Report to Main Roads Western Australia

Acceleration and deceleration testing of combination vehicles

Roadusor Systems Pty Ltd

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Quality control

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Issue control

Issue	Date	Notes
1	30/06/04	RUS internal.
2	05/07/04	First release (draft).
3	16/07/04	Added average acceleration and deceleration values.
4	02/08/04	Amendments at the request of Main Roads WA.
5	13/08/04	Amendments at the request of Main Roads WA.

Executive summary

Roaduser Systems Pty Ltd was commissioned by Main Roads Western Australia to carry out a large-scale field testing program that involved acceleration and deceleration testing of a range of combination vehicles. The following vehicle combinations were tested, with varying body type and gross combination mass:

- Tractor-semi-trailer;
- B-double;
- Truck-trailer;
- Double road train;
- Triple road train;
- A+B innovative road train;
- 2A+B innovative road train; and
- A+B3 innovative road train.

Acceleration tests determined characteristics such as time to cover distance, time to reach speed and distance to reach speed, as well as the effects of grade, GCM and driver reaction time. Deceleration tests determined characteristics such as stopping distance from various initial speeds, the effects of grade and available friction, and driver reaction time.

The comprehensive acceleration and deceleration test program provided a high degree of confidence in the results presented. Repeated tests on a reasonably large sample of vehicles and drivers provided enough data to determine the relationship between performance and GCM, and to determine average reaction times in braking and also in starting a vehicle moving from rest. The following average driver perception-reaction times are suitable for acceleration and deceleration:

- Acceleration reaction time: 3.25 sec
- Deceleration reaction time: 2.00 sec

The acceleration reaction time includes the driver's physical reaction time and the vehicle's mechanical delay in beginning to move forward (due to clutch slip time, etc).

It was found that reaction times varied significantly between drivers, and this should perhaps be considered in road and traffic design standards for heavy vehicles. 95th percentile values for acceleration and deceleration reaction times were found to be 5.42 sec and 3.95 sec respectively. There was no evidence that reaction times vary systematically with vehicle factors or road conditions.

The strong relationships observed between GCM and acceleration/deceleration performance provided linear equations that can be used to calculate acceleration time and stopping distance for a given GCM. These equations were used to fill the schedules in Table 1 and Table 2, showing acceleration times and stopping distances respectively for the range of GCMs tested (40 – 160 t). Also shown for each scenario is the associated average acceleration or deceleration. Stopping distance in wet weather braking can be determined by application of the appropriate

Wet Correction Factor in Table 2. The reaction time component is then added if it is required to account for reaction time effects in either acceleration or deceleration.

Table 1 Schedule of acceleration time and average acceleration

GCM	Acceleration time (sec)				Average acceleration (g)			
(t)	0 – 100 m	0 – 60 km/h	0 – 80 km/h	0 – 100 km/h	0 – 100 m	0 – 60 km/h	0 – 80 km/h	0 – 100 km/h
40	19.3	55	78	99	0.054	0.031	0.029	0.029
50	20.1	60	92	150	0.050	0.028	0.025	0.019
60	20.9	65	106	201	0.047	0.026	0.021	0.014
70	21.7	71	121	252	0.043	0.024	0.019	0.011
80	22.5	76	135	303	0.040	0.022	0.017	0.009
90	23.3	82	149	354	0.038	0.021	0.015	0.008
100	24.1	87	163	405	0.035	0.019	0.014	0.007
110	24.9	93	177	457	0.033	0.018	0.013	0.006
120	25.6	98	192	508	0.031	0.017	0.012	0.006
130	26.4	103	206	559	0.029	0.016	0.011	0.005
140	27.2	109	220	610	0.028	0.016	0.010	0.005
150	28.0	114	234	661	0.026	0.015	0.010	0.004
160	28.8	120	248	712	0.025	0.014	0.009	0.004
	Reaction time component + 3.25 sec							

Table 2 Schedule of stopping distance and average deceleration

GCM	Stopping distance (m)			Average deceleration (g)		
(t)	60 – 0 km/h	80 – 0 km/h	100 – 0 km/h	60 – 0 km/h	80 – 0 km/h	100 – 0 km/h
40	44.7	78.2	121.2	0.317	0.322	0.325
50	46.0	80.2	124.1	0.308	0.314	0.317
60	47.3	82.3	127.1	0.300	0.306	0.310
70	48.6	84.3	130.0	0.291	0.298	0.302
80	49.9	86.4	133.0	0.284	0.291	0.296
90	51.2	88.4	135.9	0.277	0.285	0.289
100	52.5	90.5	138.9	0.270	0.278	0.283
110	53.8	92.6	141.8	0.263	0.272	0.277
120	55.1	94.6	144.8	0.257	0.266	0.272
130	56.4	96.7	147.7	0.251	0.260	0.266
140	57.7	98.7	150.7	0.245	0.255	0.261
150	59.0	100.8	153.6	0.240	0.250	0.256
160	60.3	102.8	156.6	0.235	0.245	0.251
	Wet Correction Factor					
	x 1.12	x 1.31	x 1.50			
	Reaction time component					
	+ 33.3 m	+ 44.4 m	+ 55.5 m			
Example: Stopping distance of 140 t road train from 80 km/h on wet road (including driver reaction time)						
Stopping distance = (98.7 x 1.31) + 44.4 = 173.7 m						

It is particularly important to note that acceleration from rest through a distance of 100 m is very difficult to achieve within the time allotted by the performance levels in the PBS standard *Acceleration Capability*. Once the reaction time is included (which accounts for unavoidable clutch slip time), the performance levels required to meet the Acceleration Capability standard become impossible to achieve. It is likely that these performance levels will need to be revised so that combination vehicles utilising standard engine/transmission specifications can satisfy the requirement. Alternatively, much larger and heavier engines will need to be specified, which will lead to increased steer axle loads and higher emissions.

Acceleration from rest to a target speed has been found to be sensitive to GCM. The effect of starting reaction time is very small in comparison with the total time required to reach a high speed. Regardless of starting reaction time, the effect of vehicle GCM becomes more important when considering acceleration performance in high-speed environments.

Analysis of stopping distances found that there was very little sensitivity to GCM. This is due to the higher GCM vehicles generally having a greater number of axles, and therefore a greater amount of stopping power. There was, however, a small increase in stopping distance observed for the longer combination vehicles. This could be attributed to the driver's perception of vehicle stability under braking causing him/her to brake with less force when driving a long combination vehicle. The theoretical stopping distance of a long combination vehicle is similar to that of a shorter combination having similar axle loads.

