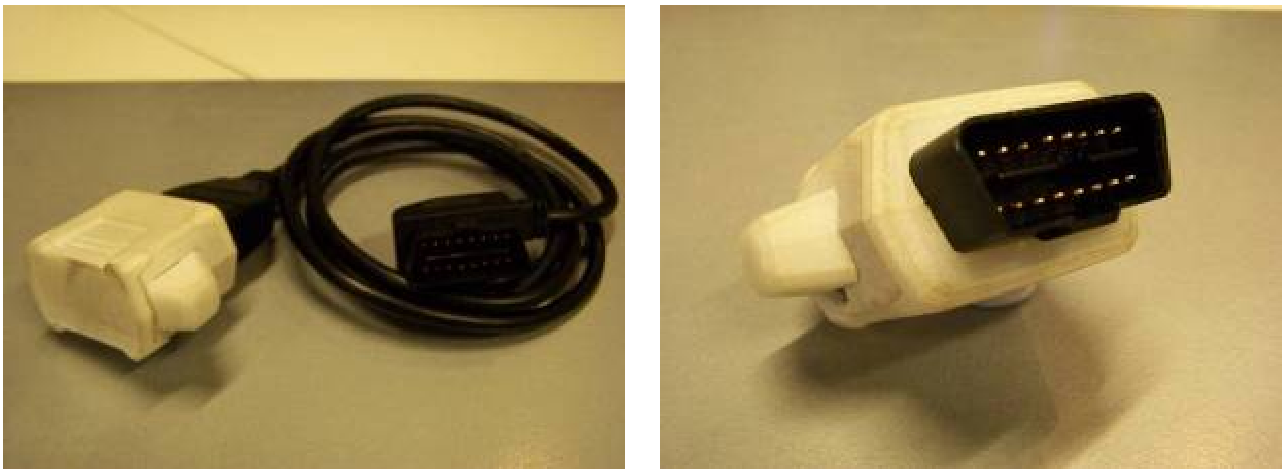


Figure C 1: GPS data logger with OBD cable and GPS data logger GPS aerial with OBD plug

To provide an accurate profile of each journey, the GPS data logger was set to record the vehicle performance and location at one second intervals. This recording interval provided the ability for a continuous analysis of the effect of changes in road geometry and conditions on vehicle performance, allowing the direct measurement of spot speeds, travel time, acceleration and deceleration rates.

C.1.2 Analysing Curve Criteria Data

For individual curves, in-vehicle speed data was compiled for a series of points (Figure C 2). This included four points along the curve approach (at 50 m intervals, five points through the curve point of curvature, quarter point, midpoint, three quarter point and point of tangency) and four points on the curve exit (at 50 m intervals). In-vehicle speed data was matched with NSV data by matching the closest GPS coordinates.

An example of a speed profile through a curve compiled using the in-vehicle data is shown in Figure C 3. This data provided an indication of the type of speed reduction that was likely to be recorded using pneumatic tube counts. However, drivers conducting the in-vehicle data collection were instructed to not exceed the posted speed limit. As speedometers typically display a speed lower than the actual speed of travel, this resulted in curve approach speeds that were typically lower than the posted speed limit. Consequently, the in-vehicle speed measurements typically had slower approach speeds than the tube count data.

Using this process, curves from candidate routes in New South Wales and Victoria were identified for conducting pneumatic tube counts. A full list of the curve sites selected is provided in Appendix D.

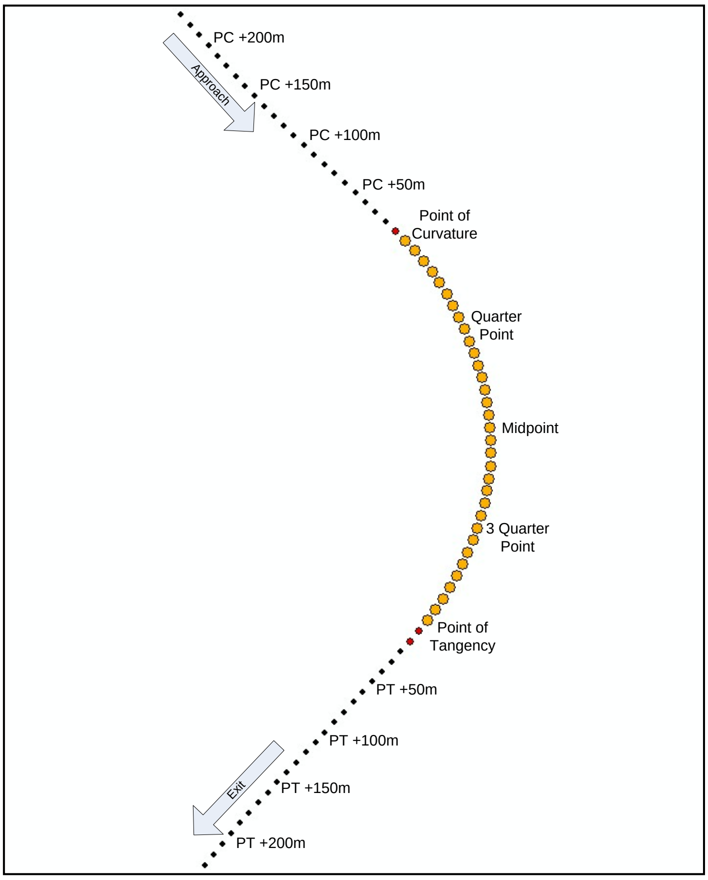


Figure C 2: Data collection points used for in-vehicle data

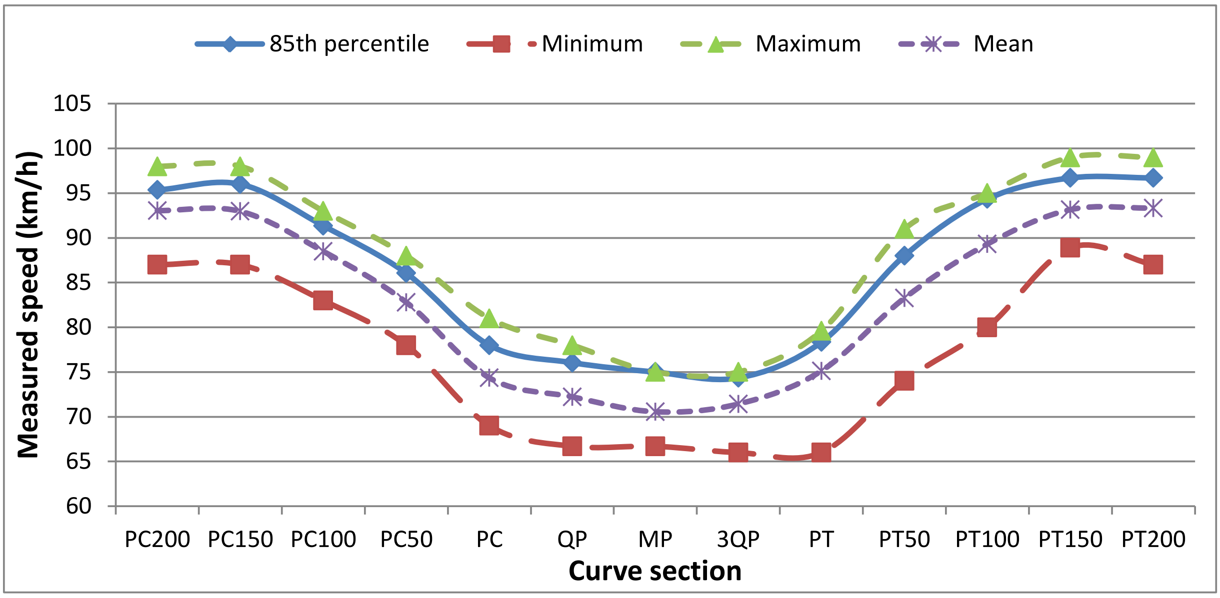


Figure C 3: Example of in-vehicle speed data collected at curve points (100 km/h posted speed limit)

C.2 Pneumatic Tube Counts

Pneumatic tube counts were conducted at the curve sites determined to have best met the desired criteria (Section 2.2.1). This allowed capture of speed data to validate both car and heavy vehicle operating speeds. Speed, traffic volume and vehicle classification data were obtained.

C.2.1 Using Tube Counts for Speed Measurements

After a review of a number of speed measurement technologies, tube counts were selected for use as part of the project. One potential issue identified with the use of tube counters was that the visible presence of the detectors may influence driver speed behaviour. This was a particular concern in the State of Victoria, where several decades ago an amphometer, employing a pair of pneumatic tube detectors, was the primary instrument used by police for speed enforcement.

However, this concern was addressed in a rural environment by Johnston and Fraser (1983) using optical detectors mounted off the roadway. These authors found that the presence or absence of tube detectors had no effect on measured mean speeds. Pitcher (1989) obtained a similar result for speeds measured on a residential street.

C.2.2 Locating Pneumatic Tube Counts

Counts were located on the approach (approximately 200 m in advance of the point of curvature), curve midpoint and downstream (approximately 200 m after the point of tangency) of the curves. Additionally, for curves in sequence, a count was located at the midpoint of the connecting straight between curves.

The counts on the curve were located as close to the midpoint as practicable. Additionally, factors such as proximity to minor intersections or property accesses also influenced count locations. Count placements typical for an isolated curve and curves in sequence are shown in Figure C 4.

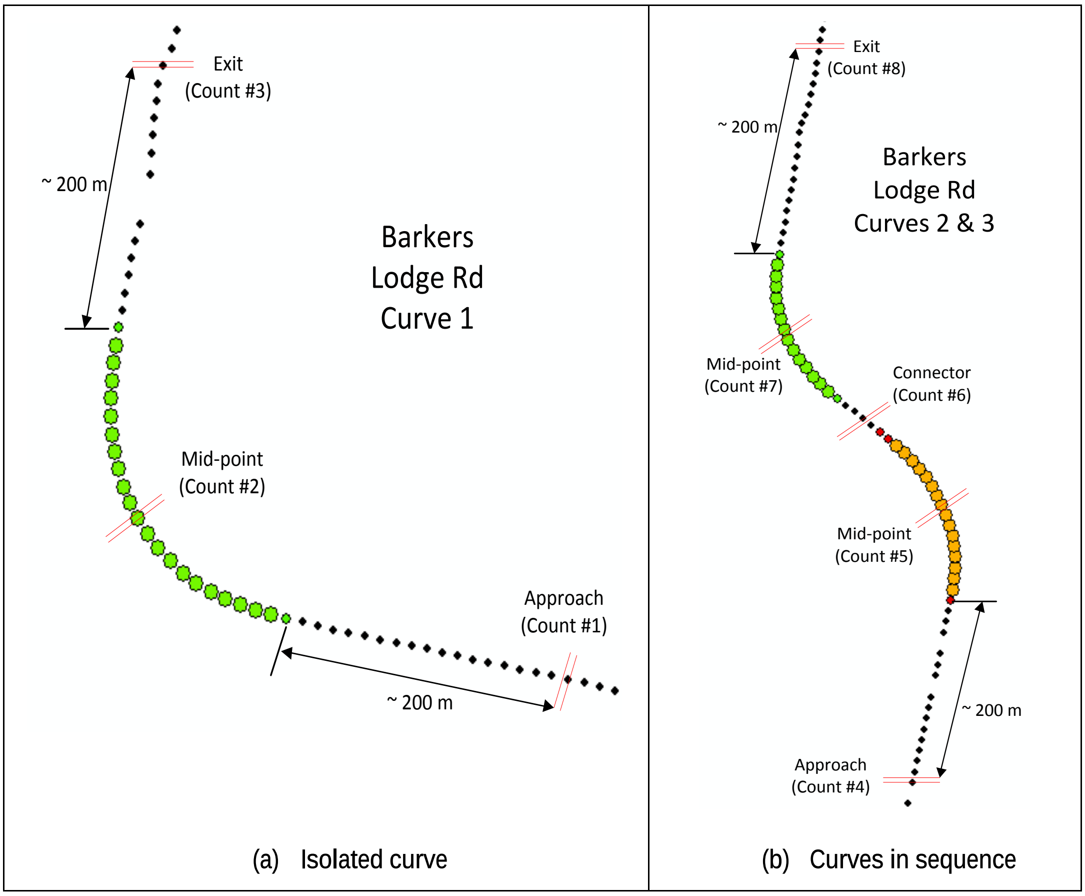


Figure C 4: Typical pneumatic tube count locations

One count placement issue of note was the use of one count at the curve midpoint to capture a vehicle's deceleration due to the curve. This may not have been the point of maximum deceleration for a curve. The example shown in Figure C 3 suggests that the maximum deceleration (for the 85th percentile speed) occurred three-quarters of the way through the curve (i.e. point 3QP) for this curve, with the speed from the in-vehicle data slightly less than at the curve midpoint (i.e. point MP). Consequently, for this curve the speed reduction for the 85th percentile speeds was slightly greater (0.6%) at point 3QP than point MP. However, as it was desirable to compile speed measurements in both directions of travel, the curve midpoint was the practical optimum to capture both directions of travel.

