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ESTABLISHING MULTI-COMBINATION VEHICLE TRAJECTORIES UNDER ACCELERATION FROM REST

Jonathan M. Bunker and Mandy J. Haldane

Abstract

Multi-combination vehicles (MCVs) that require long times to clear intersections or railway level crossings from rest can cause excessive delay to other traffic, and compromise safety if sight distances are inadequate. Intersection clearance time is of most concern in urban areas, due to its effect on vehicle productivity and the safety and efficiency of intersections. Clearance time at railway level crossings is of concern because trains require clear passage. Over a given merging distance, an MCV attains a lower speed than smaller vehicles, which may compromise the safety and efficiency of the merge area. This paper reviews current specifications for clearance time, acceleration and speed characteristics of MCVs. It reports an infield testing program conducted to measure trajectories of a range of MCVs and a model calibrated from the tests to describe vehicle trajectory. It then examines trajectories of MCVs based on the model, compares results with current specifications, and identifies avenues of future research. An understanding has been gained from this model on the retarding influences of mass and grade on acceleration capability and attained speed. Curves estimating clearance times for crossing widths, and speed as a function of travel distance, have been established for each MCV tested, across a range of grades. The model has been used to quantify acceleration capabilities of various MCVs. It is recognised that further calibration of the trajectory model is required for estimation of trajectories over longer distances and higher speeds, and for prime movers of varying power and gearing.

Introduction

Road freight efficiency and competitiveness are improving in Australia through the use of larger, innovative multi-combination vehicles (MCVs). However, this move has brought about concern over the interaction of these vehicles with existing infrastructure and other road users.

A MCV is a heavy vehicle which is larger than a standard prime mover semi-trailer combination, and which has restricted access to the road network. MCVs range from “limited access” vehicles such as B-Doubles and conventional Road Trains to vehicles of complex configuration such as four-trailer AAB-Quad combinations.

MCVs that require long times to clear intersections or railway level crossings from rest can cause excessive delay to other traffic, as well as posing a threat to safety if sight distances are inadequate. Intersection clearance time is of most concern in urban areas, due to its effect on vehicle productivity and the safety and efficiency of intersections. Clearance time at railway level crossings is of concern because trains require clear passage, and an MCV may require longer time to cross than the available sight distance permits. Over a given merging distance, an MCV attains a lower speed than smaller vehicles, which results in a larger relative speed between the MCV and the through traffic stream. This may compromise the safety and efficiency of the merge area.

This paper reviews current specifications for clearance time, acceleration and speed characteristics of MCVs. It reports an infield testing program conducted to measure trajectories of a range of MCVs and a model calibrated from the tests to describe vehicle trajectory. It then examines trajectories of MCVs based on the model, compares results with current specifications, and identifies avenues of future research.

Current Specifications

Clearance Time

As part of the *Performance Based Standards for Heavy Vehicles* Project, the Australian National Road Transport Commission (NRTC) and Austroads have proposed performance measures and initial standards for assessing vehicles and potential routes. NRTC (2001) advised that intersection clearance time performance characteristics are intersection specific and dependent on a range of factors, including grade, traffic volume and sight distance.

NRTC (2001) proposed a set of maximum values, which were determined from a series of computer-based simulations of the operation of design vehicles, as a guide to intersection clearance times: Unrestricted access to the entire network – no more than 12 seconds; arterials and major freight routes – no more than 15 seconds, and routes designated for long combination vehicles – no more than 25 seconds.

The times were established assuming that the vehicle starts from rest, accelerates at the maximum possible rate, travels straight through a 25m wide intersection on level ground with adequate sight distance.

The clearance times that were specified by NRTC vary due to the critical vehicle assumed for the road class. In the state of Queensland, unrestricted access to the entire network is provided to vehicles such as a standard semi-trailer combination. B-Doubles and some A-Double road trains operate on designated arterials and major freight routes. Routes designated for long combination vehicles, including A-Triple road trains and AAB-Quad combinations, are usually located in remote areas where traffic volumes are low and therefore longer clearance times generally do not have major impacts on intersection operation.

Acceleration

MRWA (1992) quoted values of heavy vehicle acceleration from American literature ‘ranging from 0.45m/s^2 for the acceleration of trucks in first gear, to 0.54m/s^2 over a distance of around 12m, then gradually back down to a value of 0.5m/s^2 for a distance of around 50m’. For assessing crossing visibility as a critical case, they subsequently recommended the adoption of a heavy vehicle acceleration value of 0.5m/s^2 indicating that this value has been shown ‘to be acceptable by measuring the acceleration rates of a number of fully laden trucks, which resulted in values between 0.55m/s^2 and 0.90m/s^2’.

QDMR (1998) prescribed a function to determine the minimum distance of an approaching train from the point of impact with a road vehicle accelerating from rest at a stop controlled rail crossing. The function calculates the distance travelled by the train at a constant operating speed, during the time required for the heavy vehicle to clear the crossing, which is developed using geometry. One of the terms used in estimating the clearance time of the heavy vehicle is its average acceleration in starting gear. A default value of 0.5m/s^2, based on the MRWA (1992) work, and a grade correction factor were provided.

Speed

QDMR (2000) recommended that the length of any entry lanes provided on an MCV route be sufficient to allow MCVs, when fully loaded, to accelerate to within 70 per cent of normal traffic speed at the point where the lane joins with the through road.

Test Details

Queensland University of Technology (QUT) and Queensland Department of Main Roads (QDMR) recognised that further research was required to measure infield the trajectories of various MCVs. This research would establish whether the clearance times proposed by NRTC were appropriate, whether the average acceleration rate prescribed by QDMR (1998) for use in estimating sight distance where MCVs are present is appropriate, and the speed characteristics of MCVs during the acceleration process for assessing merge geometry. The research findings would inform the QDMR Route Assessment Guidelines and potentially those of other Australian road authorities for assessment of heavy vehicle access proposals.

The infield test program, which was conducted in conjunction with Queensland Transport (QT), included the measurement of trajectories of four MCVs during the acceleration process, over a range of grades.

Test Multi-combination Vehicles

Table 1 provides the dimensional characteristics of each MCV.