Stopping distance was found to be made up of a considerable amount of distance travelled due to driver reaction time (ie. the distance travelled before the driver reacts to the signal to stop). At a speed of 100 km/h, for example, a 2 second reaction time adds 55.5 m to the stopping distance. As initial speed increases, the distance travelled during driver reaction time increases proportionally. However, stopping distance from the onset of braking increases with the square of speed. Subsequently, the proportion of stopping distance attributable to driver reaction reduces with increasing initial speed.

The analysis presented herein would be greatly enhanced by the testing of a greater number of innovative high productivity road trains in the 120 – 180 tonne GCM range. As many of these vehicles are fitted with high performance disc brakes and may have superior dynamic stability, it may be beneficial to produce additional schedules, such as those shown in Table 1 and Table 2, based purely on the test results of innovative vehicles in the 120 – 180 tonne GCM range.

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Tables

1 Introduction

Roaduser Systems Pty Ltd was commissioned by the National Transport Commission (NTC), on behalf of the Remote Areas Group (RAG), to carry out Stage 2 testing of the dynamic performance of three livestock road train combinations with varying suspension characteristics.

To maximise the utilisation of a suitable test site and the Roaduser test team and instrumentation system, the RAG Stage 2 testing was combined with a similar project for Main Roads WA, which involved testing of the acceleration and deceleration performance of combination vehicles. Queensland Transport requested Roaduser to include the testing of two innovative vehicle combinations for both lateral dynamics (as in the RAG Stage 2 project) and acceleration/deceleration performance.

The entire test program was carried out April 9 – 13 2004 in Perth WA. A section of the Great Eastern Highway Bypass near Guilford was utilised by closing one side of the freeway to traffic using contra-flow traffic control. This resulted in the availability of approximately 3 km of high quality roadway of suitable width for carrying out dynamic manoeuvres (as well as acceleration and deceleration for the Main Roads WA project). The RAG Stage 2 project also required the capture of data during normal driving, and a circuit adjacent to the freeway site was selected, approved and utilised for this purpose. The larger combinations required pilot vehicles when negotiating this circuit.

The test program was a major logistical exercise and the many elements of its organisation were co-ordinated by Main Roads WA, with input from DIPE (WA) and all other participants.

The following vehicle combinations were tested, with varying body type and gross combination mass:

- Tractor-semi-trailer;
- B-double;
- Truck-trailer;
- Double road train;
- Triple road train;
- A+B innovative road train;
- 2A+B innovative road train; and
- A+B3 innovative road train.

The results of the acceleration/deceleration tests of these vehicles are documented in this report.

2 Combination vehicles tested

A set of combination vehicles was assembled for the test program, which included various body types, prime mover makes, engines, gearboxes and gross combination masses (GCMs). Table 3 lists the details of the test vehicles in order of increasing GCM.

Table 3 Test vehicles (sorted by GCM)

Vehicle configuration	Body type	Prime mover make	Engine power (HP)	Gearbox	GCM (t)
Tractor-semi-trailer	Livestock	Kenworth	600	18 speed	43.85
Tractor-semi-trailer	End tipper	Mack	470	18 speed	47.00
Tractor-semi-trailer	Side tipper	Kenworth	600	18 speed	47.85
B-double	Container	Volvo	420	14 speed	52.75
Truck-trailer	End tipper	Volvo	420	14 speed	60.30
B-double	Livestock	Kenworth	600	18 speed	61.90
Double road train	End tipper	Mack	470	18 speed	84.80
Double road train	Side tipper	Kenworth	600	18 speed	89.05
A+B	Side tipper	Kenworth	600	18 speed	106.65
A+B3	Container	Mack	600	18 speed	111.75
Triple road train (mech trailers / mech dollies)	Livestock	Kenworth	600	18 speed	115.85
Triple road train (air trailers / air dollies)	Livestock	Western Star	600	18 speed	117.90
Triple road train (air trailers / mech dollies)	Livestock	Western Star	600	18 speed	118.40
2A+B (20.0 tonne triaxles)	Side tipper	Kenworth	600	18 speed	147.85
2A+B (23.5 tonne triaxles)	Side tipper	Kenworth	600	18 speed	166.20

Photographs of the test vehicles are shown in the following figures.

Figure 1 Tractor-semi-trailer (livestock)

Figure 2 Tractor-semi-trailer (end tipper)

Figure 3 Tractor-semi-trailer (side tipper)

Figure 4 B-double (container)

Figure 5 Truck-trailer (end tipper)

Figure 6 B-double (livestock)

Figure 7 Double road train (end tipper)

Figure 8 Double road train (side tipper)

Figure 9 A+B (side tipper)

Figure 10 A+B3 (container)

Figure 11 Triple road train (livestock) (all mech. susp.)

Figure 12 Triple road train (livestock) (all air susp.)

Figure 13 Triple road train (livestock) (air trailers / mech dollies)

Figure 14 2A+B (side tipper)

3 Test and analysis procedures

The test procedures adopted for the study were based on research previously conducted by Haldane [2] and comments from the Queensland Department of Main Roads, with certain differences as outlined in the following sections.

3.1 Acceleration tests

The acceleration zone featured slight variations in grade as shown in the survey data in Figure 15. All acceleration tests were carried out from rest in a left-to-right direction on the chart.

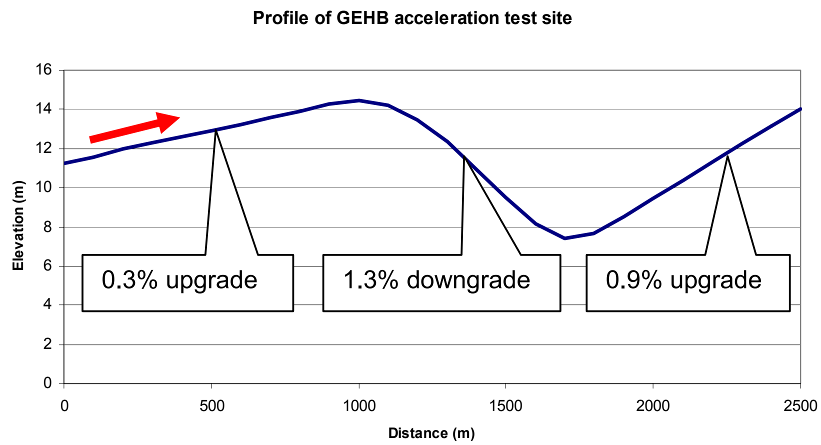

Figure 15 Profile of acceleration zone

A Roaduser engineer was in the cab at all times to instruct the driver and to log test data. Drivers were instructed to engage first gear and wait for a verbal signal to begin accelerating. This was intended to represent a typical situation where the driver is stopped at a red traffic light (or railway level crossing) and is waiting for the green light to illuminate (or the red flashing lights to stop flashing).