C.3 Data Collection

Data was typically collected over a one-week period, although for some sites data was extended to 1.5 weeks to obtain a larger sample size. The counts provided traffic volume, vehicle classification and vehicle speed data over the course of the analysis period.

Vehicles were tracked as they proceeded through the set of pneumatic tube counts and were removed from the dataset if they could not be identified at all stages of the curve or set of curves. Omitted vehicles may have resulted from turning into a driveway or side road.

To minimise time periods where the speed of vehicles may have been influenced by other vehicles, only isolated vehicles or the lead vehicle in a bunch were included in the analysis. Vehicles following another vehicle were omitted. A four second headway between a lead and following vehicle was used as the criterion for omitting following vehicles.

C.4 Vehicle Classification

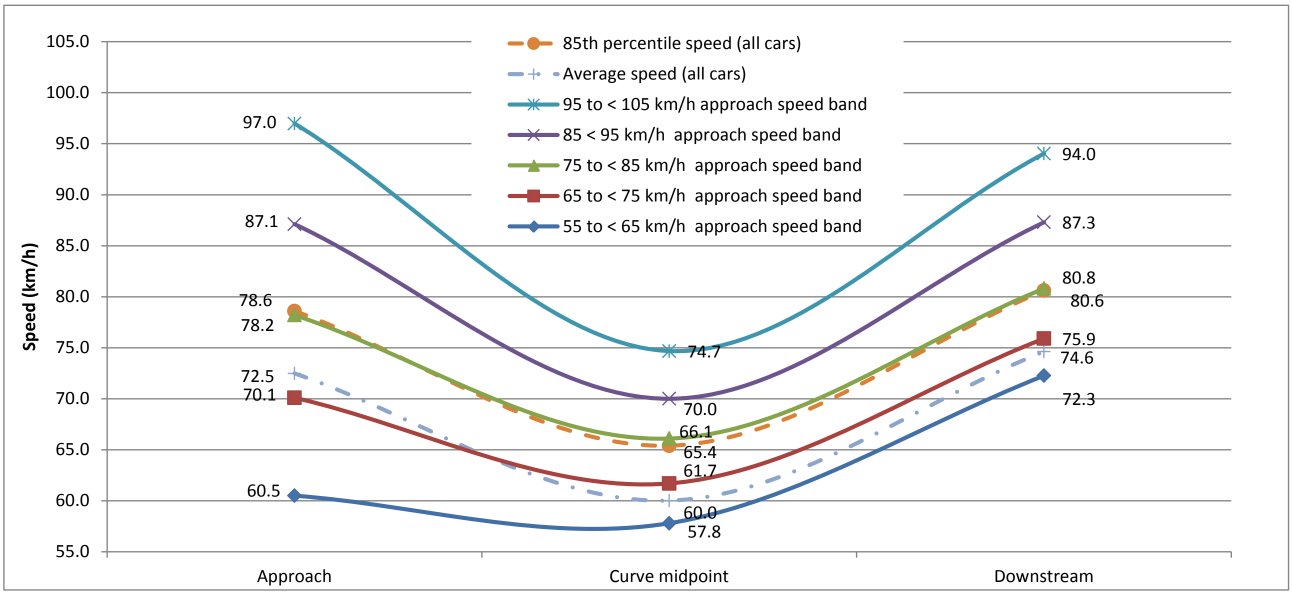
The ARX vehicle classification system was used for the vehicle-type determination by Metrocount Traffic Executive software. ARX is a modification of the Austroads 94 vehicle classification, the difference being that bicycles and motorcycles are recognised as Class 1 and all Austroads classes increase by one, while triple road trains are merged with double road trains. For the analysis:

- Cars were defined as Austroads Class 2 and 3.
- Heavy vehicles were defined as Classes 4–12 with
  - articulated vehicles representing Classes 7–12
  - rigid vehicles representing Classes 4–6.

C.5 Banded Speeds

Due to the limited number of curve sites available for analysis, it was desirable to obtain speed data for a wider range of approach speeds to assist in the validation of the operating speed model. Banding the speed data was used to expand the number of approach speeds that could be considered at a curve site.

This method consisted of grouping speed data into 10 km/h bands between 55 and 105 km/h. Figure C 5 shows an example of the banded approach applied to car speed data at the Greenwell Point Road site. As shown, the solid lines represent the 85th percentile speeds banded based on the approach speed to a site. The figure also includes the average and 85th percentile speeds for all approaching cars.



Note: Data from Greenwell Point Road (80 km/h posted speed limit, 90 m radius).

Figure C 5: Banded 85th percentile speeds (cars), average and 85th percentile speeds (all cars)

C.5.1 Developing Banded Speed Profiles

In order to develop banded speed profiles, speed data was divided into the 10 km/h bands. This process was conducted separately for cars and articulated trucks.

Each isolated curve site had three points at which speed was measured (five for curves in sequence). To find the speed of a vehicle at each stage along the curved road segment, vehicles were identified and tracked through each collection point.

In order to track vehicles, a process was developed matching vehicles at each count location by considering the timestamp of each record and the vehicle classification. This process built up a set of unique matched vehicles. Where no match was found, the data was discarded. For one curve site, the automated process was checked against a manual data aligning method. The automated process was found to be highly accurate with minimal additional data removal necessary.

C.5.2 Application of Banded Speed Data

By using banded speeds, a greater number of model validation sites were available than if speed was only compiled at each site for all speed measurements. From the 12 curve sites, 57 banded speed profiles were developed to validate the deceleration on curves graph (Table C 1).

For some curves, there were very few speed measurements in the 55 to 65 km/h grouping. Thus, it was only possible to obtain banded speed profiles at 9 of the 12 sites. Additionally, at some sites no speed reduction was observed for a particular approach speed grouping. This was most evident for the 55 to 65 km/h grouping, where there were only two sites where there was a measured reduction of speed on the curve.

Additionally, it was not possible to develop banded speed profiles for articulated trucks at a number of sites due to the smaller sample sizes recorded for this vehicle type.

Table C 1: Banded approach speed sites

Banded approach speed grouping[1] (km/h)	Group A			Group B			Total (approach speed grouping)
	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[2]	Curve radius (m)	Isolated curves per grouping	Curves in sequence per grouping[2]	
55 to less than 65	50 to less than 100	1	–	100 to less than 350	6	2	9
65 to less than 75	50 to less than 100	1	–	100 to less than 450	7	4	12
75 to less than 85	50 to less than 150	3	2	150 to less than 500	5	2	12
85 to less than 95	50 to less than 200	6	2	200 to less than 550	2	2	12
95 to less than 105	50 to less than 250	6	3	250 to less than 600	2	1	12
Total (all sites)							57

1 Approach speed grouping is based on the banded operating speed car speed, measured on the approaches to a curve.
2 Paired curves in sequence are listed as two separate curves in the table. The approach speed grouping is based on the operating speed (cars) for the exterior approaches to curves in sequence.

C.6 Determining Speed Reduction on Curve

C.6.1 Aligning Banded and Operating Speed Measurements

As the banded speed data represented a subset of all approaching vehicles, it was necessary to consider how this data could be applied to the analysis. Of particular interest was the speed reduction between the curve approach and midpoint.

The existing deceleration on horizontal curves graph is based on the operating (i.e. 85th percentile) speed for all vehicles. However, as shown in Table C 2, the speed reduction due to the 85th percentile speed for banded data differed from the operating speed for all vehicles. It was necessary to determine an 'operating speed equivalent' reduction for banded data.

For each curve site, the operating speed for all approaching vehicles was compared with the banded approach speed for which it most closely aligned (Table C 2).

The comparison showed that:

- the percentage speed reduction for the banded 85th percentile speeds was greater than the operating speed reduction for all cars
- the percentage speed reduction for the banded average speeds was less than the operating speed reduction for all cars.

To compensate for these differences, a reduction equivalent to that for the operating speed for all vehicles was determined. The median of the banded 85th percentile and average speed reductions was used for this value. As shown in Table C 2, this produced speed reduction within 0.5% of the reduction for the operating speed for all car data.

Table C 2: Comparison of banded speed data with speed data for all cars

Curve site	Approach speed data	Speed measurement(1)	Approach speed (km/h)	Curve midpoint speed (km/h)	Speed reduction (%)
Greenwell Point Road (90 m radius)	All cars	Operating speed	78.6	65.4	16.8
	75 to less than 85	85th percentile	78.2	66.1	15.5
	75 to less than 85	Average	75.0	61.5	18.0
	75 to less than 85	Operating speed equivalent			16.7
Barkers Lodge Road (120 m radius)	All cars	Operating speed	99.3	80.6	18.8
	95 to less than 105	85th percentile	102.9	84.4	18.0
	95 to less than 105	Average	99.2	78.8	20.6
	95 to less than 105	Operating speed equivalent			19.3
Healesville-Kinglake Road (150 m radius)	All cars	Operating speed	90.4	79.3	12.3
	85 to less than 95	85th percentile	92.4	82.1	11.1
	85 to less than 95	Average	89.1	76.7	13.9
	85 to less than 95	Operating speed equivalent			12.5
Culburra Road (180 m radius)	All cars	Operating speed	90.9	82.9	8.8
	85 to less than 95	85th percentile	92.2	84.8	8.0
	85 to less than 95	Average	88.8	80.1	9.7
	85 to less than 95	Operating speed equivalent			8.9
Healesville-Koo Wee Rup (Woori-Yallock) Road (320 m radius)	All cars	Operating speed	93.8	92.8	1.1
	85 to less than 95	85th percentile	92.7	92.5	0.02
	85 to less than 95	Average	89.3	87.7	1.8
	85 to less than 95	Operating speed equivalent			0.9

1 Operating speed equivalent is the median speed reduction of the banded speed measurements (average and 85th percentile).

C.6.2 Other Considerations

While the objective of the project was to use curve sites with neutral features, at some locations the characteristics did not comply with these criteria. At the Barkers Lodge Road 110 m radius site, the lane width was found to be 2.7 m which was less than the desired lane width. Appendix C in Austroads (2010a) suggests that operating speeds are reduced by about 3 km/h where traffic lane width is 3 m or less. To reduce the influence of the narrower cross-section at this location, the midpoint curve speed was increased by 3 km/h.

C.6.3 Applying Speed Measurements

The banded speed measurements and the measurements for all cars were collated for each approach speed. Figure C 6 shows the collated data for approach speeds from 85 to less than 95 km/h. This includes sites where the approach operating speed (all cars) was in this range. Banded speed data from other sites was included to provide additional data with varying curve radii.