[Table 1]

The smallest of the MCVs tested, the B-Double, is coupled by a turntable assembly between the prime mover and first trailer, and another assembly at the rear of the first trailer supporting the second trailer. Pearson *et al* (2000) noted that the B-train concept originated in Canada in the 1970s and was introduced to Australia in the 1980s, originally with a 23m maximum length. The test vehicle reflects the current maximum allowable length in Queensland of 25m. These vehicles have an improved safety performance compared with smaller trucks (Ramsay 1998). This is attributed to the turntable articulation, which is more stable than the conventional converter-dolly articulation, and to the antilock braking systems specified for prime movers and trailers carrying dangerous goods in bulk.

The A-Double, also referred to as a Type 1 Road Train, is coupled by a turntable assembly between the prime mover and first trailer, and a converter dolly between the first and second trailer. The converter dolly incorporates a turntable assembly mounted on an axle group supporting the rear trailer, and a drawbar connecting to the first trailer. This drawbar connection yields additional axes of rotation, therefore this coupling is less stable than the B coupling.

The A-Triple, also referred to as a Type 2 Road Train, is coupled by a turntable assembly between the prime mover and first trailer, and converter dollies between the first and second trailer, and second and third trailers.

The AAB-Quad, an innovative combination being introduced in restricted circumstances in Queensland, is coupled by a turntable assembly between the prime mover and first trailer, converter dollies between the first and second, and second and third trailers, and a turntable assembly between the third and fourth trailers. It is basically a combination of an A-Double towing, using a converter dolly, a B-Double trailer configuration.

Haldane (2002) provides further detail on the characteristics and application of these MCVs.

All combinations tested were hauled by a 1995 single-steer, tandem-drive Kenworth with 18 speed transmission, 50:50 drive torque distribution rated at 550 horsepower (410 kW) towing side tipper trailers. Each vehicle was loaded with ballast to attempt to achieve the regulation operating axle masses. The same prime mover was used for all combinations for reasons of practicality and availability. It is recognised that, in service, prime movers would vary somewhat in power and gearing with the size of combination.

Test Measurement

Performance characteristics of the test vehicles were measured using a portable instrumentation module consisting of roto-pulse attached to the front drive axle and operated from the centre of the right side wheel for measuring the distance travelled, internal computer time clock for measuring time, accelerometers for measuring lateral and longitudinal acceleration on the prime mover steer axle and at the centre of gravity position of last trailer chassis, and two video cameras attached to the roof of the prime mover facing rearwards and above the drive axles of the prime mover facing forwards. This analysis of vehicle trajectory used the distance data measured by the roto-pulse at 300mm intervals and the corresponding time stamps recorded by the computer.

With the front of the test vehicle positioned on a painted marker on the road surface, simulating a stop line, the instructors of the test vehicles were instructed to accelerate at full throttle from a standing position over a distance of approximately 200m. The standard instrumentation recorded time, distance, speed and acceleration data during the acceleration process.

For each test vehicle, five successful trials were performed on the following grades; -5 per cent, -2 per cent, 0 per cent, 2 per cent, and 5 per cent.

Modelling Vehicle Trajectory

For each test vehicle on each grade, the raw data was processed to produce trajectory profiles in approximately 6m increments, corresponding to 20 pulses each measuring a 300mm distance. The profiles included distance travelled, time of travel, average speed (6m backward to 6m forward), and average acceleration (6m backward to 6m forward). The trajectory profiles from the five trails were subsequently consolidated to determine an average trajectory profile for each vehicle on each grade. *Fig. 1* provides an example being the trajectory profile for the AAB-Quad combination on a -2 per cent grade.

[Fig. 1]

It was established from regression analysis that the following third order polynomial function best explained the processed distance versus time data, for each of the MCVs on each grade:

$$d = \frac{C}{6}t^3 + \frac{a_0}{2}t^2 \qquad (1)$$

where d is the distance travelled from rest (m) at instant t (s), and C and a_0 are constants.

Equation 1 may be differentiated to estimate speed, v (m/s), at instant t as follows:

$$v = \frac{C}{2}t^2 + a_0 t \qquad (2)$$

In turn, *Equation 2* may be differentiated to estimate acceleration, a (m/s^2), at instant t as follows:

$$a = C\,t + a_0 \tag{3}$$

In these equations, a_0 represents the acceleration at time t equal to 0, and constant C, being negative in all cases, the reduction in acceleration with time.

The values of the regression constants C and a_0, and the coefficient of regression R^2, using *Equation 1*, are provided in *Table 2* for each test vehicle on each grade. The values of R^2 are close to 1.0 across all MCVs on all grades, indicating that *Equation 1*, although empirical, provides a valid model of vehicle trajectory. Also provided are the maximum distances and corresponding times used in calibrating these equations. These were determined through inspection of the speed profiles. Beyond these distances and times the vehicle trajectories were affected by inconsistencies in driver behaviour and are not considered valid.

[Table 2]

Fig. 2 illustrates the speed versus time data, and *Fig. 3* the acceleration versus time data, for the AAB-Quad combination on a -2 per cent grade, against the estimating functions of *Equations 2* and *3* respectively, using the constants for this MCV listed in *Table 2*. *Fig. 2* indicates that *Equation 2* provides a reasonable model of the speed profile of the vehicle while it is accelerating. The vertical line at 35s corresponds to the maximum distance used in calibrating *Equation 1*, beyond which it is obvious from the data that the driver reduced speed.

[Fig. 2]

While there was little spread in the processed distance versus time data and speed versus time data, *Fig. 3* illustrates that the acceleration versus time data is very noisy as a result of data processing. Even so, a reduction in acceleration with time is evident in the data, which is reflected in *Equation 3*. It must be recognised that *Equation 3* is a simplistic explanation of the relationships between acceleration and time.

[Fig. 3]

Trajectory Model Examination

According to *Equation 3*, acceleration would reduce to a value of 0 at time $-a_0/C$. Inspection of *Table 2* revealed that the maximum times used in calibrating these equations are lower in all cases than this time value. These equations should not be used to model trajectories “late” in the acceleration process beyond the maximum calibrated times and distances. This limitation should be overcome in future testing by accelerating vehicles over longer distances and to cruising speeds.