The data-logger was started by the test engineer at the instant the instruction to accelerate was given. A reaction time could then be determined which included the driver's own physical reaction time and any mechanical reaction time such as that due to pedal movement and clutch slip. The total reaction time was taken to be the time from the initial call to when the vehicle began to move forward measurably.

Drivers were instructed to accelerate purposefully under full power until a speed of 100 km/h (or the vehicle's top speed) was reached. During this time, the data logger recorded speed and acceleration while the test engineer recorded timestamps every 100 m for additional data (indicated by lines painted on the road). This differs from the Haldane work, where the timestamp method was the basis of the work.

All of the Roaduser acceleration tests were measured using the front of the vehicle as a reference. The overall length of the vehicle (which relates to intersection clearance time) was not considered, because the current Performance-Based Standard at the time of testing was

Acceleration Capability, which involves simply the measurement of a distance-time curve for the front of the vehicle. This standard replaced the *Intersection Clearance Time* standard, which required the measurement of the time taken for the rear of the vehicle to clear a certain distance. Haldane's work focused on intersection clearance time, and therefore used the rear of the vehicle to record distance-time data.

3.2 Deceleration tests

All deceleration tests were carried out on the slight upgrade section near the end of the test site. This position allowed a suitable stopping distance (with safety margin) before the signalised intersection at the end of the closed section of road.

A test layout similar to that illustrated in Figure 16 was set up at the test location. The layout included a "brake application zone" and three "brake application signals". For each test, one of the three brake application signals was selected at random to be illuminated when the vehicle was at some random point in the brake application zone. This provided two levels of uncertainty for the driver:

- A different signal was illuminated for each test; and
- The point of brake initiation was never the same.

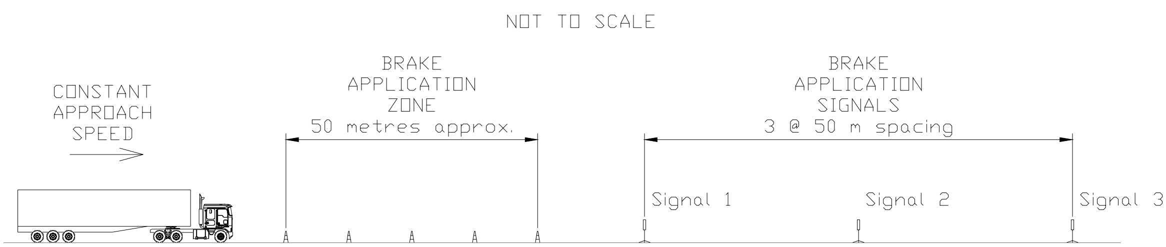

Figure 16 Layout of deceleration test site

By using a different brake application signal for each test, the driver was forced to survey the general scene ahead instead of focusing on one signal. The random timing of the signal meant that the driver had to maintain full contact with the accelerator pedal (to maintain vehicle speed) until the light was illuminated. A true reaction time could then be determined, being the time from illumination of the brake application signal to depression of the brake pedal (measured using the test equipment).

Tests were carried out under both wet and dry conditions. Dry tests were conducted first. The road was then saturated using a water truck, with water being reapplied between tests as necessary to maintain adequate wetting of the surface.

Figure 17 shows the driver's view of the test site from within the brake application zone. The three brake application signals can be seen (with traffic cones to aid visibility).

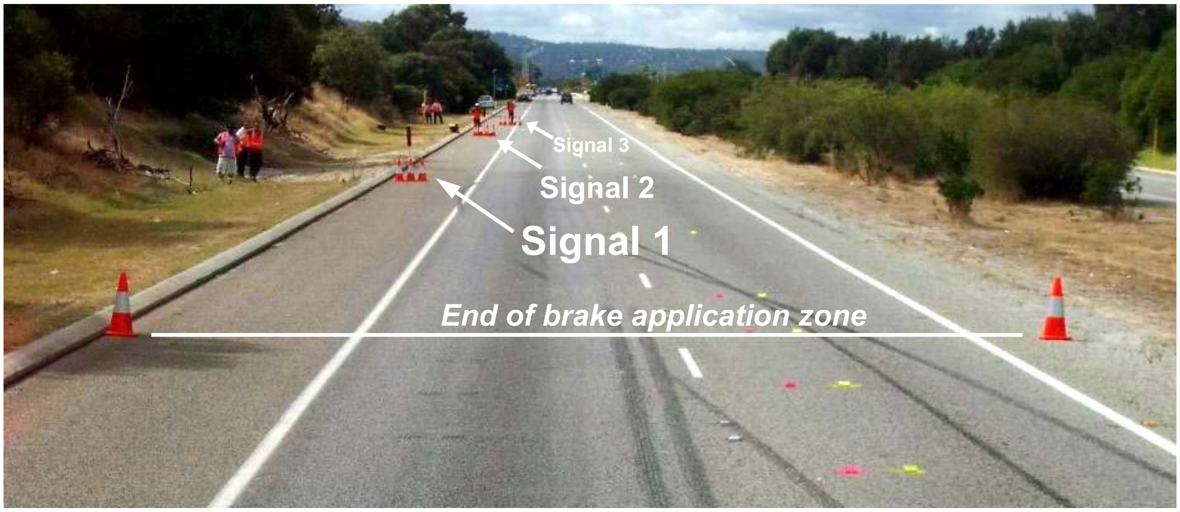

Figure 17 Braking test site as viewed by driver in brake application zone

3.3 Simulation modelling

For each test vehicle, a computer simulation model was constructed and calibrated to the test results. Calibration was achieved by adjusting some of the model parameters (eg. brake power, engine power, aerodynamic drag coefficient, etc) to obtain a close match between simulated and measured distance-time trajectories.

Distance-time trajectories were simulated and calibrated on the actual profile of the test site and then used to generate results for arbitrary profiles.

The models were used to generate many of the results presented in this report. They were particularly useful in generating results for tests that could not be conducted on the Great Eastern Highway Bypass test site, or in the time allocated for the test program, such as:

- Performance on various upgrades and downgrades;
- Performance at various GCMs; and
- Performance that could not be recorded by the available test equipment.