The results of applying this method included:

- seven sites where the operating speed measurement data was available in the 85 to less than 95 km/h approach speed for all cars
- using the banded approach speed method
  - four sites with a posted speed limit of less than 90 km/h
  - two sites with a 90 km/h posted speed limit
  - five sites with a posted speed limit greater than 90 km/h.

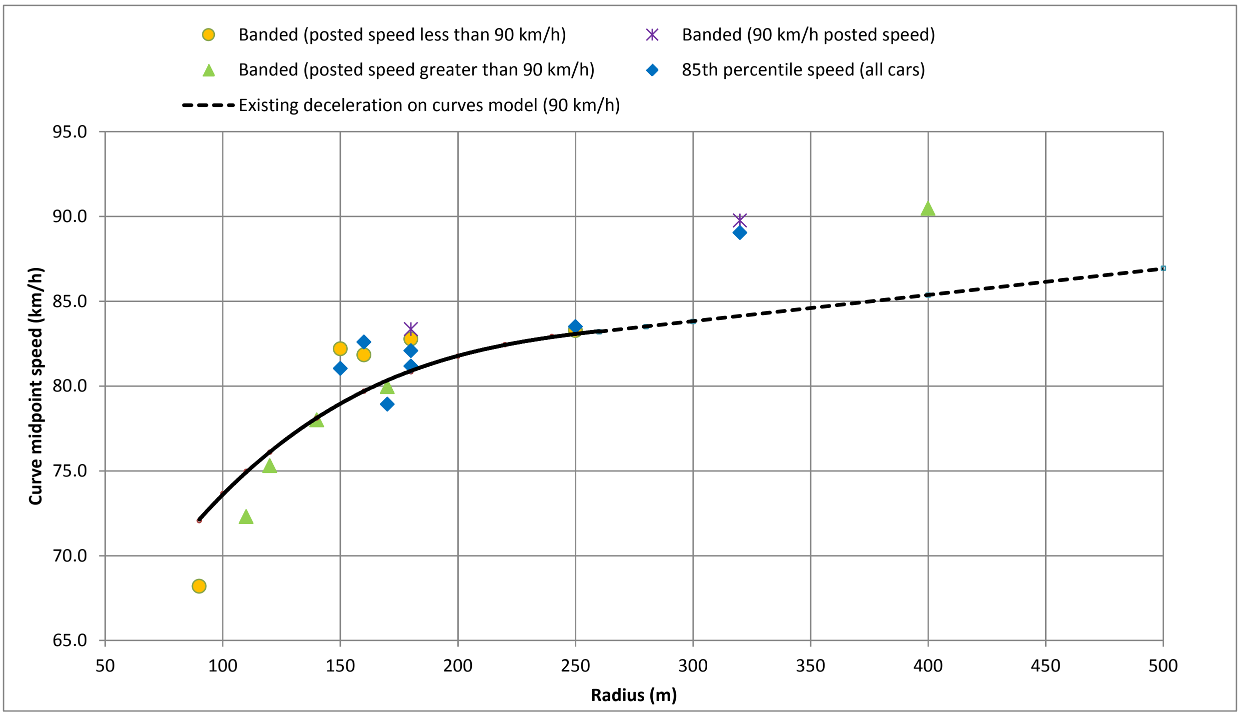


Figure C 6: 85 to less than 95 km/h approach speed measurements (banded and all data)

By applying the banded approach speed method, ten additional speed measurements were included in the analysis. This included measurements at radii where speed measurements would otherwise have been unavailable from the data collection sites included in the study.

C.6.4 Factors Related to Use of Banded Speed Data

A number of factors were identified that should be considered with the use of banded speed data. A method of determining a speed reduction for the banded speed data was developed by comparing banded speed measurements with those determined for the operating speeds for all vehicles. Based on the analysis, an equivalent speed reduction was determined for the banded data. However, it was only possible to compare one speed band with the operating speed for all vehicles per curve site and it was not possible to determine whether this relationship extended to other speed bands. Therefore, using this method assumes that the procedure outlined in Appendix C.6.1 would apply to all speed bands at a particular site.

One factor that should be considered is that the banded speed data represented drivers that displayed specific behaviours in relation to the speed environment for a desired speed of travel. Bands of faster approach speeds represent drivers willing to take greater risks. Conversely, slower approach speed bands represent risk-adverse drivers. This may have influenced the banded equivalent operating speed reduction determined. However, it was not possible to examine these influences as part of the project.

In addition, validating different sections of the deceleration on horizontal curves graph would result in different types of banded speed data being available for the analysis. For example, to validate the 90 km/h approach speed, data was available for bands with posted speeds with the same, faster and slower speed environments. However, for the 100 km/h approach speed, banded data was available with the same or slower posted speed limit for the analysis. For the 60 and 70 km/h approach speeds, banded speed data was only available from sites with faster speed environments.

APPENDIX D CURVE SITES

The curve sites where pneumatic tube counts were conducted are listed in Table D 1.

Table D 1: Curve sites included

Site	State	Route	Radius (m)	Curve length (m)	Posted speed limit (km/h)	Approach speed group (km/h)[1]	Average grade (%)	Average cross slope (%)	Lane width (m)	Pavement condition	Curve advisory speed signs[2]	Curve type	Latitude	Longitude
1	NSW	Barkers Lodge Rd	110	110	100	95 to less than 105	1.6	6.3	2.7	Good	AS	Isolated	–34.135	150.508
2	NSW	Barkers Lodge Rd	140	90	100	95 to less than 105	1.5	10.2	3.4	Good	AS	In sequence	–34.121	150.510
3	NSW	Barkers Lodge Rd	120	70	100	95 to less than 105	2.4	8.0	3.0	Good	AS	In sequence	–34.120	150.508
4	NSW	Greenwell Point Rd	90	80	80	75 to less than 85	0.5	7.0	3.1	Good	AS	Isolated	–34.902	150.670
5	NSW	Culburra Rd	180	210	80	85 to less than 95	0.5	5.2	3.1	Excellent	AS	Isolated	–34.927	150.692
6	Vic	Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	50	80	85 to less than 95	2.2	6.4	3.0	Good	AS	Isolated	–37.901	145.511
7	Vic	Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	110	90	85 to less than 95	1.7	5.2	3.0	Good	AS	Isolated	–37.886	145.532
8	Vic	Healesville-Koo Wee Rup Rd	180	40	90	85 to less than 95	0.3	5.2	3.0	Good	AS	Isolated	–37.865	145.532
9	Vic	Healesville-Koo Wee Rup (Dairy) Rd	400	270	100	95 to less than 105	1.1	5.3	3.1	Good	No	Isolated	–37.703	145.522
10	Vic	Healesville-Kinglake Rd	170	310	100	85 to less than 95	2.4	5.8	3.0	Good	AS	Isolated	–37.538	145.456
11	Vic	Healesville-Kinglake Rd	250	160	80	85 to less than 95	1.2	4.0	3.0	Good	No	In sequence	–37.537	145.358
12	Vic	Healesville-Kinglake Rd	160	190	80	85 to less than 95	1.1	8.1	3.0	Good	CWC	In sequence	–37.535	145.358

1 Approach speed grouping was based on the 85th percentile speed recorded on the approaches to an isolated curve or exterior 85th percentile approach speeds for curves in sequence.
2 AS – Advisory speed sign, CWC – Curve warning concealed sign.

APPENDIX E SPEED DATA

The project compiled speed data for the 12 curve sites detailed in Appendix D. These sites were located on roadways where the approach operating speeds for all cars ranged between 75 and 105 km/h. Also included is speed data for the banded speed measurements created between 55 and 105 km/h.

Included in the tables are the sample size, average speed, 85th percentile speed recorded for cars and articulated trucks at the curve sites.

E.1 Cars

Car speed measurements are shown for:

- all cars (i.e. non-banded, Table E 1)
- banded approach speeds from 95 to less than 105 km/h (Table E 2)
- banded approach speeds from 85 to less than 95 km/h (Table E 3)
- banded approach speeds from 75 to less than 85 km/h (Table E 4)
- banded approach speeds from 65 to less than 75 km/h (Table E 5)
- banded approach speeds from 55 to less than 65 km/h (Table E 6).

In Table E 6, some sites had few measured speeds available for the 55 to less than 65 km/h approach speed and data was not included. This included sites with less than 50 measurements available.

Table E 1: Cars – all speed measurements

Route	Radius (m)	Sample size	Average speed (km/h)			Operating (85th percentile) speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	19 001	72.5	60.0	74.6	78.6	65.4	80.6
Barkers Lodge Rd	110	4 480	89.6	68.2	88.3	100.7	75.7	98.2
Barkers Lodge Rd	120	2 231	87.4	72.9	79.4	99.3	80.6	87.4
Barkers Lodge Rd	140	1 903	92.6	77.9	80.8	103.8	86.4	89.3
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	12 347	81.2	73.0	81.5	89.4	80.5	89.8
Healesville-Kinglake Rd	160	3 213	77.8	71.4	74.9	85.1	78.1	81.7
Healesville-Kinglake Rd	170	4 446	81.0	71.7	78.0	90.4	79.3	87.7
Culburra Rd	180	18 006	83.9	77.2	83.3	90.9	82.9	89.5
Healesville-Koo Wee Rup Rd	180	11 090	84.0	75.5	81.2	92.8	83.7	89.5
Healesville-Kinglake Rd	250	2 976	79.7	74.3	73.5	87.2	80.9	80.1
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	11 866	85.3	84.3	85.6	93.8	92.8	93.9
Healesville-Koo Wee Rup (Dairy) Rd	400	16 605	88.1	87.0	89.4	96.9	95.7	97.6
Total all sites	–	108 164	–	–	–	–	–	–

Table E 2: Banded car speed measurements – 95 to less than 105 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	145	94.2	69.5	88.3	97.0	74.7	94.0
Barkers Lodge Rd	110	1062	99.0	72.8	95.5	102.6	78.1	100.9
Barkers Lodge Rd	120	457	99.2	78.8	85.6	102.9	84.4	91.4
Barkers Lodge Rd	140	554	99.3	81.9	84.8	102.5	87.3	90.0
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	581	98.4	84.3	94.7	101.9	91.2	101.8
Healesville-Kinglake Rd	160	57	98.4	81.3	86.2	100.9	87.2	91.0
Healesville-Kinglake Rd	170	260	98.3	82.4	92.2	100.9	88.3	98.9
Culburra Rd	180	1168	98.3	84.8	92.2	101.4	90.0	98.1
Healesville-Koo Wee Rup Rd	180	959	98.6	84.1	89.8	101.9	92.2	97.2
Healesville-Kinglake Rd	250	76	97.9	85.9	84.8	101.1	90.4	90.5
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	1279	98.6	95.6	96.4	101.7	100.7	101.8
Healesville-Koo Wee Rup (Dairy) Rd	400	3245	98.5	95.7	97.1	101.7	100.7	102.2
Total all sites	–	9843	–	–	–	–	–	–

Table E 3: Banded car speed measurements – 85 to less than 95 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	1 500	84.1	65.2	82.4	87.1	70.0	87.3
Barkers Lodge Rd	110	1 635	90.0	68.1	88.2	93.4	73.2	93.6
Barkers Lodge Rd	120	762	89.8	74.1	80.5	93.3	79.2	85.4
Barkers Lodge Rd	140	609	90.3	76.6	79.5	93.6	82.8	85.1
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	3 057	88.9	78.6	87.7	92.3	84.3	93.6
Healesville-Kinglake Rd	160	432	88.4	77.8	82.0	91.5	83.2	87.5
Healesville-Kinglake Rd	170	1 171	89.1	76.7	84.7	92.4	82.1	91.0
Culburra Rd	180	5 673	88.8	80.1	86.1	92.2	84.8	91.2
Healesville-Koo Wee Rup Rd	180	3 884	89.2	79.2	84.5	92.6	85.8	91.1
Healesville-Kinglake Rd	250	624	88.4	80.1	78.8	91.7	84.8	83.8
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	4 737	89.3	87.7	88.5	92.7	92.5	93.6
Healesville-Koo Wee Rup (Dairy) Rd	400	7 190	89.8	88.5	90.8	93.2	93.7	96.2
Total all sites	–	31 274	–	–	–	–	–	–