Inspection of *Table 2* reveals that, for each MCV tested, both C and a_0 generally reduce with a positive change in grade, indicating that the acceleration profile reduces with a positive change in grade. This reduction is attributed to the effect of the longitudinal component of gravity on achievable acceleration. On steeper downgrades, a higher acceleration will be achievable due to the assistance of gravity. Conversely, on steeper upgrades, gravity will produce a retarding effect on acceleration. Notwithstanding, the differences in these acceleration constants are not only attributable to grade. The values would suggest that the driver operated the MCV differently on different grades, applying less power on downgrades.

Further inspection of *Table 2* reveals that, across all grades, as MCV size increase both C and a_0 reduce, indicating that the acceleration profile reduces with an increase in vehicle mass. This is attributed to a reduction in power/mass ratio. This ratio for each MCV is provided in *Table 1*.

Clearance Time

Figs. 4, 5 and *6* illustrate, for all MCVs tested, the relationships between clearance time and crossing width, for grades of -5 per cent, 0 per cent, and 5 per cent respectively. Crossing width is equal to distance calculated using *Equation 1* less vehicle length. For reference, the figures show crossing widths of 17.1m, representing a perpendicular, double narrow gauge (1067mm) rail crossing, and 25m, representing the standard intersection width.

[Figs. 4, 5, 6]

It is evident from the plots that, for a given crossing width, clearance time increases with tested MCV size. This is partly attributed to the decrease in acceleration capability brought about by a decrease in power/mass ratio, as was discussed earlier. Further, the increase in length will increase the total travel distance required to clear the intersection.

Comparison between the plots again demonstrates the significant effect of grade. It is apparent from the plots that grade has a greater effect on clearance time for the longer, heavier combinations, due to the greater proportion of available power required to overcome the longitudinal component of gravity.

Fig. 5 demonstrates that the tested B-Double and A-Double would clear a 25m wide intersection on a flat grade in 12.3s and 12.6s respectively. NRTC (2001) recommended performance characteristics of no more than 15s for routes upon which these MCV categories are likely to operate. The data suggest that, for the MCVs tested, this is a slightly conservative criterion.

A-Triple Road Trains and AAB-Quads operate in Queensland on routes designated for long combination vehicles. *Fig. 5* indicates that the tested vehicles would clear a 25m wide intersection on a flat grade in 16.5s and 19.8s respectively. These times are also less than the NRTC performance characteristic of 25s for long combination routes. This criterion is conservative but reasonable for the tested vehicles.

The intersection clearance times for each MCV tested were interpolated between grades, to determine the maximum grades for which the NRTC performance characteristics were acceptable. The results are provided in *Table 3*.

[Table 3]

Figs. 4, 5 and *6* also identify clearance times required to cross the 17.1m double rail crossing, for the various MCVs tested, on each grade. Sight distance required may be established by multiplying the clearance time, plus a perception/reaction time, by the design speed of the rail vehicle. For non-perpendicular crossings and other crossings of different dimensions, the actual crossing width must first be computed prior to use of these figures.

MCVs having power/mass ratios similar to those tested, but with greater length, will require greater clearance time, which in the absence of further testing, may be estimated using *Equation 1* and the constants in *Table 2*, less the actual vehicle length.

For an MCV with different power and mass characteristics from those tested, its power/mass ratio may be interpolated between those of the MCVs tested in *Table 1*. Clearance time may be estimated by interpolating from *Table 2* the trajectory model constants between those corresponding to the power/mass ratios of the test MCVs, less the actual vehicle length. Notwithstanding, further investigation is required through in-field testing of vehicles with engines of different power. This is particularly important considering that the same prime mover was used for all combinations tested, whereas a range of power and gearing would be adopted across the combinations in service.

The performance measures proposed by NRTC (2001) related to the clearance of a 25m intersection on a flat grade. However, the width of intersections vary, and grade may differ. Whilst it is understood that the NRTC is currently reviewing the proposed values, it is recommended that, when assessing intersections for use by MCVs, the trajectory model document herein be used, interpolating as appropriate, as it covers a greater range of operating conditions.

Acceleration

Table 4 lists, for each MCV tested, the equivalent constant acceleration rate that would achieve the required distance to clear a 17.1m double rail crossing on a level grade in the time calculated using *Equation 1*.

The values listed in *Table 4* indicate that the acceleration rate of 0.5m/s^2 suggested by QDMR (1998) to estimate heavy vehicle acceleration from rest for estimation of sight distances at rail crossings would be conservative for the B-Double and A-Double, and acceptable for the A-Triple tested. It is reasonable to expect that the value of 0.5m/s^2 would remain suitable for B-Doubles and A-Doubles, even when hauled by lower powered prime movers.

Conversely, the equivalent constant acceleration rate listed in *Table 4* for the AAB-Quad indicates that a value of 0.5m/s^2 would overestimate acceleration capability. When reviewing sight distances at level crossings used by these large combinations, it is recommended that the values in *Table 4* be adopted when applying the QDMR (1998) procedure. Should higher powered prime movers be used to haul these combinations, a higher value may be appropriate.

Alternatively, as discussed above, clearance times may be estimated from the trajectory model presented herein, with compensation made for any power/mass variation as appropriate, and sight distances to rail vehicles then computed for these times.

Speed

The trajectory model described by *Equations 1* and *2* and *Table 2* enables speed to be calculated for a given distance, and interpolated for grade, for any of the MCVs tested, provided that the distance does not exceed the maximum calibrated distance. *Figs. 7, 8* and *9* illustrate the speed as a function of distance, calculated for each MCV tested using the model, on the -5 per cent, 0 per cent, and 5 per cent grades respectively. The functions are illustrated only within the calibrated ranges of distance.

[Figs. 7, 8, 9]

By comparing *Figs. 7, 8* and *9* it is clear that, for each MCV tested, grade has a significant effect on attainable speed, due to its effect on acceleration. This effect is more pronounced for the larger combinations. On the -5 per cent grade, the speed of the B-Double is approximately 15 per cent higher than that of the AAB-Quad across the measured distances. Whereas, on the 5 per cent grade, across the measured distances the speed of the B-Double is approximately 60 per cent higher than that of the AAB-Quad. Careful consideration must be given to assessing the ability of the larger MCVs to merge on upgrades.

As an example of the application of the trajectory model, consider an MCV accelerating from rest over an available length of 100m on a 0 per cent grade, onto a through road with operating speed 60km/h. *Fig. 8* indicates that the B-Double would attain a speed of 9.7m/s or 35km/h, the A-Double 9.3m/s or 33km/h, the A-Triple 8.4m/s or 30km/h, and the AAB-Quad 7.4m/s or 27km/h. None of the MCVs would therefore meet the QDMR (2000) criterion of 11.7m/s or 42km/h. The B-Double would only meet that speed criterion within 190m.