The simulation models are available for further research by Main Roads WA should it be required to carry out further research in this area. A full-scale test program will not be required if the models are used to represent the same test vehicles carrying out additional manoeuvres.

4 Analysis of results

4.1 Acceleration tests

4.1.1 Correlation analysis

The effect of GCM on acceleration performance was first examined by creation of a series of scatter plots. Examples of these are detailed in this section, while the full set is documented in Appendix B, Section B.1.

The scatter plots were used to find correlations between GCM and the following measures:

- Time to cover distance;
- Time to reach speed;
- Distance to reach speed; and
- Reaction time.

Strong correlations were found for the first three of these measures. There was virtually no variation of acceleration reaction time with vehicle GCM.

Figure 18, Figure 19 and Figure 20 show examples of the correlations found between GCM and the three correlated measures.

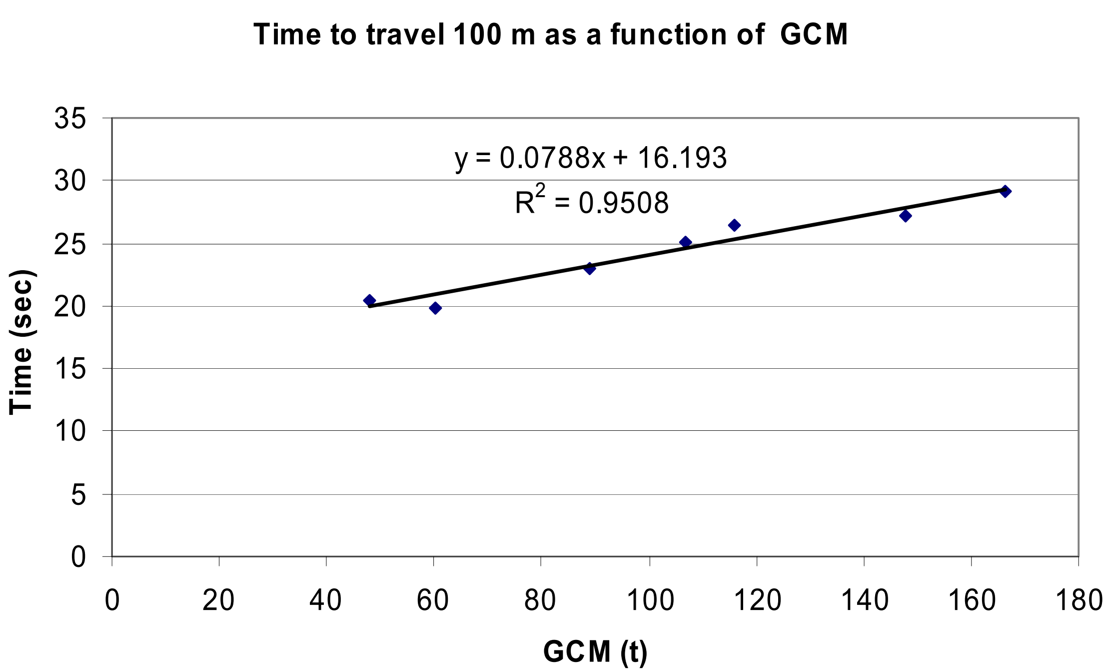

Figure 18 Time to travel 100 m as a function of GCM

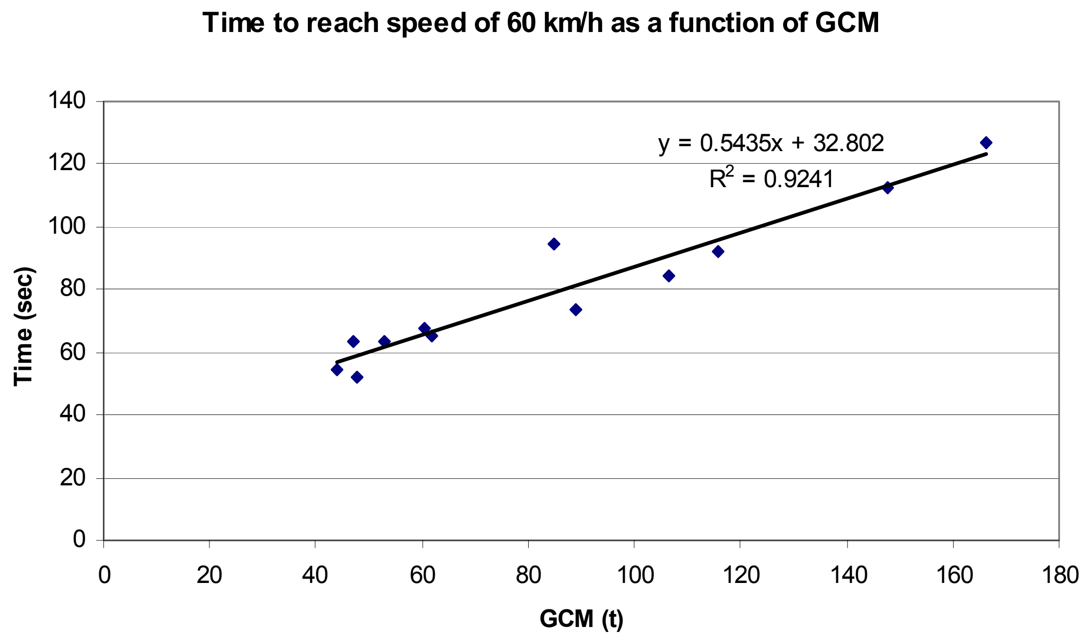

Figure 19 Time to reach speed of 60 km/h as a function of GCM

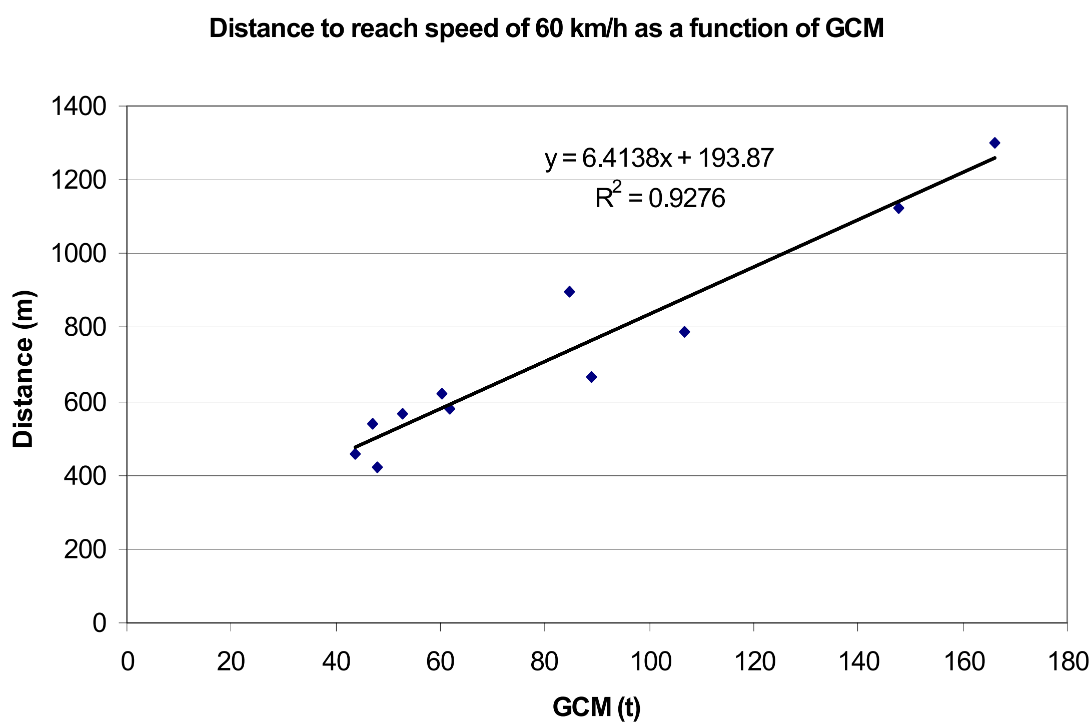

Figure 20 Distance to reach speed of 60 km/h as a function of GCM

The scatter plots show that there are vast differences in the effect of GCM on the range of measures. From the equations fitted to the data, the slope of the trendline indicates the degree of variation in performance due to GCM. A summary is provided in Table 4 for the full set of measures.

Table 4 Effect of GCM on acceleration performance

Measure	Sensitivity to GCM
Time to travel 100 m	0.08 sec/tonne
Time to travel 250 m	0.06 sec/tonne
Time to travel 500 m	0.11 sec/tonne
Time to travel 1000 m	0.20 sec/tonne
Time to reach speed of 60 km/h	0.54 sec/tonne
Time to reach speed of 80 km/h	1.42 sec/tonne
Time to reach speed of 100 km/h	5.11 sec/tonne
Distance to reach speed of 60 km/h	6.41 m/tonne
Distance to reach speed of 80 km/h	24.23 m/tonne
Distance to reach speed of 100 km/h	68.73 m/tonne