Table E 4: Banded car speed measurements – 75 to less than 85 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	9 744	75.0	61.4	76.3	78.2	66.1	80.8
Barkers Lodge Rd	110	1 016	80.7	63.6	81.1	83.9	68.7	86.5
Barkers Lodge Rd	120	574	80.6	69.0	75.0	83.9	73.7	79.5
Barkers Lodge Rd	140	346	80.8	71.3	73.4	84.0	77.2	79.5
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	6 091	79.9	72.2	80.4	83.3	77.3	85.8
Healesville-Kinglake Rd	160	1 614	79.5	72.8	76.3	82.9	77.7	81.1
Healesville-Kinglake Rd	170	1 857	79.9	71.0	76.8	83.3	76.0	82.8
Culburra Rd	180	9 728	80.5	75.4	81.2	83.5	79.7	85.3
Healesville-Koo Wee Rup Rd	180	4 437	80.4	73.6	79.2	83.6	78.7	85.2
Healesville-Kinglake Rd	250	1 542	79.9	74.4	73.7	83.1	78.7	78.3
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	4 347	80.6	80.0	81.6	83.8	84.6	86.5
Healesville-Koo Wee Rup (Dairy) Rd	400	4 820	80.7	80.8	83.8	83.8	85.8	89.3
Total all sites	–	46 116	–	–	–	–	–	–

Table E 5: Banded car speed measurements – 65 to less than 75 km/h

Curve site	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Curve	Downstream	Approach	Curve	Downstream
Greenwell Point Rd	90	6 999	67.3	57.3	71.0	70.1	61.7	75.9
Barkers Lodge Rd	110	303	71.3	59.6	74.8	74.3	65.4	80.4
Barkers Lodge Rd	120	233	71.2	63.8	69.9	73.9	68.9	74.8
Barkers Lodge Rd	140	99	71.1	67.0	69.4	73.8	72.5	75.8
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	2 257	71.5	65.5	73.6	74.2	70.3	78.9
Healesville-Kinglake Rd	160	978	71.0	66.9	70.0	74.0	71.4	74.8
Healesville-Kinglake Rd	170	981	70.9	65.1	69.5	73.9	70.2	75.6
Culburra Rd	180	1 268	72.6	69.9	77.7	74.5	73.7	82.0
Healesville-Koo Wee Rup Rd	180	1 403	71.3	66.7	73.1	74.2	71.1	78.9
Healesville-Kinglake Rd	250	623	71.4	68.4	67.8	74.2	72.8	72.6
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	1 147	71.4	72.4	75.1	74.2	76.6	79.8
Healesville-Koo Wee Rup (Dairy) Rd	400	989	72.2	74.5	78.1	74.4	78.8	83.0
Total all sites	–	17 280	–	–	–	–	–	–

Table E 6: Banded car speed measurements – 55 to less than 65 km/h

Curve site	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Curve	Downstream	Approach	Curve	Downstream
Greenwell Point Rd	90	570	58.4	53.4	66.7	60.5	57.8	72.3
Barkers Lodge Rd	110	73	61.5	55.7	71.4	64.1	63.7	79.3
Barkers Lodge Rd	120	53	61.6	62.7	70.3	63.8	68.3	77.3
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	246	61.8	61.8	71.0	64.3	68.1	79.3
Healesville-Kinglake Rd	160	120	62.2	60.8	64.0	64.2	64.9	68.5
Healesville-Kinglake Rd	170	136	62.0	60.6	63.8	64.3	65.7	71.7
Healesville-Koo Wee Rup Rd	180	196	61.5	60.9	68.5	64.2	65.7	75.3
Healesville-Kinglake Rd	250	92	62.0	63.6	64.0	64.5	68.0	68.3
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	145	61.8	68.8	73.1	64.2	75.3	80.8
Total all sites	–	1 631	–	–	–	–	–	–

E.2 Articulated Trucks

The number of speed measurements available for articulated trucks was small when compared to the data available for cars. The compiled speed measurements for all articulated trucks are shown in Table E 7.

It was possible to determine banded articulated truck speeds for the 85 to less than 95 km/h, 75 to less than 85 km/h and 65 to less than 55 km/h approach speeds (Table E 8, Table E 9 and Table E 10 respectively). It was not possible to develop articulated truck speeds for other approach speeds due to the lack of available data.

Table E 7: Articulated trucks – all speed measurements

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	463	66.7	53.7	–	73.6	59.8	–
Barkers Lodge Rd	110	82	81.8	63.6	82.0	93.2	70.5	90.9
Barkers Lodge Rd	120	35	84.3	69.2	75.1	90.9	76.4	80.3
Barkers Lodge Rd	140	39	88.2	73.5	74.1	97.1	80.6	82.0
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	520	77.6	70.2	77.5	83.9	76.8	83.5
Healesville-Kinglake Rd	160	94	77.1	68.4	71.9	82.7	75.6	79.2
Healesville-Kinglake Rd	170	58	73.0	67.3	68.2	81.9	73.3	79.4
Culburra Rd	180	201	81.7	75.2	–	87.8	80.6	–
Healesville-Koo Wee Rup Rd	180	495	79.8	72.1	76.2	88.3	79.6	83.8
Healesville-Kinglake Rd	250	89	78.2	73.3	72.7	83.8	78.0	77.1
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	454	76.2	78.0	81.3	86.9	87.5	89.9
Healesville-Koo Wee Rup (Dairy) Rd	400	348	88.0	84.8	87.1	97.1	92.0	94.1
Total all sites	–	2878	–	–	–	–	–	–

Table E 8: Banded articulated truck speed measurements – 85 to less than 95 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Barkers Lodge Rd	110	21	90.4	66.4	87.1	93.3	71.8	92.0
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	58	88.2	76.2	83.8	90.7	80.2	89.3
Culburra Rd	180	51	88.7	79.7	–	91.5	83.5	–
Healesville-Koo Wee Rup Rd	180	109	88.9	78.6	82.2	91.7	85.2	88.6
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	83	89.2	89.4	90.0	92.7	94.3	94.1
Total all sites	–	474	–	–	–	–	–	–

Table E 9: Banded articulated truck speed measurements – 75 to less than 85 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	116	75.2	57.0	–	77.1	62.5	–
Barkers Lodge Rd	110	33	81.4	64.3	81.5	84.1	68.2	86.9
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	286	79.3	72.1	79.3	82.6	76.7	83.3
Healesville-Kinglake Rd	160	56	79.2	69.8	73.2	82.5	75.8	79.8
Culburra Rd	180	114	80.3	74.4	–	83.6	78.8	–
Healesville-Koo Wee Rup Rd	180	233	79.7	72.5	76.4	82.9	77.8	82.1
Healesville-Kinglake Rd	250	58	79.8	74.3	73.9	82.9	77.9	77.3
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	143	80.1	80.6	82.3	83.4	84.5	86.1
Healesville-Koo Wee Rup (Dairy) Rd	400	100	80.8	79.0	81.8	83.7	83.7	87.2
Total all sites		1139	–	–	–	–	–	–

Table E 10: Banded articulated truck speed measurements – 65 to less than 75 km/h

Route	Radius (m)	Sample size	Average speed (km/h)			85th percentile speed (km/h)		
			Approach	Midpoint	Downstream	Approach	Midpoint	Downstream
Greenwell Point Rd	90	243	66.2	53.2	–	69.4	58.6	–
Healesville-Koo Wee Rup (Woori-Yallock) Rd	150	164	71.4	65.4	72.4	74.3	70.9	77.4
Healesville-Kinglake Rd	160	30	71.1	63.6	67.5	73.9	68.6	72.4
Healesville-Kinglake Rd	170	22	70.0	64.6	65.0	73.0	69.3	72.9
Culburra Rd	180	25	71.8	68.4	–	73.9	71.8	–
Healesville-Kinglake Rd	250	21	71.7	69.7	69.0	73.8	74.4	73.4
Healesville-Koo Wee Rup Rd	180	122	70.8	65.3	70.1	73.9	70.4	75.6
Healesville-Koo Wee Rup (Woori-Yallock) Rd	320	165	70.1	72.6	77.6	73.9	76.7	82.6
Total all sites	–	792	–	–	–	–	–	–

APPENDIX F REVISED DECELERATION ON CURVES MODEL

To validate the existing model, previous models developed by Botterill (1994) and McLean (1979, 1981) were used as a basis for assessing the speeds obtained as part of the project. These models had helped to form the basis of the current Austroads deceleration on curves graph. Of the models investigated, the multiplicative-origin model (Equation A1) was used to develop a revised deceleration on curves model as it showed behaviour and stability suitable for the range of curves and approach speeds investigated.

$$V = \frac{B \times V_d}{\left(1+\frac{C}{r}\right)} \quad \text{A1}$$

where

V = Speed on curve (km/h)

r = Radius of curve (m)

V_d = Approach speed (i.e. desired speed, km/h)

B and C = Coefficients specific to a curve approach speed (V_d), refer to Table F 1 and Table F 2

Regression was conducted using SPSS Statistics version 21 to determine the best cases for regression coefficients. The best cases for model coefficients are shown in Table F 1 (cars) and Table F 2 (articulated trucks).

Table F 1: Coefficients for best cases – revised deceleration on curves model for cars

Curve approach speed (km/h)	Curve sites	Curve radii range included	Coefficient values		Coefficient +/- errors		Adjusted r^2
			B	C	B	C	
100	12	90–400	1.079	39.861	0.026	4.899	0.937
90	12	90–400	1.093	37.385	0.020	3.747	0.939
80	11	90–320	1.069	27.086	0.019	3.119	0.922
70	11	90–320	1.056	18.627	0.018	2.899	0.856

Table F 2: Coefficients for best cases – revised deceleration on curves model for articulated trucks

Curve approach speed (km/h)	Curve sites	Curve radii range included	Coefficient values		Coefficient +/- errors		Adjusted r^2
			B	C	B	C	
90	7	110–400	1.086	37.403	0.034	6.471	0.889
80	10	90–400	1.060	27.363	0.019	3.458	0.917

APPENDIX G ANALYSIS RESULTS

G.1 Introduction

To validate and identify potential enhancements to the existing deceleration on horizontal curves model, the measured 85th percentile speed data was used to develop a series of models including:

- revised deceleration on horizontal curves model for cars
- revised deceleration on horizontal curves model for articulated trucks.

In addition, the measured 85th percentile speed data was analysed at the curves in sequence sites.

G.2 Car Deceleration on Horizontal Curves

G.2.1 Results

The revised deceleration on horizontal curves models developed based on speed data from the curve sites are shown in:

- Figure G 1 (100 km/h approach speed)
- Figure G 2 (90 km/h approach speed)
- Figure G 3 (80 km/h approach speed)
- Figure G 4 (70 km/h approach speed).

Each figure shows the existing deceleration on curves models and the revised models based on the speed measurements for different curve radii. The revised models are shown for the curve radii where speed data was collected (i.e. 90 to 400 m). The speed measurements used to develop the revised models are also shown for each approach speed group.

The speed measurements are included for banded speed data and for all approaching vehicles (i.e. all cars). For the 60 and 70 km/h approach groups, only banded speed data was available.

The focus of the project was on small radius curves and nine of the curve sites had a radius of less than 200 m. The remaining three sites were between 200 and 400 m. No speed data was collected at curves with radii greater than 400 m.

It was not possible to develop a revised model for the 60 km/h approach speed (Figure G 5) as speed reduction at the curve midpoint was only observed at two curve sites. At all curve sites, the reduction in speed was greater than that predicted by the existing operating speed model. However, all curve sites available from the study were for posted speed limits of 80, 90 or 100 km/h. Banded speed data from these sites was applied to this approach speed. The use of sites from greater posted speed zones may have contributed to the limited speed reduction observed.