Should this merge be located on a -5 per cent grade, *Fig. 7* indicates that the B-Double and A-Double would meet, the A-Triple would nearly meet, and the AAB-Quad would be within 5km/h, of the criterion of 11.7 m/s. Should the merge be located on a 5 per cent upgrade, it is apparent from *Fig. 8* that none of the MCVs tested would be able to approach this speed criterion.

As another example, given an initial speed of 6m/s or 22km/h, the incremental distance required to achieve a desired operating speed of 11.7m/s for the B-Double on a 0 per cent grade may be established from *Fig. 7* as 160m.

As with the clearance time functions, speed/distance functions may be estimated for MCVs with different power/mass characteristics, by interpolating between those of the MCVs tested.

It is recognised that further calibration of the trajectory model is required for estimating trajectories over longer distances and higher speeds, and across a broader range of vehicle characteristics consistent with those used in service.

Further Applications and Needs

Haldane and Bunker (2002) documented a pilot study for testing of through passenger car equivalences (PCEs) of three types of MCV, which was conducted during this test program. The testing synthesised a limited range of signalised intersection conditions, with the MCV positioned relatively early in queue. The trajectory models documented herein will enable a greater range of queuing conditions to be modelled so that passenger car equivalences may be estimated across a range of traffic and geometric conditions.

NRTC (2001) stated that a heavy vehicle should be able to safely attain a desirable level of deceleration during braking for a range of load, speed and road conditions, and stop within specified distances without loss of directional control or stability. NAASRA (1985) noted that vehicles under extreme braking conditions are more liable to instability, leading to jack-knifing and trailer swing, with an increasing number of articulation points. Ramsay (1998) advocated that, while braking has been found to be a rare event in rural and inter-urban operation, stability of multi-articulation vehicles is of major concern.

Previous testing and computer modelling has mostly addressed these issues by testing under maximum braking conditions. However, for safe and efficient road element design and route designation, braking behaviour of MCVs under normal, or desirable, conditions should be considered. To this end it would be useful to conduct similar tests of MCVs to establish trajectory profiles during the deceleration process to assist in sight distance calculations and other road design activities.

Conclusion

This study has established from infield testing a model of the trajectory of multi-combination vehicles (MCVs) accelerating from rest. The model, which estimates travelled distance, speed and acceleration as a function of time, was calibrated from regression on trajectory data. Model parameters represent an initial acceleration and a reduction in acceleration with time. These constants have been calibrated for grades between -5 per cent and 5 per cent, for four MCV types, which vary in size. All were hauled by a prime mover rated at 410kW. An understanding has been gained from this model on the retarding influences of mass and grade on acceleration capability and attained speed.

Curves estimating clearance times for crossing widths have been established for each MCV across the range of grades. These may be used to establish clearance times for MCVs crossing intersections and rail crossings, for use in sight distance calculations and traffic operational analysis. Clearance times proposed by NRTC (2001) for MCVs crossing a 25m intersection on flat grades were established to be conservative using the trajectory model.

The trajectory model has been used to quantify acceleration capabilities of various MCVs tested and to examine the appropriateness of use of a constant value of 0.5 m/s^2 suggested by QDMR (1998) for use in calculating sight distance at stop controlled rail crossings on level grades. The model indicates that this value is representative for the B-Double, A-Double and A-Triple tested. A lower value has been determined herein for the AAB-Quad. Alternatively, the trajectory model may be used directly to estimate clearance times.

Curves estimating speed as a function of travelled distance have been established for each MCV tested across the range of grades. These may be used to establish the adequacy of merge geometry on MCV routes in terms of merging speed relative to through road speed.

Trajectories of MCVs with different power/mass characteristics may be estimated by interpolating between the functions of the MCVs tested.

The trajectory models will enable a range of queuing conditions to be modelled in future research to estimate passenger car equivalences of MCVs at signalised intersections.

It is recognised that further calibration of the trajectory model is required for estimation of trajectories over longer distances and higher speeds. Further investigation should be undertaken through in-field testing of vehicles hauled by prime movers of varying power and gearing characteristics, consistent with the range used in service across the MCV categories. A trajectory model of deceleration under normal operating conditions should also be investigated.

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Author Biographies

Jonathan Bunker completed his Bachelor of Engineering (Civil) (Hons) in 1991, and Doctor of Philosophy on Microscopic Modelling of Freeway Operations in 1995, both at QUT. He has practiced as a consulting transport engineer with Kittelson & Associates, Inc. in Portland, Oregon, and Eppell Olsen & Partners in Brisbane, undertaking development transport planning, urban and regional integrated transport planning, road hierarchy and network analysis studies, design of transport facilities, and public engagement activities. He contributed with Kittelson & Associates to the development of *Roundabouts, An Information Guide* for the US FHWA. Jonathan is now lecturer in transport engineering in the School of Civil Engineering, QUT. He teaches and coordinates transport engineering/planning and professional studies courses at undergraduate and postgraduate levels. Jonathan is currently active on research projects including pavement asset management, heavy vehicle management, freeway operations, and freight logistics.

Mandy Haldane obtained her Bachelor of Engineering (Civil) (Hons) from Central Queensland University in 1995. She has since been working for the Queensland Department of Main Roads (QDMR) and Queensland Department of Transport, holding positions in infrastructure delivery, bridge design, vehicle operation and safety, and heavy vehicle management. In her position of Senior Engineer (Heavy Vehicle Management) Mandy has provided advice to QDMR regions and districts on policy and strategy for the management of heavy vehicle impacts on the road network, and has developed Route Assessment Guidelines for use in assessing the suitability of state controlled roads proposed for the operation of multi-combination vehicles. Mandy recently completed a Master of Engineering (Research) degree at the School of Civil Engineering, Queensland University of Technology.