It can be seen that the time required to reach a particular speed is far more sensitive to GCM than the time required to travel a particular distance. Looking at time and distance required to reach a particular speed, in all cases the sensitivity increases with increasing target speed. Both the time and distance required to reach a particular speed were found to be approximately 10 times more sensitive to GCM when the target speed was 100 km/h as they were when the target speed was 60 km/h.

It can be concluded from this analysis that combination vehicle GCM becomes increasingly important when considering vehicle acceleration in high-speed environments.

4.1.2 Reaction time analysis

Acceleration reaction time was measured as the time from the instant the signal to begin accelerating was given by the test engineer and the instant at which the test engineer noticed the vehicle beginning to move forward.

Four different drivers were included in the analysis of reaction time. Table 5 lists the statistical data describing the variations in driver performance. Figure 21 is a histogram of the data.

Table 5 Summary of driver acceleration reaction time

Driver	Mean (sec)	Standard deviation (sec)
Driver A	2.55	1.06
Driver B	3.59	1.07
Driver C	3.19	1.01
Driver D	3.65	1.20
All drivers	**3.24**	**1.09**

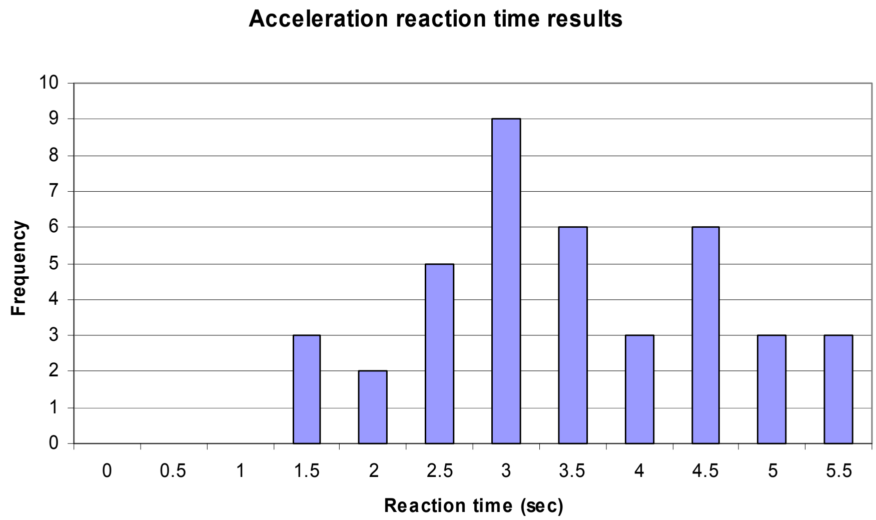

Figure 21 Starting reaction time histogram

4.1.3 Time to cover distance

Time to cover distance was found to be the measure least sensitive to GCM. The acceleration performance measure in the Performance-Based Standards project is a measure of the time to travel 100 m from rest. This measure was evaluated for all of the vehicles, as well as for distances of 250 m, 500 m and 1000 m. All results are documented in Appendix B, Section B.2.

Figure 22 shows results for time to travel 100 m, where it can be seen that there is little variation in performance across the range of vehicles. Included in the results is acceleration reaction time; this has been incorporated by determining the time to travel the required distance *without reaction time*, then adding 5th percentile, mean and 95th percentile reaction times.