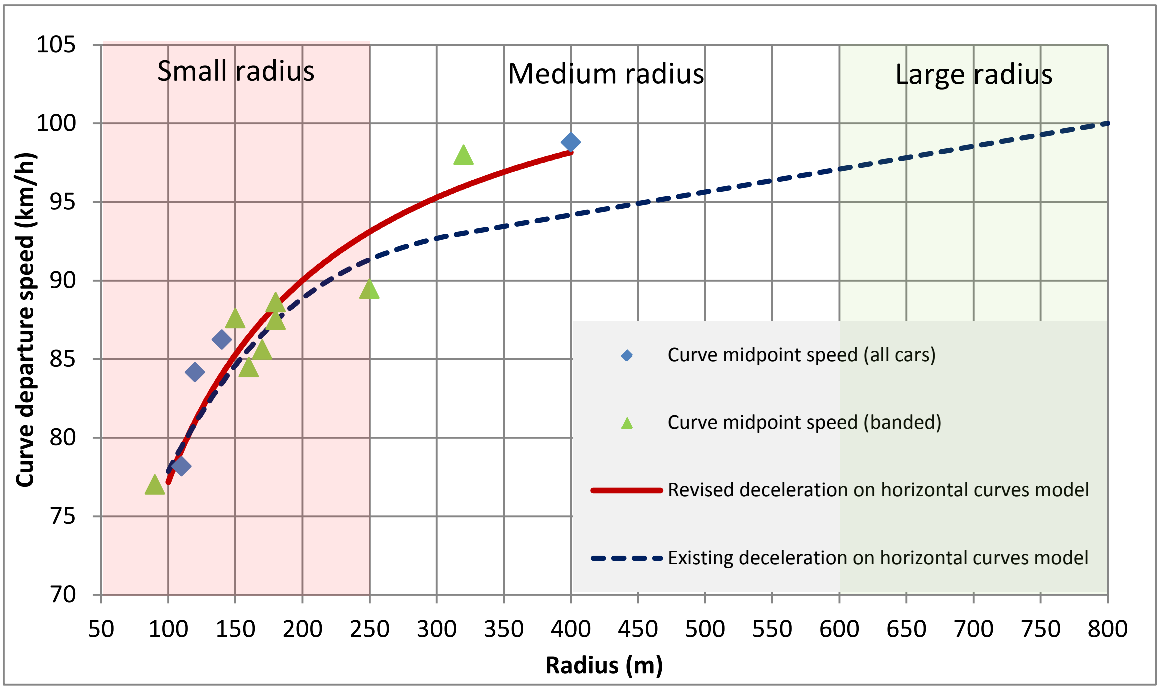


Figure G 1: 100 km/h approach speed, revised and existing models

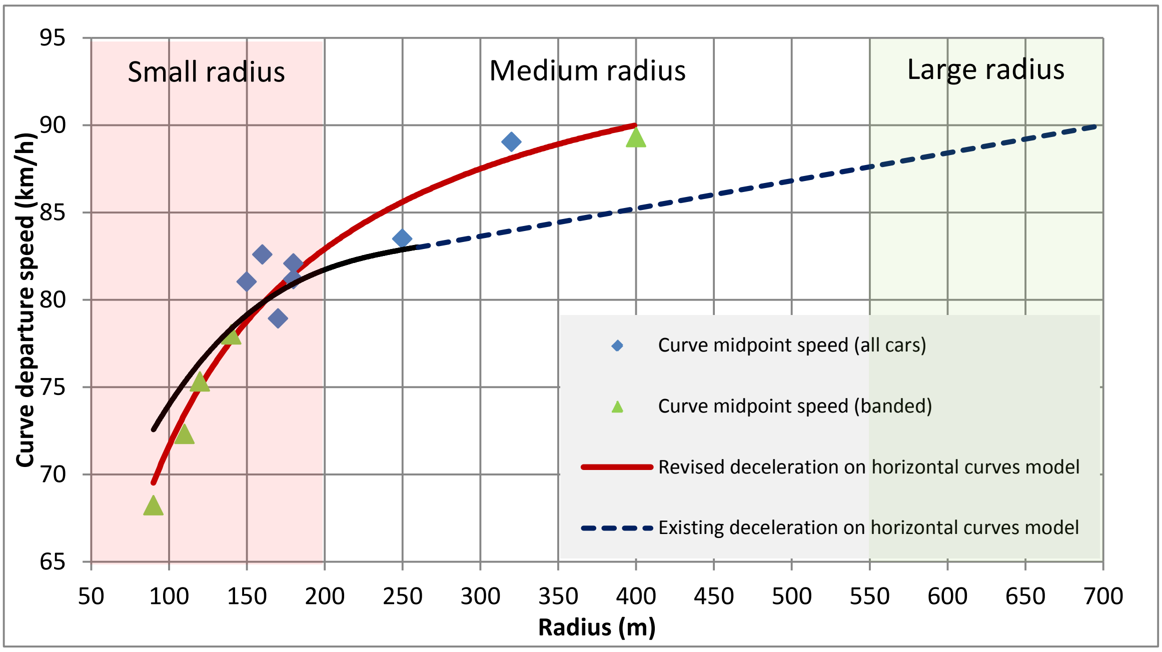


Figure G 2: 90 km/h approach speed, revised and existing models

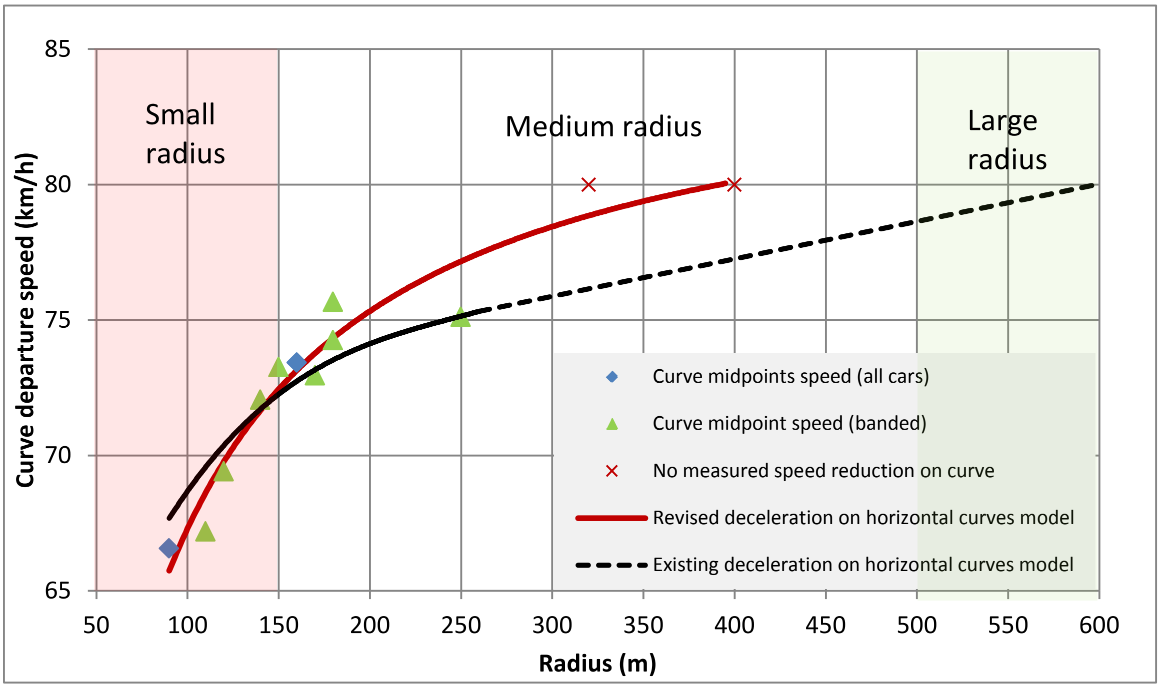


Figure G 3: 80 km/h approach speed, revised and existing models

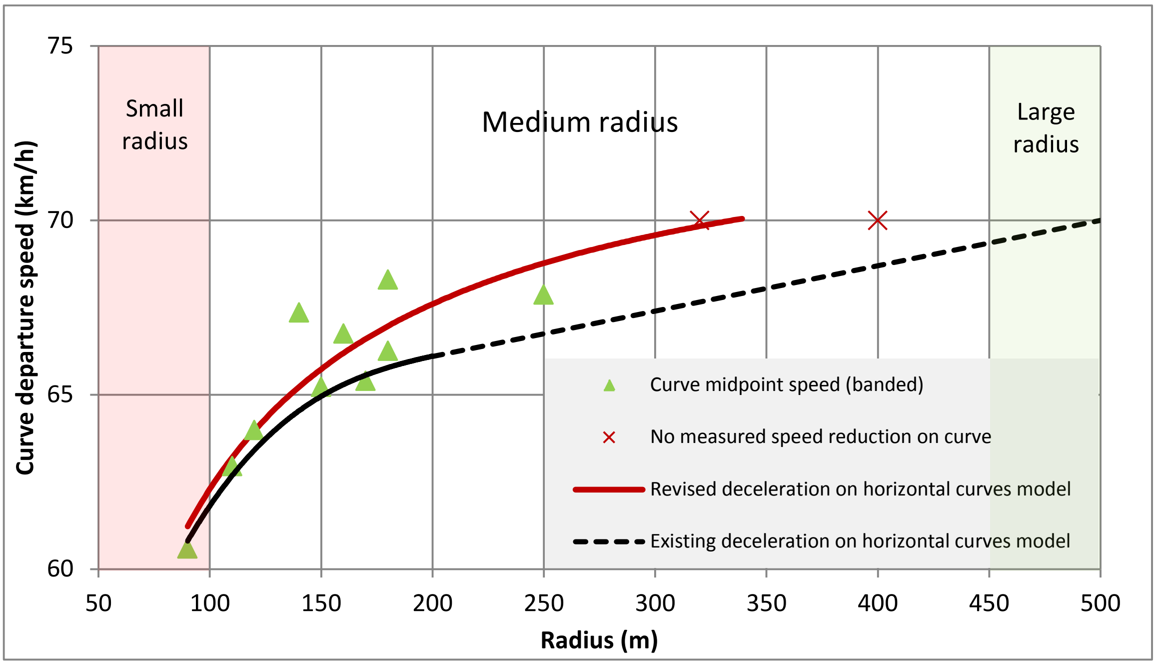


Figure G 4: 70 km/h approach speed, revised and existing models

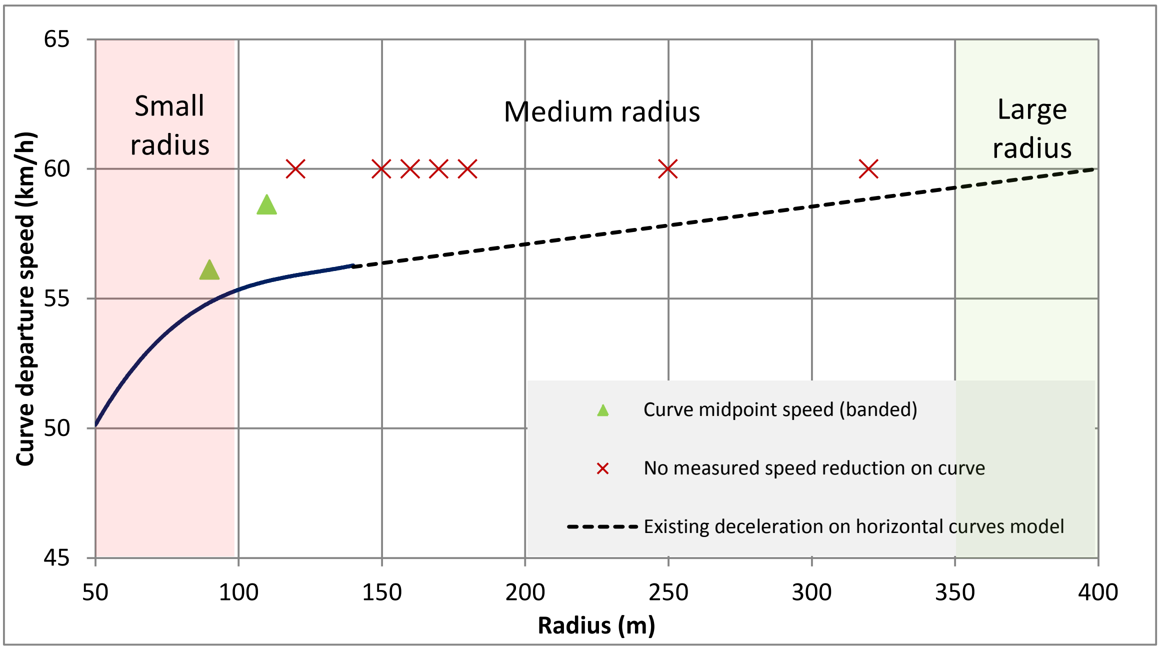


Figure G 5: 60 km/h approach speed, curve midpoint speed (cars) and existing model

G.2.2 Comparison of Existing and Revised Models

Small radius curves

Table G 1 summarises the differences in predicted curve departure speed between the existing and revised deceleration on horizontal curves models.