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Tables and Figures

Table 1: Test Multi-combination Vehicle Characteristics

Characteristic	B-Double	A-Double	A-Triple	AAB-Quad
Length	25.36 m	27.43 m	40.78 m	48.85 m
Width	2.5 m	2.5 m	2.5 m	2.5 m
Tested GCM	62.10 t	79.88 t	115.83 t	142.50 t
Regulation GCM	62.50 t	79 t	119 t	146 t
Payload	36.44 t	48.14 t	66.73 t	87.30 t
Configuration	12(S3)2	12S3-2S3	12S3(-2S3)2	12S3-2S3-2(S3)2
Tyres	34	42	62	74
Power/mass (kW/t)	6.60	5.13	3.54	2.88

Table 2: Trajectory Model Constants, Coefficient R^2, Maximum Calibration Distance and Time

Vehicle	C	a_0	R^2	Maximum Distance (m)	Maximum Time (s)
		-5 per cent grade			
B-Double	-0.0373	1.060	0.999	263	27
A-Double	-0.0252	0.930	0.996	371	34
A-Triple	-0.0263	0.894	0.996	345	34
AAB-Quad	-0.0228	0.798	0.999	325	35
		-2 per cent grade			
B-Double	-0.0285	0.817	0.999	213	28
A-Double	-0.0257	0.809	0.992	212	27
A-Triple	-0.0127	0.621	0.995	498	49
AAB-Quad	-0.0152	0.573	0.997	243	35
		0 per cent grade			
B-Double	-0.0227	0.741	0.993	230	30
A-Double	-0.0238	0.719	0.997	216	30
A-Triple	-0.0175	0.587	0.997	196	31
AAB-Quad	-0.0144	0.450	0.996	239	40
		2 per cent grade			
B-Double	-0.0214	0.668	0.998	214	31
A-Double	-0.0167	0.588	0.998	247	35
A-Triple	-0.0150	0.478	0.997	162	32
AAB-Quad	-0.0086	0.332	0.996	167	39
		5 per cent grade			
B-Double	-0.0154	0.471	0.992	145	30
A-Double	-0.0116	0.394	0.998	151	34
A-Triple	-0.0053	0.242	0.993	166	45
AAB-Quad	-0.0044	0.192	0.993	124	44

Table 3: Grades Exceeding NRTC Clearance Time Requirements for MCVs Tested

MCV Type	Route Type	NRTC Clearance Time (s)	Grades Exceeding NRTC Requirement (per cent)
B-Double	Arterial and major freight routes	15	4.0
A-Double	Arterial and major freight routes	15	2.7
A-Triple	Long combination vehicle routes	25	4.8
AAB-Quad	Long combination vehicle routes	25	2.5

Table 4: Equivalent Average Acceleration Rates for MCVs to Clear 17.1m Double Rail Crossing on Level Grade

MCV Type	Crossing Distance (m)	Clearance Time (s)	Equivalent Average Acceleration Rate (m/s^2)
B-Double	42.5	11.4	0.65
A-Double	44.5	11.9	0.62
A-Triple	57.9	15.2	0.50
AAB-Quad	66.0	19.2	0.36