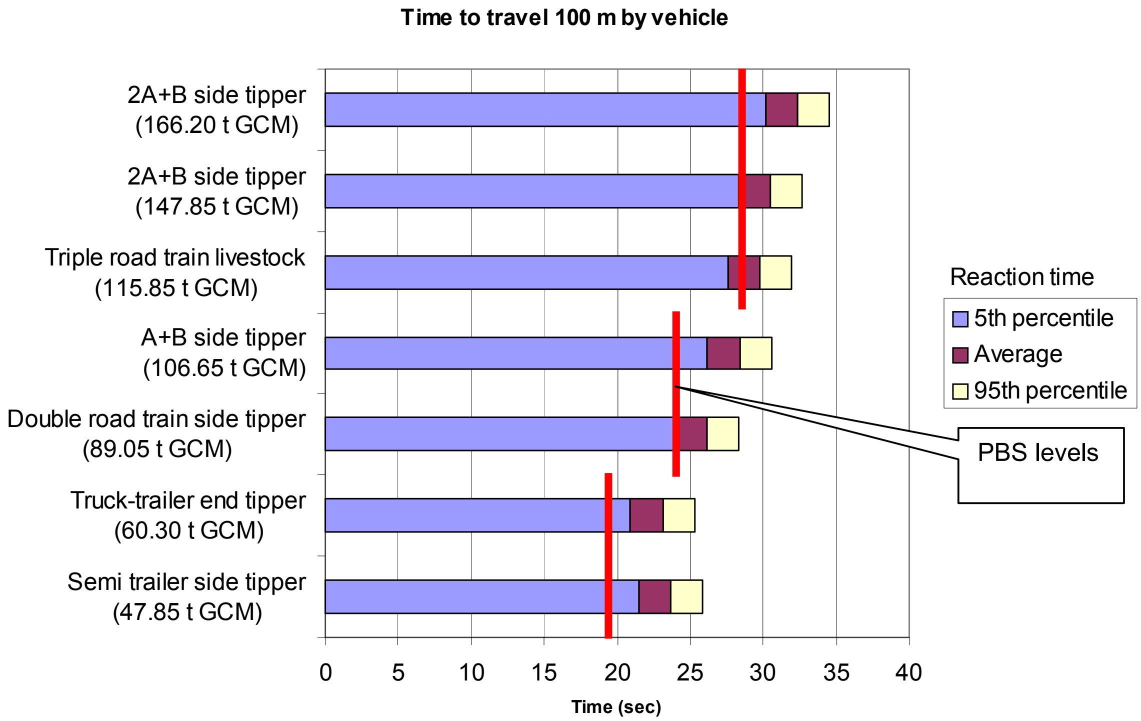

Figure 22 Time to travel 100 m by vehicle

The acceleration performance levels required by the PBS standard *Acceleration Capability* are shown in Table 6 [1]. It can be seen that the test vehicles cannot satisfy the performance standard if reaction time is included, and are on the borderline if reaction time is excluded[1]. The performance standard specifies that timing is to be commenced when the vehicle commences forward motion, which excludes reaction time. Considering that the vehicles are on the borderline when reaction time is excluded, the Acceleration Capability standard may need to be reviewed in light of these results.

Table 6 PBS acceleration performance levels

Road classification	Time to travel 100 m from rest (sec)
Level 1	19.5
Level 2	22.5
Level 3	24.0
Level 4	28.5

[1] Semi-trailer and truck-trailer are considered to be Level 1 vehicles. Double road train and A+B are considered to be Level 3 vehicles. Triple road train and 2A+B are considered to be Level 4 vehicles.

4.1.4 Time to reach speed

Time to reach speed was recorded for target speeds of 60 km/h, 80 km/h and 100 km/h. All results are documented in Appendix B, Section B.3. Figure 23 shows an example (60 km/h). Again, the time was calculated as the time to reach the target speed *without reaction time* plus the 5th percentile, mean and 95th percentile reaction times.

Reaction time does not have a significant effect on this performance measure, although the variation due to GCM is far more significant. The effect of reaction time is reduced for higher target speeds, as the (constant) reaction time makes up a smaller percentage of the total acceleration time.