For curve radii and approach speeds where the revised model predicted slower curve departure speeds than the existing model, the largest differences occurred for the 80 and 90 km/h approach speeds and a 90 m radius.

For a curve radius of 200 to 250 m, the revised models predicted faster curve departure speeds than the existing model.

Table G 1: Small radius curves: difference between existing and revised deceleration on horizontal curves models

Radius (m)	Difference in predicted curve departure speed (km/h)			
	Approach speed (km/h)(1)			
	70	80	90	100
90	0.2	–2.3	–2.5	
100	0.3	–1.7	–2.4	–0.8
125		–0.7	–1.2	–0.2
150		0.4	–0.2	0.3
175			0.1	0.9
200			0.9	1.0
250				2.1

1 Positive values indicate that the revised model predicted a curve departure speed greater than the existing model.

Medium radius curves

For medium radius curves, the revised model predicted faster curve departure speeds than the existing model for all curve radii and approach speed combinations. The largest differences were predicted for a 400 m radius curve and the faster approach speeds (90 and 100 km/h), where the revised model predicted a curve departure speed of more than 4 km/h greater than the existing model (Table G 2).

At the 320 and 400 m radius data collection sites, very little or no speed reduction was measured. This contributed to the larger differences between the existing and revised models.

Table G 2: Medium radius curves: difference between existing and revised deceleration on horizontal curves models

Radius (m)	Difference in predicted curve departure speed (km/h)			
	Approach speed (km/h)(1)			
	70	80	90	100
125	0.3			
150	0.7	0.4		
175	0.8	1.1		
200	1.6	1.3		
250	1.8	2.2	2.6	
300	2.6	2.4	3.5	2.3
350	2.0	2.4	3.9	3.9
400	1.0	3.0	4.8	4.2

1 Positive values indicate that the revised model predicted a faster curve departure speed than the existing model.

Summary of differences between the existing and revised models

Overall, the revised models were developed from the curve measurements at 12 sites. Comparing the revised and existing models:

- For small radius curves, the revised model predicted speeds that differed from the existing model, particularly for the smallest and largest radii in this grouping.
- For medium radius curves, the revised model predicted a greater curve departure speed than for the existing model for all curve radii and approach speed combinations.
- Differences in speed deceleration between the existing and revised models were greatest for medium radius curves (i.e. curve radii greater than 200 m) and faster approach speeds (90 and 100 km/h).
- The largest curve radius at which a reduction in curve departure speed was predicted was smaller for the revised model than for the existing model.

The differences between models for medium radius curves should be considered in the context of the limited number of sites, which may have limited the capability of the revised models to predict speeds for this range of curve radii.

G.3 Articulated Truck Deceleration on Horizontal Curves

G.3.1 Difference between Articulated Truck and Car Speed on Horizontal Curves

Table 3.4 of the *Guide to Road Design Part 3* (Austroads 2010a) suggests that as an average condition, articulated trucks (defined as a 19 m semi-trailer) travel at speeds 10 km/h slower than cars for speeds between 70 and 100 km/h. The average condition is defined to include factors such as grades and poorer acceleration.

Table G 3 shows the speed relationships between the 85th percentile speeds for cars and articulated trucks at the curve sites. At all sites, the difference in car and articulated truck speed was less than 10 km/h. However, gradient is one of the factors noted as contributing to reduced truck speeds. As all sites had gradients of less than 3%, this may have contributed to the smaller differences in speeds between cars and articulated trucks than noted in Austroads (2010a).

Other observations from the table include that:

- Generally across all sites, articulated trucks were observed to travel slower than cars on both approaches and at the curve midpoint, with the exception of the 400 m radius curve where the 85th percentile articulated truck and car speeds were virtually the same.
- At six sites, the percentage speed reduction was similar (i.e. less than 1% difference) for articulated trucks and cars.
- At four sites, cars had a greater percentage reduction in speed than articulated trucks.
- At two sites, cars had a smaller percentage reduction in speed than articulated trucks.

Table G 3: Car/truck speed relationships at curve sites

Radius (m)	Cars			Articulated trucks			Notes
	85th percentile speed (km/h)		Speed reduction (%)	85th percentile speed (km/h)		Speed reduction (%)	
	Curve approach	Curve midpoint		Curve approach	Curve midpoint		
160	85.1	78.1	8.2	82.7	75.6	8.6	Similar speed reduction for cars and articulated trucks
180	90.9	82.9	8.8	87.8	80.6	8.2	
180	92.8	83.7	9.8	88.3	79.6	9.9	
250	87.2	80.9	7.2	83.8	78.0	6.9	
110	100.7	75.7	24.8	93.2	70.5	24.4	
140	103.8	86.4	16.8	97.1	80.6	17.0	
120	99.3	80.6	18.8	90.9	76.4	16.0	Greater speed reduction for cars than articulated trucks
150	89.4	80.5	10.0	83.9	76.8	8.5	
170	90.4	79.3	12.3	81.9	73.3	10.5	
320	93.8	92.8	1.1	86.9	87.5	–0.7	
90	82.6	65.4	20.8	77.6	59.8	22.9	Less speed reduction for cars than articulated trucks
400	96.9	95.7	1.2	97.1	92.0	5.3	

G.3.2 Articulated Truck Deceleration on Horizontal Curves

A similar approach to that for cars was used to examine the deceleration measured for articulated trucks on horizontal curves. However, due to the smaller sample size of articulated trucks, it was not possible to obtain banded speed profiles at all sites. As a result, there was only sufficient data to examine the deceleration of articulated trucks on horizontal curves for approach speeds of 80 and 90 km/h.

Figure G 6 and Figure G 7 show the deceleration on horizontal curve models for articulated truck deceleration at 90 and 80 km/h approach speeds respectively. Each figure includes:

- curve midpoint speeds measured for both articulated trucks and cars
- horizontal curve deceleration model for articulated trucks
- revised and existing horizontal curve deceleration models for cars.

Generally, the models for articulated trucks at 80 and 90 km/h approach speeds predicted slightly slower curve departure speeds for articulated trucks than for cars (difference of less than 1 km/h). This result aligns with Table G 3, where half the curve sites were found to have minimal differences in speed reduction between cars and articulated trucks.

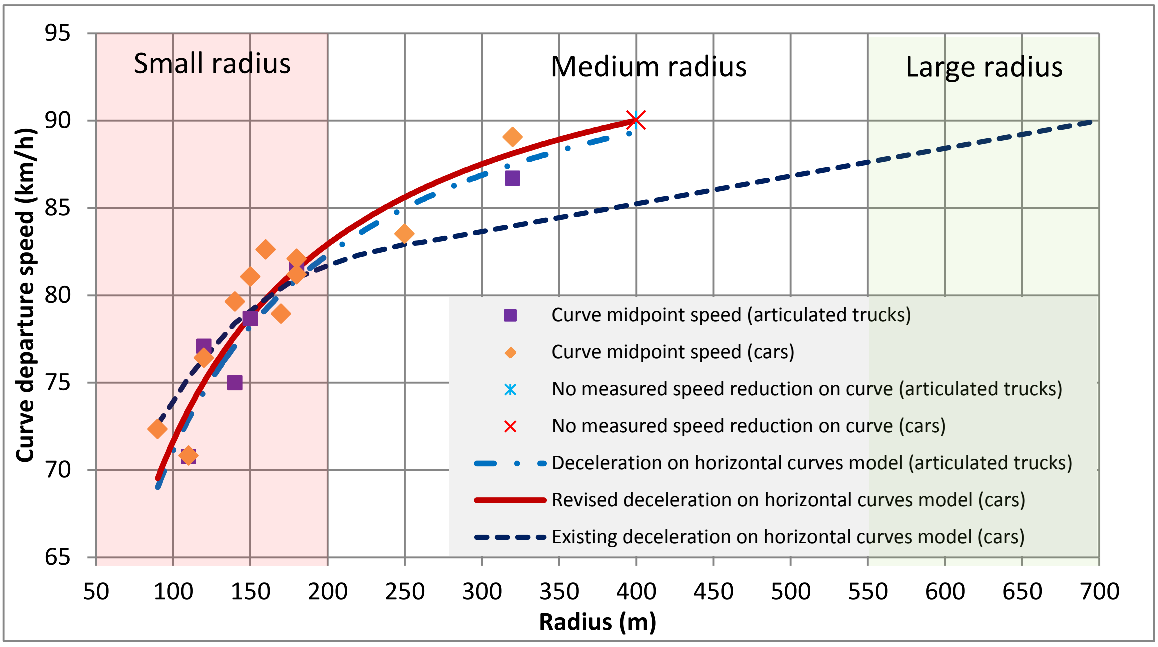


Figure G 6: 90 km/h approach speed, measured speed on curve (articulated trucks and cars)

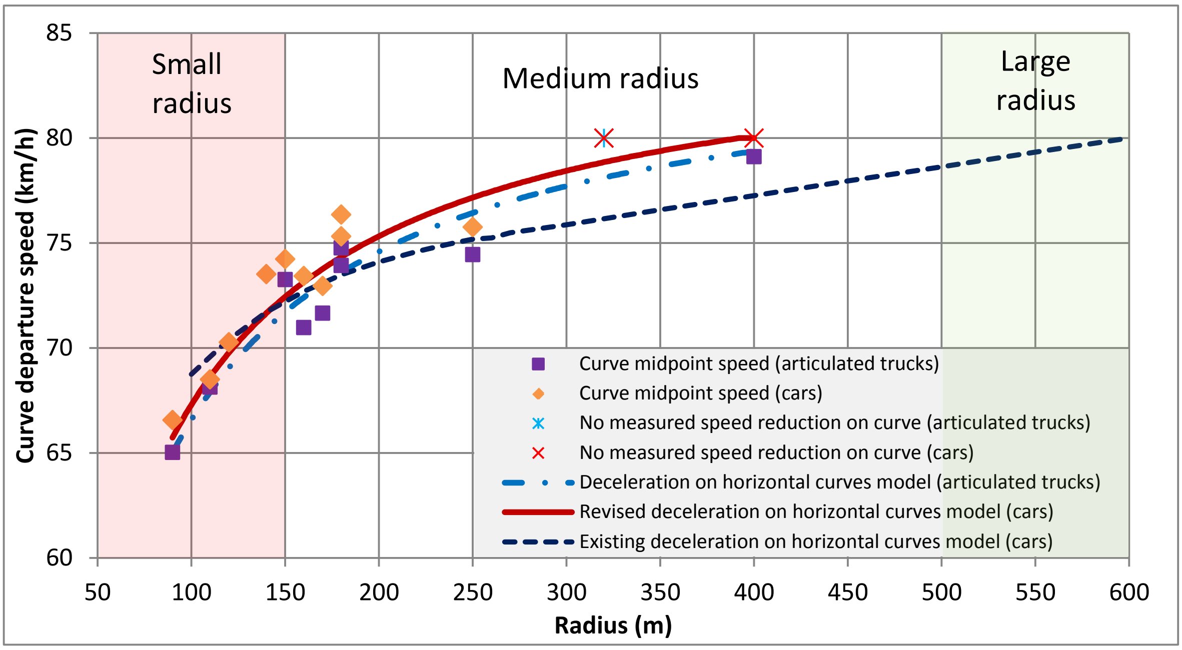


Figure G 7: 80 km/h approach speed, measured speed on curve (articulated trucks and cars)

G.4 Curves in Sequence

This section contains additional figures comparing the results of the curves in sequence analysis discussed in Section 3.4. For each pairing of curves, the speed measurements are compared with the existing operating speed model. Predicted speed measurements using the revised deceleration on curves models discussed in Section 3.2 are also included in the comparisons.