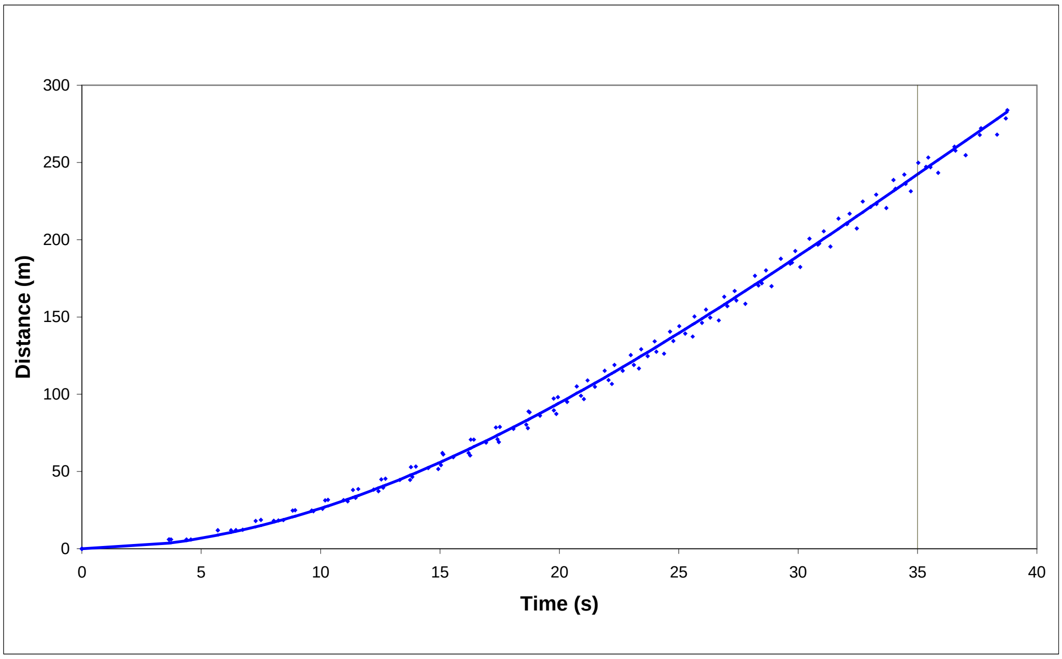

Figure 1: Distance vs Time, AAB-Quad Combination, -2 per cent grade

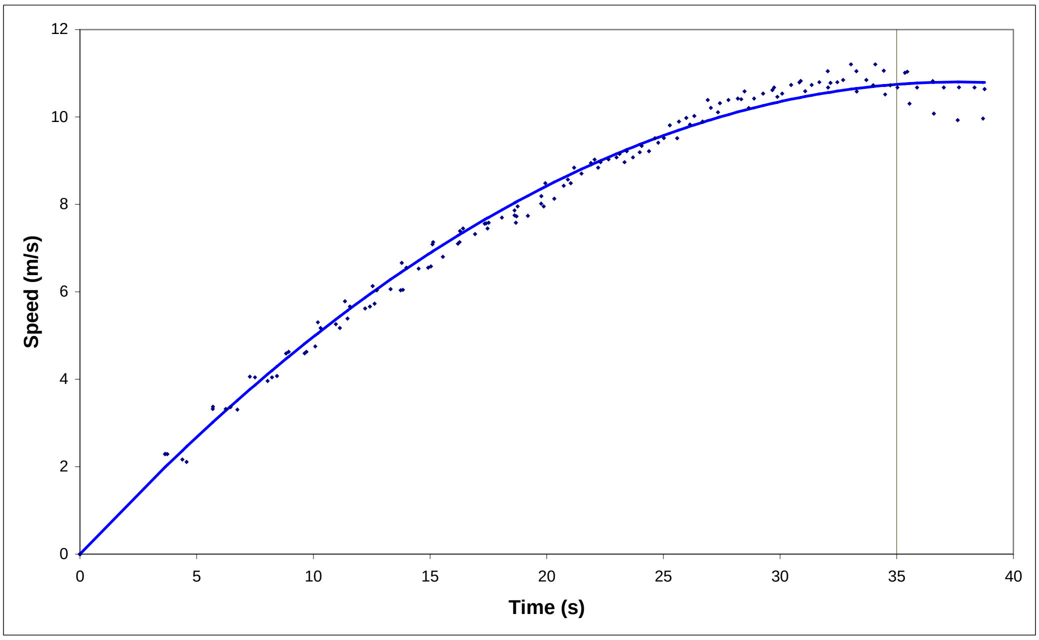

Figure 2: Speed vs Time, AAB-Quad Combination, -2 per cent grade

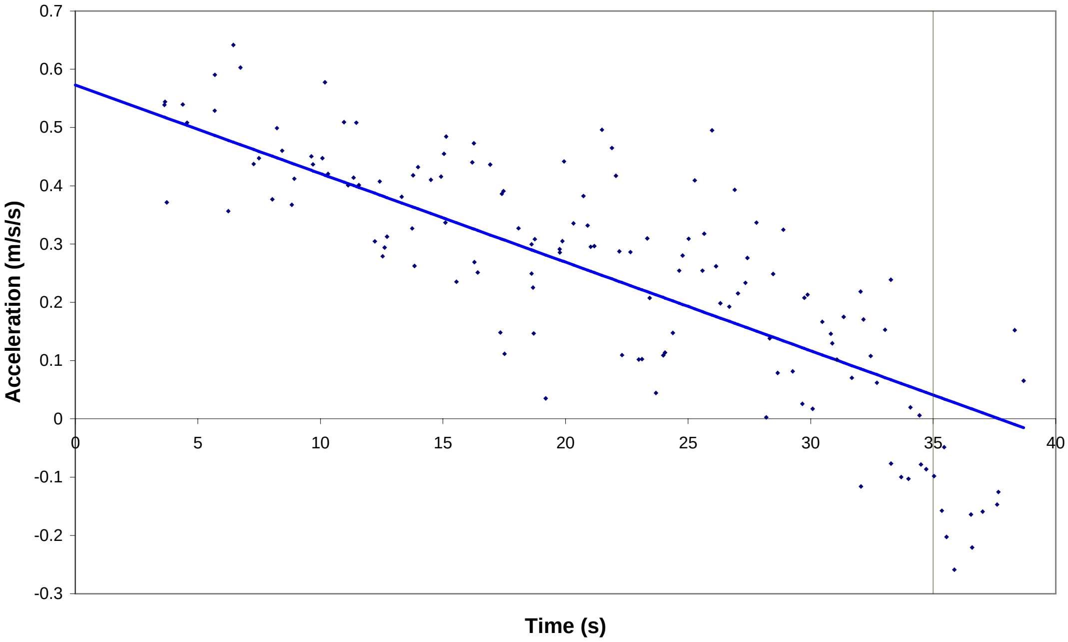

Figure 3: Acceleration vs Time, AAB-Quad Combination, -2 per cent grade