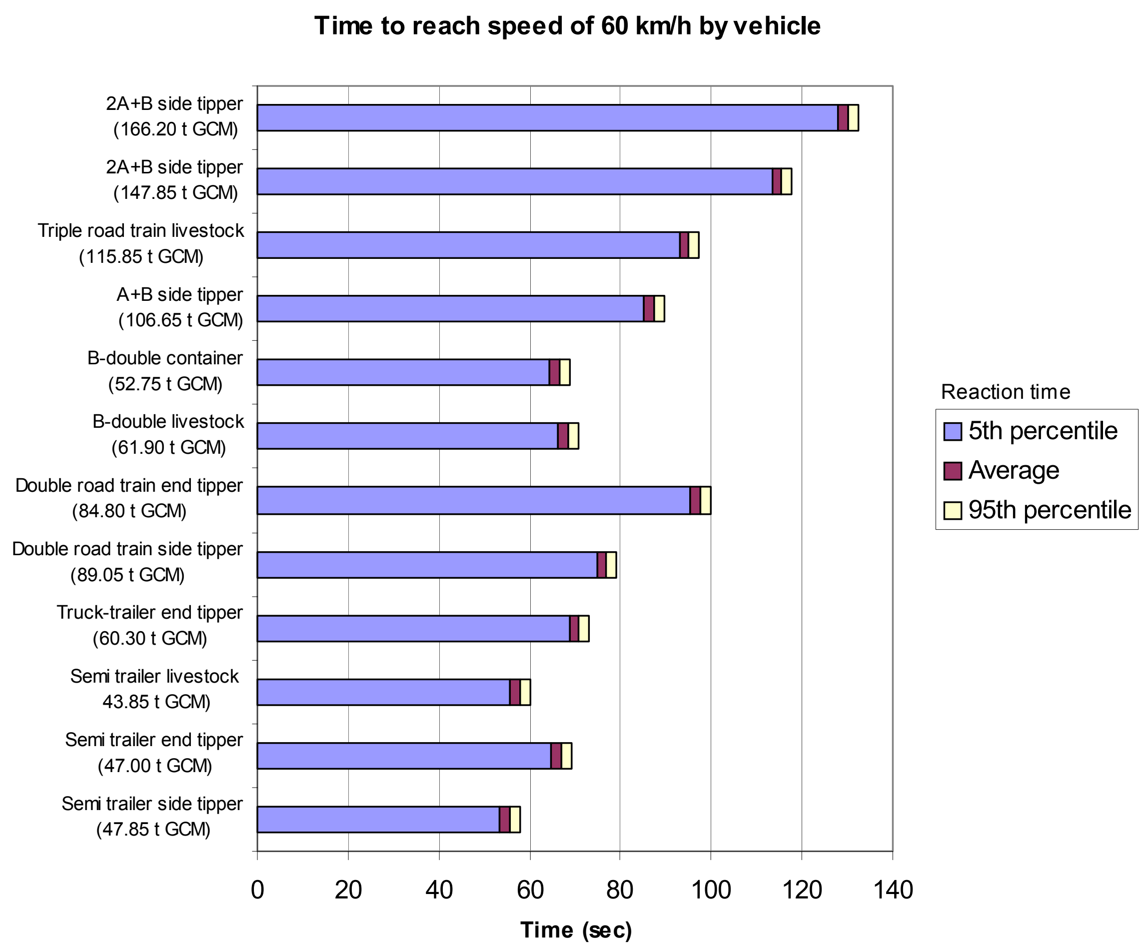

Figure 23 Time to reach speed of 60 km/h by vehicle

4.1.5 Distance to reach speed

Distance to reach speed was recorded for target speeds of 60 km/h, 80 km/h and 100 km/h. All results are documented in Appendix B, Section B.4. Figure 24 shows an example (60 km/h).

This measure is not affected by starting reaction time, but is affected significantly by GCM.

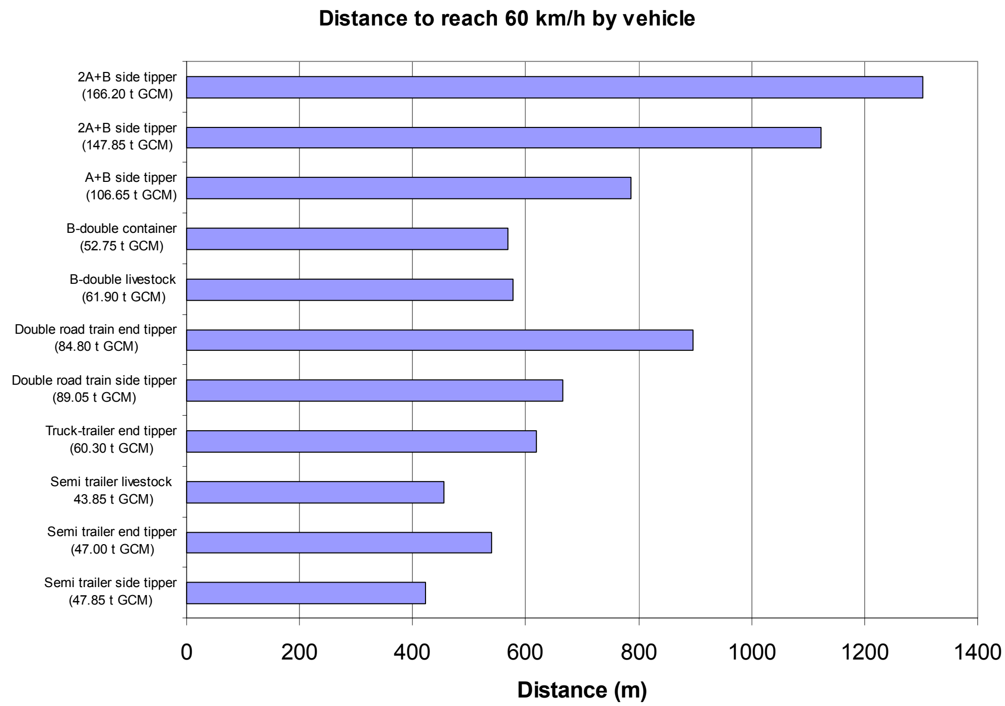

Figure 24 Distance to reach 60 km/h by vehicle

4.1.6 Effect of grade

The calibrated simulation models were able to be used to determine distance-time trajectories for various upgrades (+1%, +2%, +5%) and downgrades (-1%, -2%, -5%). Figure 25 shows an example of the results obtained for the semi-trailer side-tipper. All results are documented in Appendix B, Section B.5.

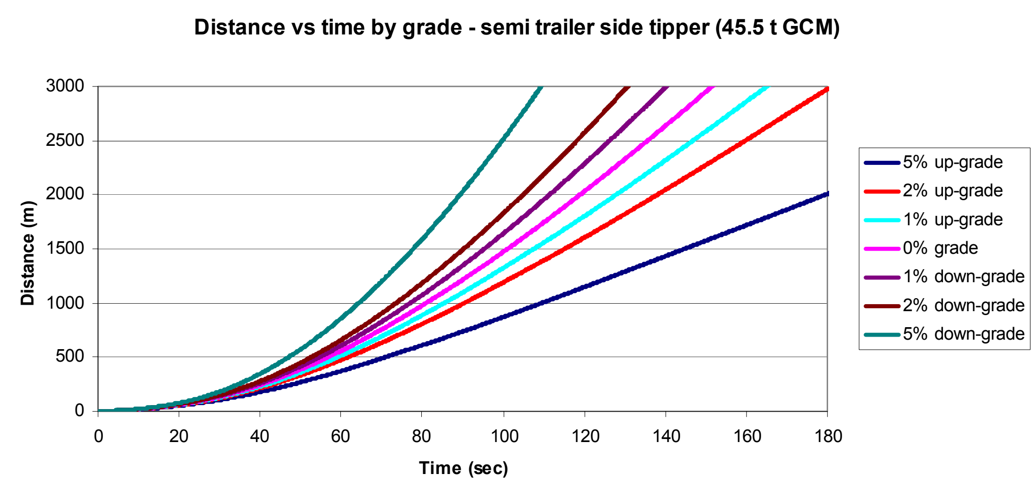

Figure 25 Distance vs time by grade – semi trailer side tipper (45.5 t GCM)

4.1.7 Top speeds in urban travel

When travelling in an urban environment, combination vehicles rarely have the opportunity to reach the prevailing speed limit before having to stop at an intersection. To quantify this, some analysis has been done on the speed profiles of vehicles starting from rest, accelerating under full power and stopping at a specified point down the road.

Figure 26 shows an example of the speed profile of a 45.5 t semi-trailer accelerating from rest on a flat grade and stopping at intersections either 250 m, 500 m or 1000 m down the road. The top speeds obtained before braking are around 40 km/h, 55 km/h and 75 km/h respectively.

The figure also quantifies the effect of driver error (ie. missed gear in the early stages of acceleration) on the speed profile.