Additional in-vehicle measurements that had been collected on Barkers Lodge Road are included for this route to provide a supplemental source of speed data.

G.4.1 Barkers Lodge Road Curves in Sequence

Barkers Lodge Road northbound direction

In the northbound direction, the sequential curves on Barkers Lodge Road consisted of a larger radius curve (140 m) followed by a smaller radius curve (120 m). A comparison of the measured speeds and changes predicted by existing and revised operating speed models are shown in Figure G 8. In-vehicle data collected in the northbound direction of Barkers Lodge Road are shown in Figure G 9.

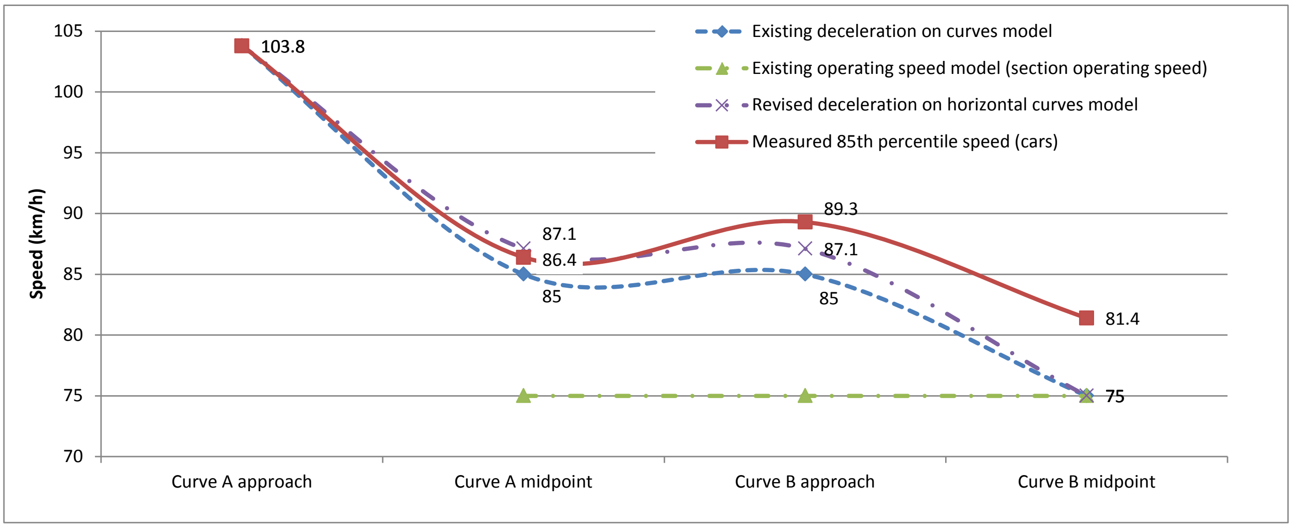


Figure G 8: Barkers Lodge Road northbound direction (tube count data)

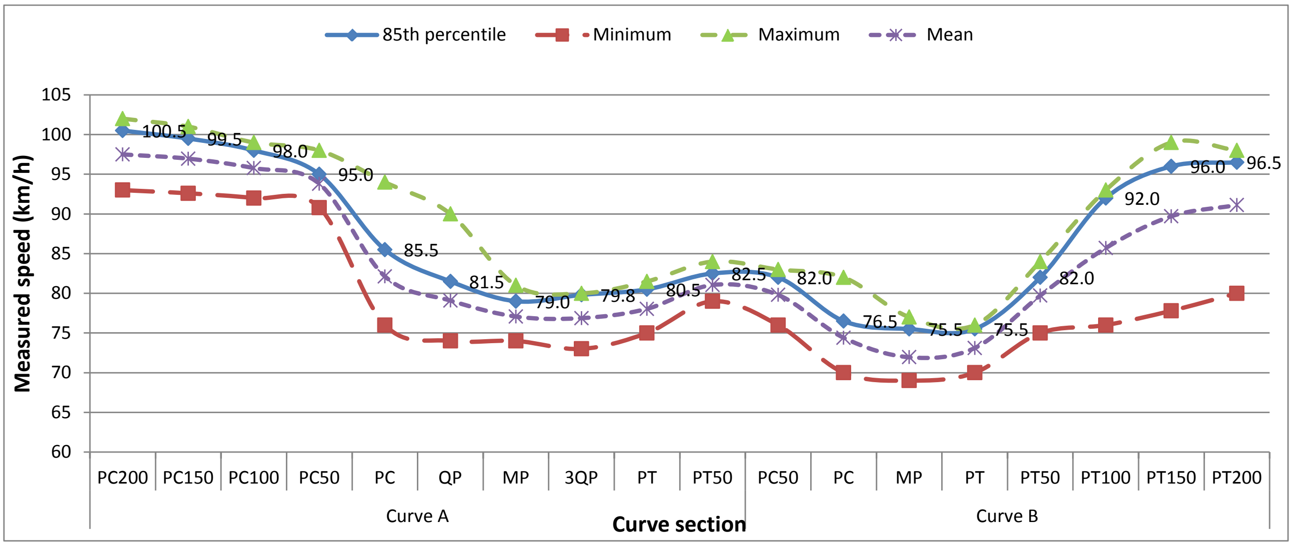


Figure G 9: Barkers Lodge Road northbound direction (in-vehicle data)

Barkers Lodge Road southbound direction

In the southbound direction, Barkers Lodge Road transitions from a smaller (120 m) radius curve to a larger (140 m) radius curve. The comparison of measured speed data for this direction of travel is shown in Figure G 10. Figure G 11 shows the in-vehicle data collected in the southbound direction of Barkers Lodge Road.

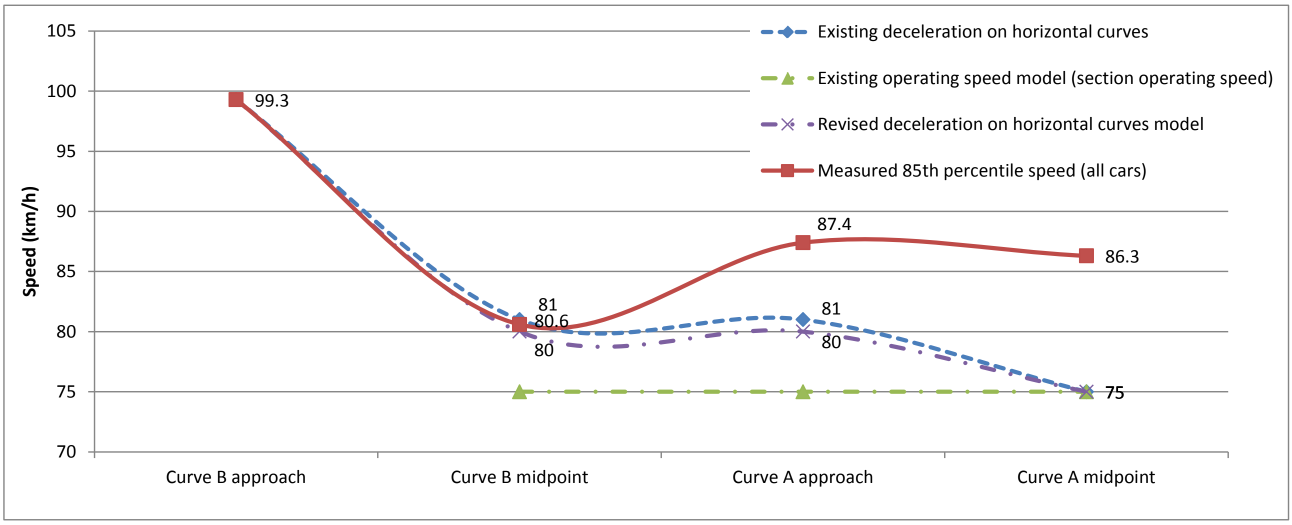


Figure G 10: Barkers Lodge Road southbound direction (tube count data)

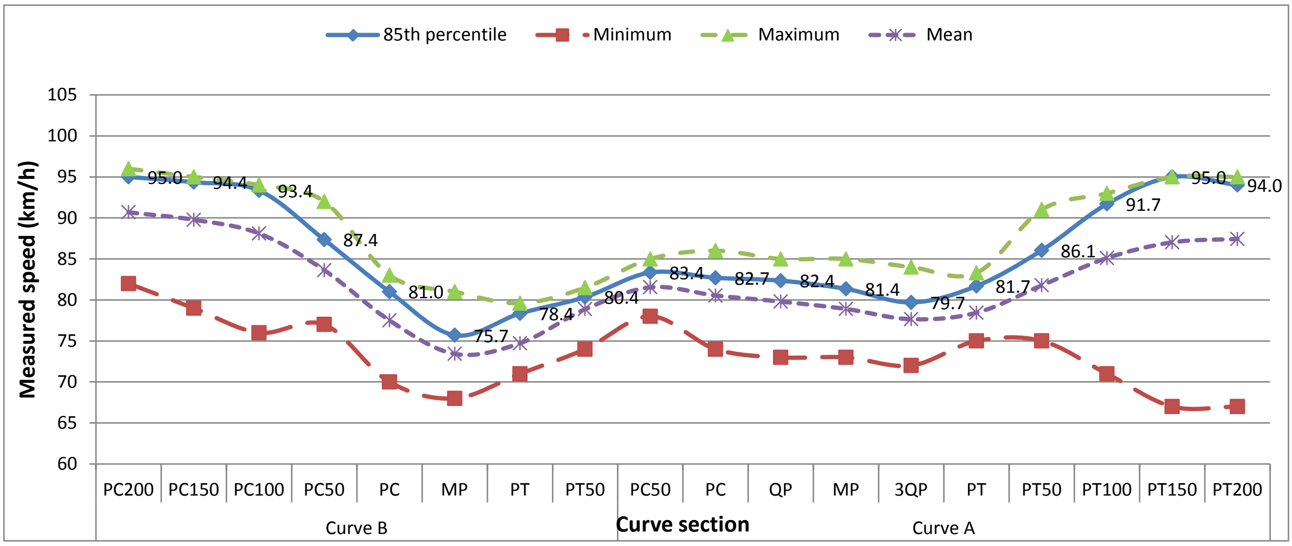


Figure G 11: Barkers Lodge Road southbound direction (in-vehicle data)

G.4.2 Healesville-Kinglake Road Curves in Sequence

Healesville-Kinglake Road westbound direction

The westbound direction of Healesville-Kinglake Road consisted of a larger radius curve (250 m) followed by a smaller radius curve (160 m). A comparison of the measured speeds and the speed changes predicted by the operating speed model is shown in Figure G 12.