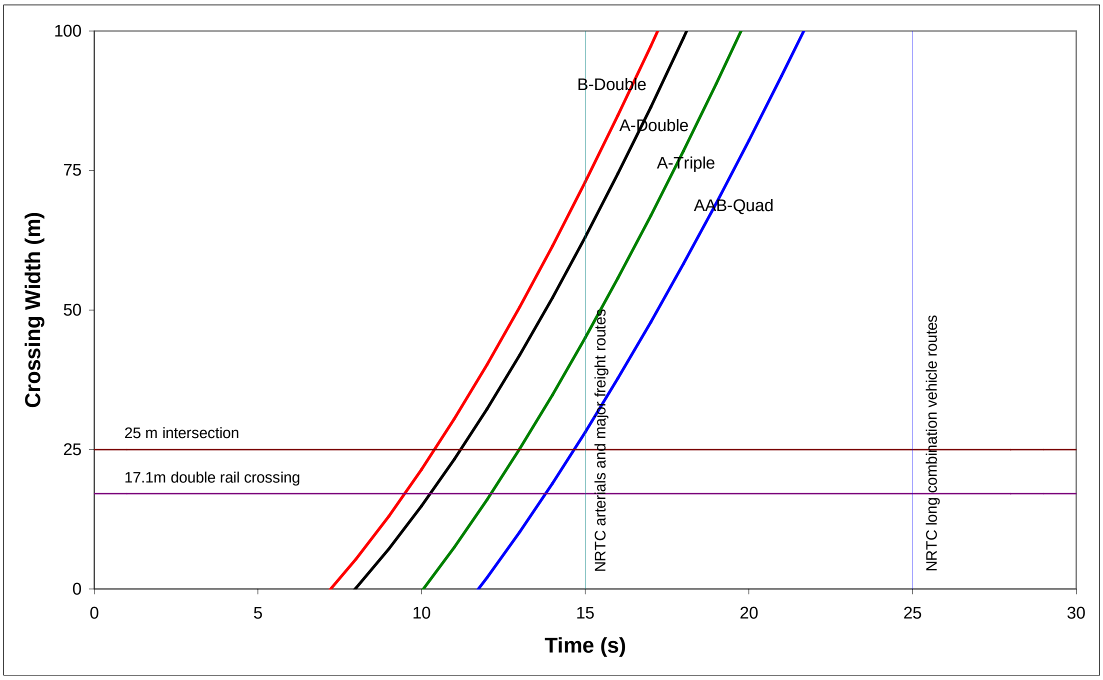

Figure 4: Clearance Time vs Crossing Width, -5 per cent grade

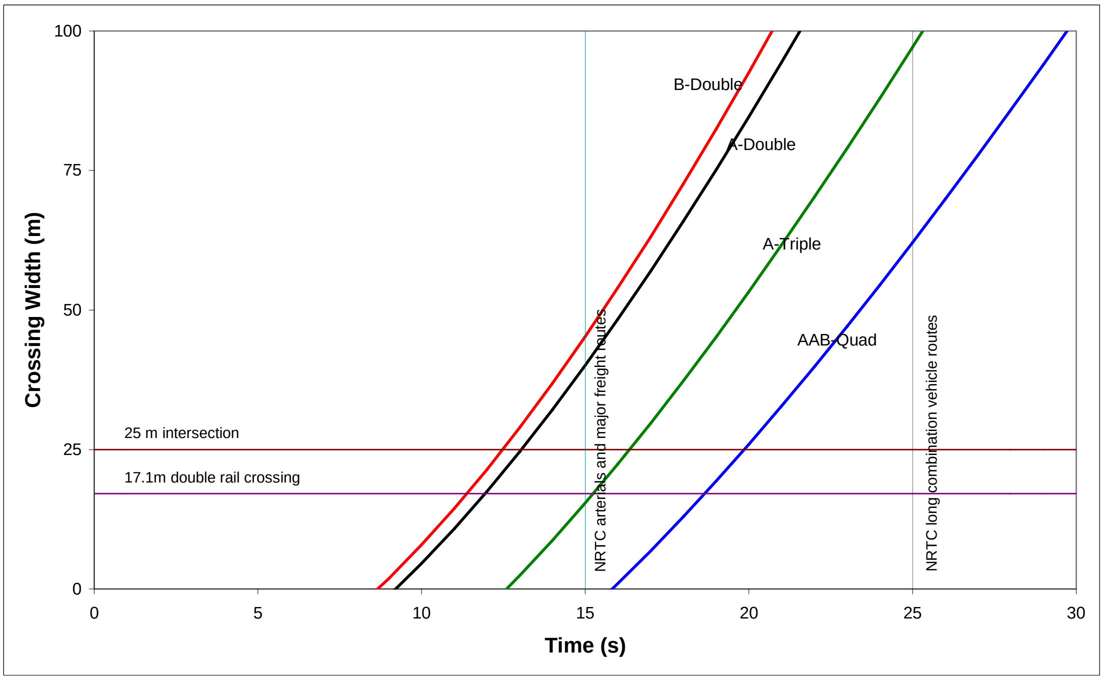

Figure 5: Clearance Time vs Crossing Width, 0 per cent grade

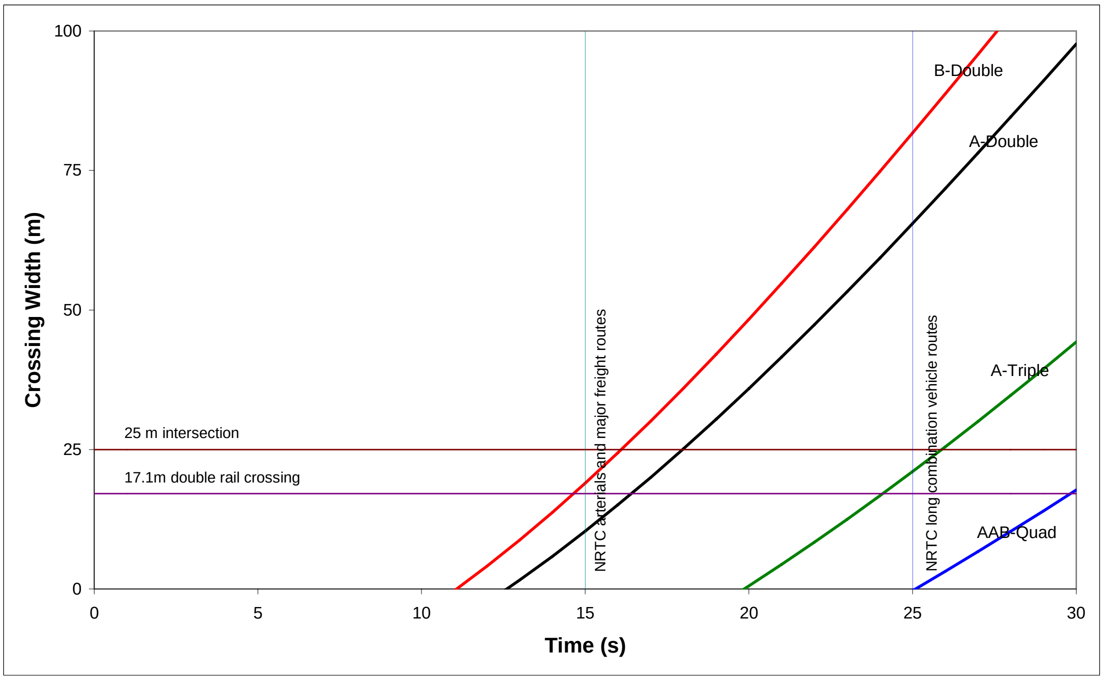