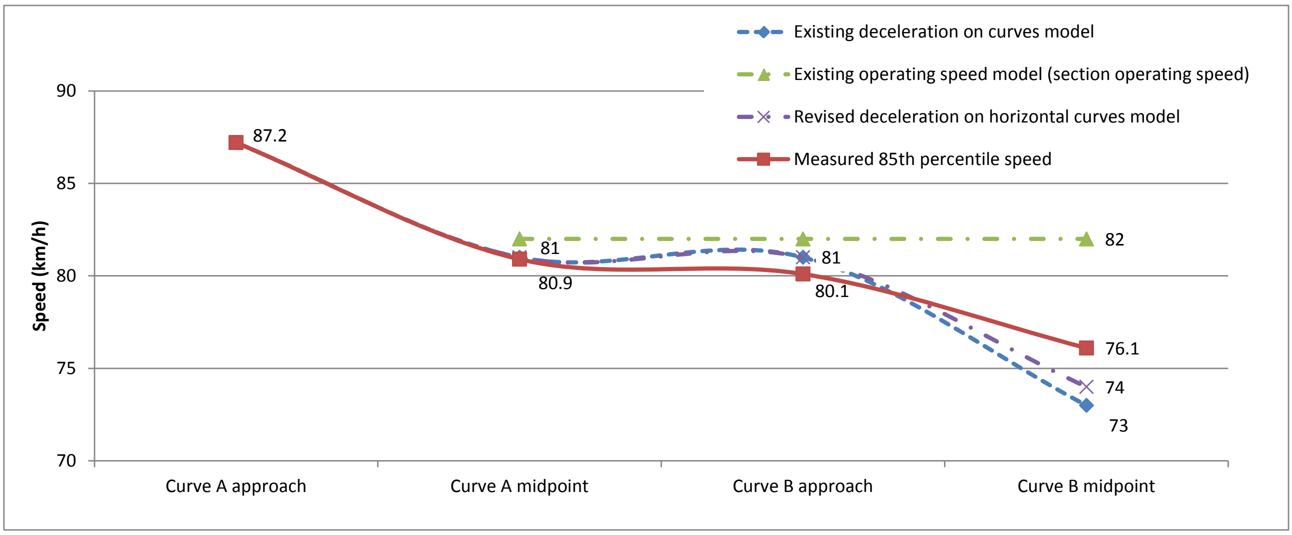


Figure G 12: Healesville-Kinglake Road westbound direction

Healesville-Kinglake Road eastbound direction

In the eastbound direction, a smaller radius curve (160 m) is followed by a larger radius curve (250 m). A comparison of the measured speeds and the operating speed model predictions is shown in Figure G 13.

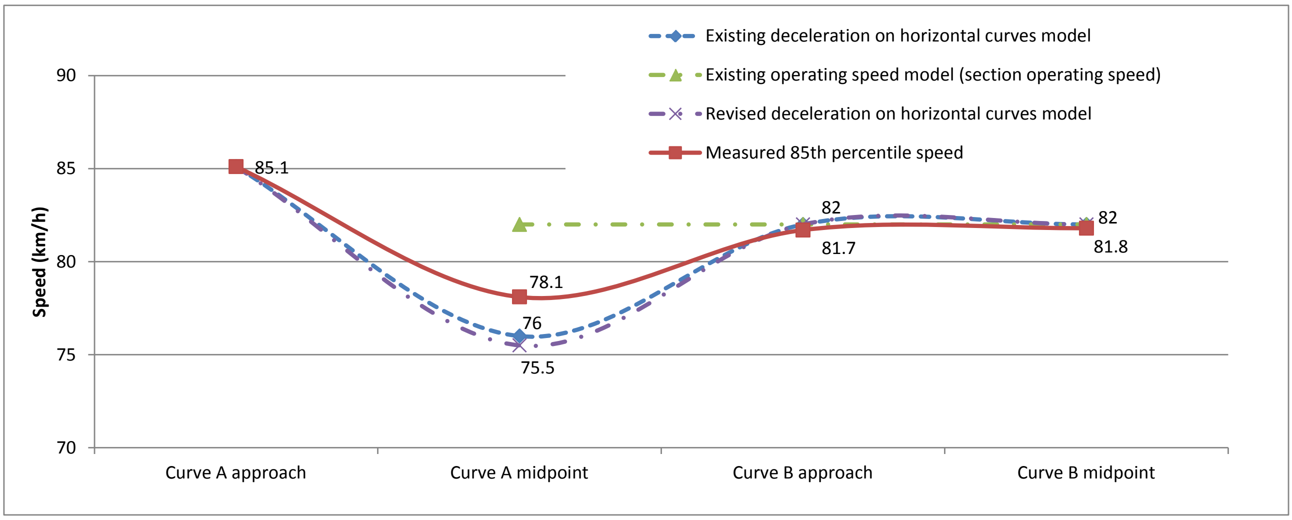


Figure G 13: Healesville-Kinglake Road eastbound direction

APPENDIX H SUPERELEVATION

As noted in Section 2.2.2, the Austroads (2010a) maximum recommended superelevation was exceeded at some sites. This appendix compiles the superelevation at the curve sites and the speed measurements recorded at isolated curves and curves in sequence.

Previous research has considered the influence of superelevation on operating speed. McLean (1981) examined a range of variables that influenced operating speed and found that superelevation accounted for less than 1% of the variability in operating speed and failed to show a statistically significant effect on operating speed. Other overseas research (McFadden et al. 2001) resulted in similar findings.

H.1 Isolated Curves

Table H 1 provides the superelevation and curve departure speeds (measured and predicted) at the isolated curve sites. The measured superelevation was slightly greater than the maximum recommended superelevation at one isolated curve (highlighted). However, this did not result in an observable difference in curve departure speed.

Table H 1: Superelevation at isolated curve sites

Curve radius grouping	Curve radius (m)	Superelevation		Curve approach speed measured (km/h)	Curve departure speed (km/h)		
		Measured	Recommended maximum(1)		Measured	Predicted(2)	Difference(3)
Small	90	7.0%	7%	78.6	65.4	67	–1.6
Small	110	6.3%	6%	100.7	75.7	77	–1.3
Small	150	6.4%	7%	89.4	80.5	79	1.5
Small	170	5.8%	7%	90.4	79.3	81	–1.7
Small	180	5.2%	7%	90.9	82.9	82	0.9
Small	180	5.2%	7%	92.8	83.7	83	0.7
Medium	320	5.2%	6%	93.8	92.8	87	5.8
Medium	400	5.3%	6%	96.9	95.7	91	4.7

1 From Table 7.7 of Austroads (2010a).
2 Based on existing deceleration on curves graph (Austroads 2010a).
3 Negative value indicates that the measured speed was less than the speed predicted by the operating speed model.

H.2 Curves in Sequence

The differences in speed were examined for both the upstream and downstream curves of the curves in sequence, as well as the connecting straights between curves.

H.2.1 Upstream Curves

Table H 2 shows the actual superelevation values and the maximum values recommended by Austroads (2010a) for the upstream curve sites. Included are the speeds measured and predicted by the operating speed model at the upstream curve sites.

As shown, only the Healesville-Kinglake Road 250 m radius curve had a superelevation that met the Austroads recommended maximum. At the remaining locations, superelevation exceeded the recommended maximum, with the 140 m radius curve on Barkers Lodge Road having the highest superelevation and greatest deviation from the recommended maximum values.

The measured speeds at the 250 m radius curve on Healesville-Kinglake Road most closely aligned with the existing model predictions. This curve was the only location from Table H 2 that met the recommended maximum for superelevation.

For the sites where the recommended maximum superelevation was exceeded, two of the sites had a measured speed greater than the predicted speed. For the 120 m curve on Barkers Lodge Road, the measured speed was slightly less than the predicted speed.

Table H 2: Upstream curves – superelevation and curve departure speeds

Route	Curve radius (m)	Direction	Superelevation		Upstream curve departure speed		
			Actual	Recommended maximum(1)	Measured	Predicted(2)	Difference(3)
Barkers Lodge Rd	140	Northbound	10.2%	6%	86.4	85	1.4
Barkers Lodge Rd	120	Southbound	8.0%	6%	80.6	81	–0.4
Healesville-Kinglake Rd	160	Eastbound	8.1%	7%	78.1	76	2.1
Healesville-Kinglake Rd	250	Westbound	4.0%	7%	80.9	81	–0.1

1 From Table 7.7 of Austroads (2010a).
2 Based on existing operating speed model deceleration on curves graph (Austroads 2010a).
3 Negative value indicates that the measured speed was less than the speed predicted by the operating speed model.

H.2.2 Connecting Straights

Table H 3 shows the actual superelevation values and the maximum values recommended by Austroads (2010a) upstream and downstream from the connecting straight. Included are the speeds measured and predicted on the connecting straight. As shown, differences were greater for the Barkers Lodge Road curves.

Table H 3: Connecting straights – superelevation and curve departure speeds

Route	Direction	Curve location	Curve radii (m)	Superelevation		Connecting straight speed (km/h)		
				Actual	Recommended maximum(1)	Measured	Predicted(2)	Difference(3)
Barkers Lodge Rd	Northbound	Upstream	140	10.2%	6%	89.3	85	4.3
		Downstream	120	8.0%	6%			
Barkers Lodge Rd	Southbound	Upstream	120	8.0%	6%	87.4	81	6.4
		Downstream	140	10.2%	6%			
Healesville-Kinglake Rd	Eastbound	Upstream	160	8.1%	7%	81.7	82	–0.3
		Downstream	250	4.0%	7%			
Healesville-Kinglake Rd	Westbound	Upstream	250	4.0%	7%	80.1	81	–0.9
		Downstream	160	8.1%	7%			

1 From Table 7.7 of Austroads (2010a).
2 Based on existing operating speed model (Austroads 2010a) for approach to downstream curve.
3 Negative value indicates that the measured speed was less than the speed predicted by the operating speed model.

H.2.3 Downstream Curves

Table H 4 shows the superelevations and curve departure speeds for the downstream curves. As shown:

- For the 250 m radius curve on Healesville-Kinglake Road, where the superelevation was less than the recommended maximum, the measured curve departure speed closely aligned with the predicted speed.
- For the 140 m radius curve on Barkers Lodge Road, where there was the greatest deviation from the recommended maximum superelevation, the greatest difference occurred between the measured and predicted speed on the downstream curve.
- For the remaining two curves, where the recommend maximum superelevation was exceeded, the measured speeds were greater than predicted on the downstream curve.

When compared with the upstream curves, the results suggested that the influence of superelevation may have been greater for the downstream curves.

Table H 4: Downstream curves – superelevation and curve departure speeds

Route	Curve radius (m)	Direction	Superelevation		Downstream curve departure speed		
			Actual	Recommended maximum(1)	Measured	Predicted(2)	Difference(3)
Barkers Lodge Rd	120	Northbound	8.0%	6%	81.4	75	6.4
Barkers Lodge Rd	140	Southbound	10.2%	6%	86.3	75	11.3
Healesville-Kinglake Rd	250	Eastbound	4.0%	7%	81.8	82	–0.2
Healesville-Kinglake Rd	160	Westbound	8.1%	7%	76.1	73	3.1

1 From Table 7.7 of Austroads (2010a).
2 Based on existing operating speed model deceleration on curves graph (Austroads 2010a).
3 Negative value indicates that the measured speed was less than the speed predicted by the operating speed model.

INFORMATION RETRIEVAL

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Keywords:

operating speed, operating speed for trucks, deceleration on horizontal curves, curves in sequence

Abstract:

Austroads Project TS1456 (Expanded Operating Speed Model) was established to update and expand the road design operating speed models used in Australia. In particular, the project reviewed the validity of the existing operating speed model for rural roads and identified adjustments to the model that reflect changes in driver speed behaviour. This included the deceleration of cars and heavy vehicles on horizontal curves and the influence of horizontal curves in sequence.

This report documents the process used to collect and analyse speed data on horizontal curves, and assesses the implications in terms of the deceleration on curves for cars and trucks and the influence of curves in sequence. The report includes potential revisions for the existing operating speed model for horizontal curves.