Figure 6: Clearance Time vs Crossing Width, 5 per cent grade

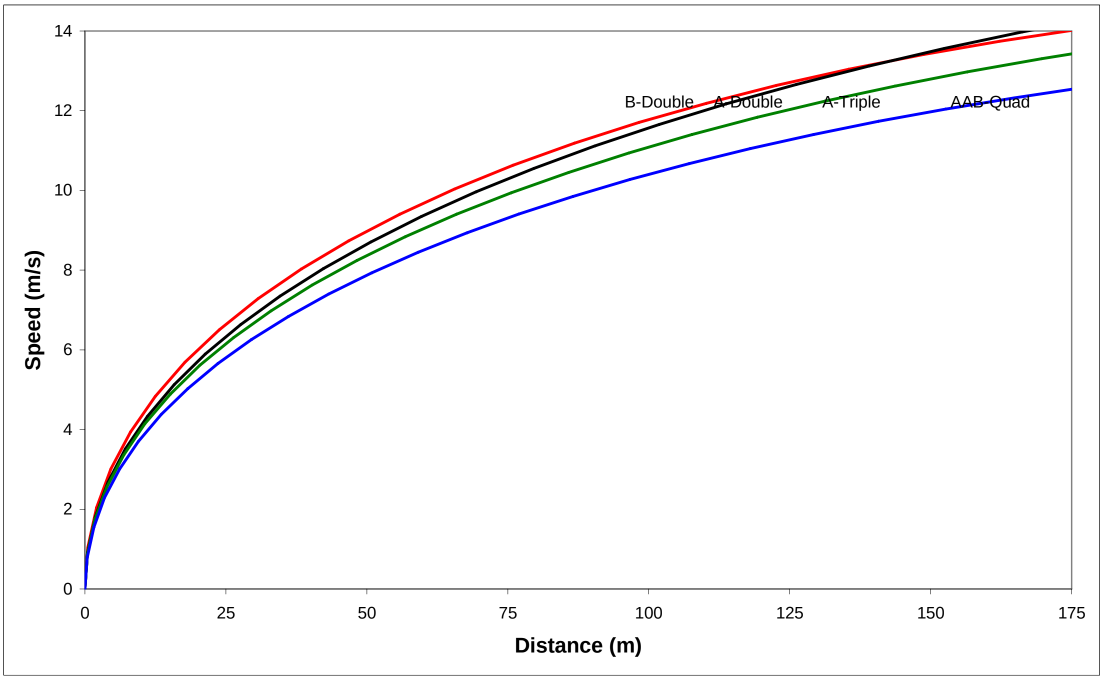

Figure 7: Speed vs Distance, -5 per cent grade

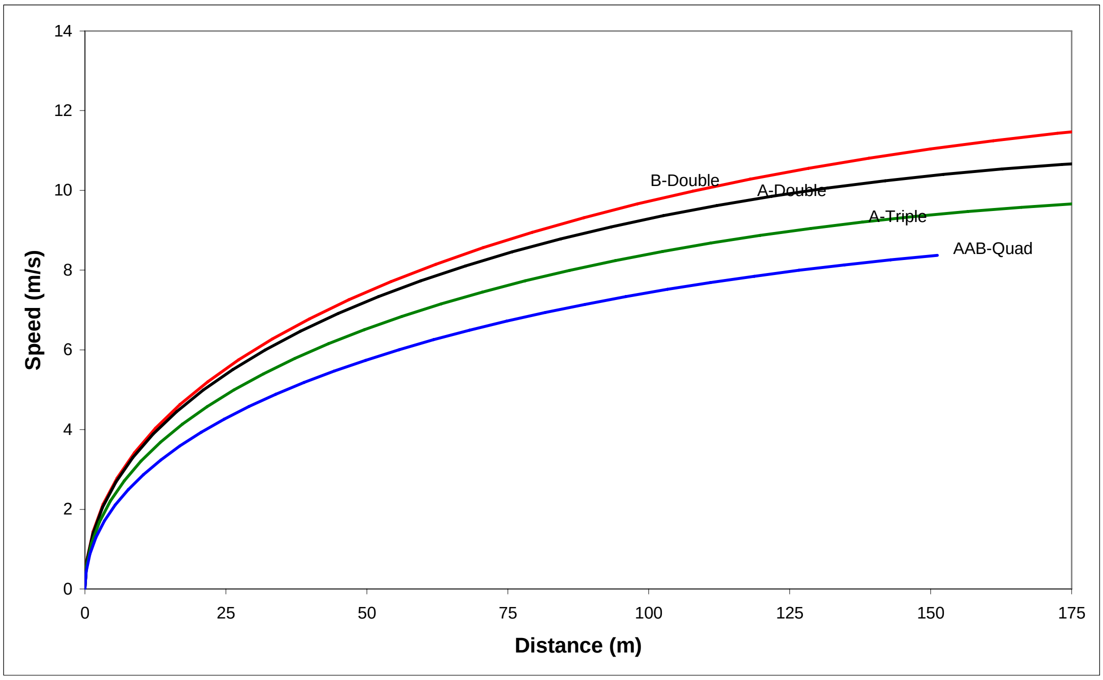

Figure 8: Speed vs Distance, 0 per cent grade

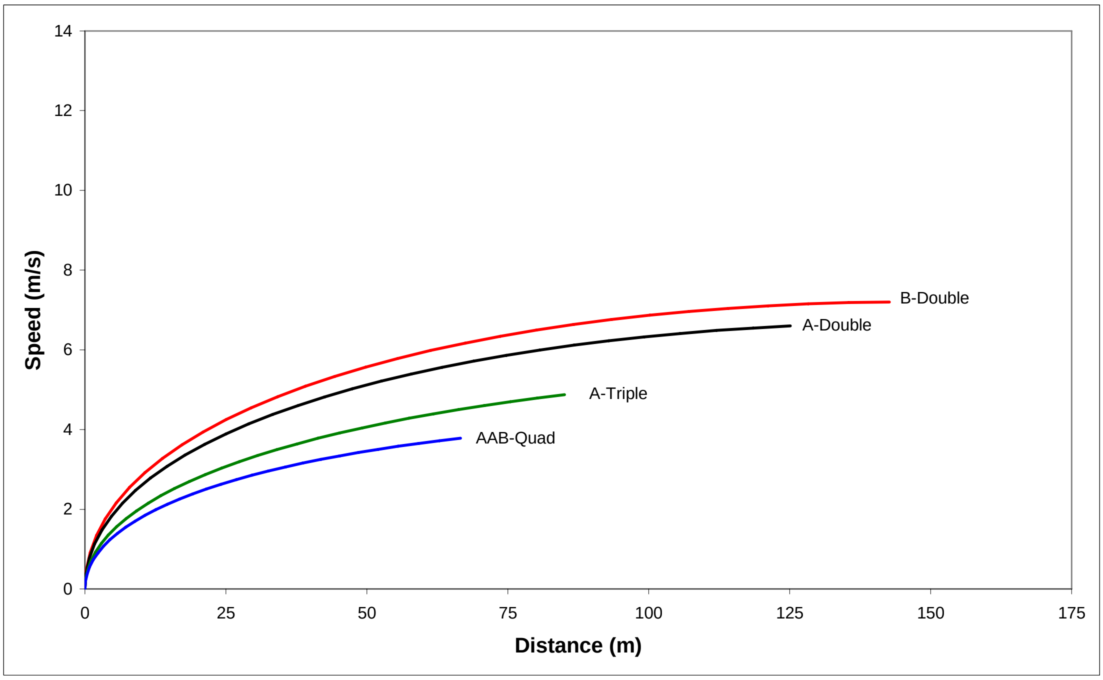

Figure 9: Speed vs Distance, 5 per cent grade