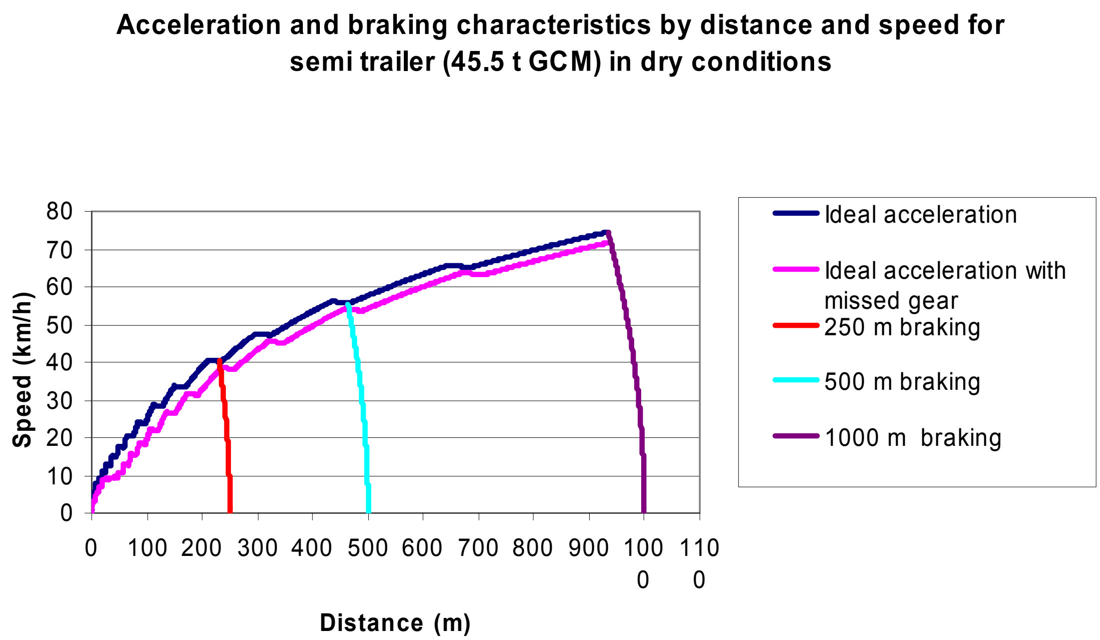

Figure 26 Speed profile for semi trailer (45.5 t GCM)

Additional vehicles have been evaluated in this manner in Appendix B, Section B.6.

4.2 Deceleration tests

4.2.1 Correlation analysis

The effect of GCM on deceleration performance was observed using the scatter plot method. Stopping distances for initial speeds of 60 km/h, 80 km/h and 100 km/h were recorded and documented in Appendix C, Section C.1.

Figure 27 shows an example (60 km/h). The data has been split into two types of freight: sensitive freight (such as livestock) and non-sensitive freight. It is considered that stopping distance will be affected by the driver's perception of what is a safe deceleration level for the type of load being hauled. By splitting the data, it can be seen that there are two distinct trends for the two types of freight; the sensitive freight vehicles demonstrated considerably longer stopping distance. All vehicles demonstrated very little sensitivity to GCM (as low as 0.17 m/tonne for the non-sensitive freight vehicles). This implies that a further 17 m is required to stop a vehicle having an additional 100 tonnes GCM.

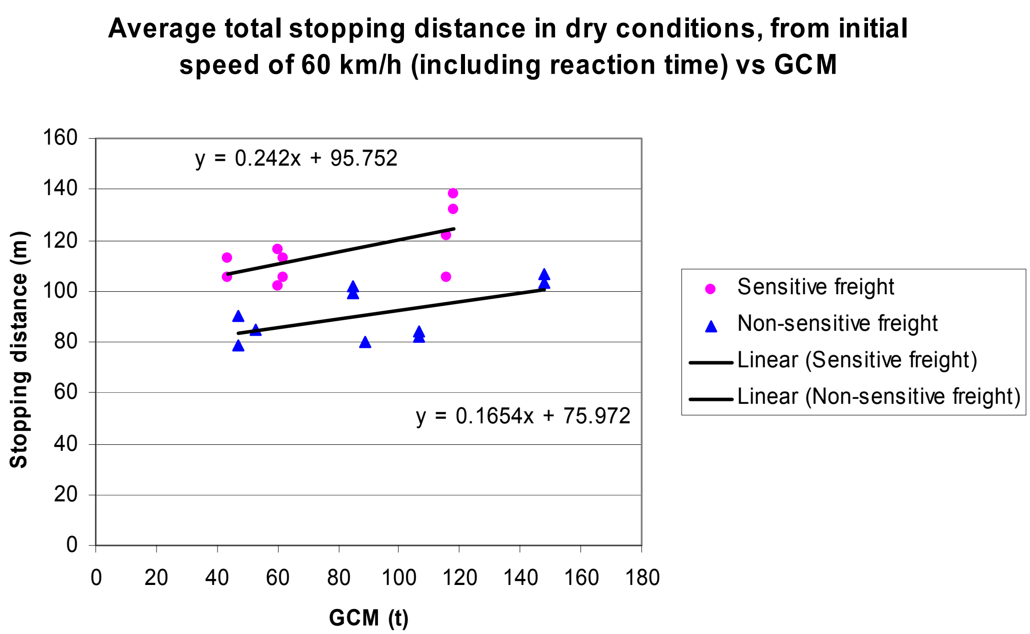

Figure 27 Stopping distance from initial speed of 60 km/h vs GCM

Provided all axles are laden to their legal mass limit, a vehicle should theoretically stop in the same distance regardless of how many axle groups it contains; each axle group is designed to stop the mass that it supports. Additional mass is usually accompanied by additional axles. The trend towards slightly increased stopping distance for the heavier combinations could possibly be attributed to the driver's perception of vehicle stability under braking. A driver will probably decelerate with decreased brake pressure when driving a long combination vehicle.

No trend was observed linking braking reaction time to GCM.

4.2.2 Reaction time analysis

Braking reaction times were measured as the time elapsed from the instant the brake application signal was issued to the instant the driver depressed the brake pedal. Four different drivers were included in the analysis, with statistical data shown in Table 7. Figure 28 shows a histogram of the data.

Table 7 Braking reaction time by driver and road condition

Driver	Conditions	Mean reaction time (sec)	Standard deviation (sec)
Driver A	All conditions	2.87	0.88
Driver B	All conditions	1.96	1.34
Driver C	All conditions	1.69	0.75
Driver D	All conditions	2.30	0.88
All drivers	Dry conditions	2.10	0.96
All drivers	Wet conditions	1.62	0.99
All drivers	**All conditions**	**2.01**	**0.97**

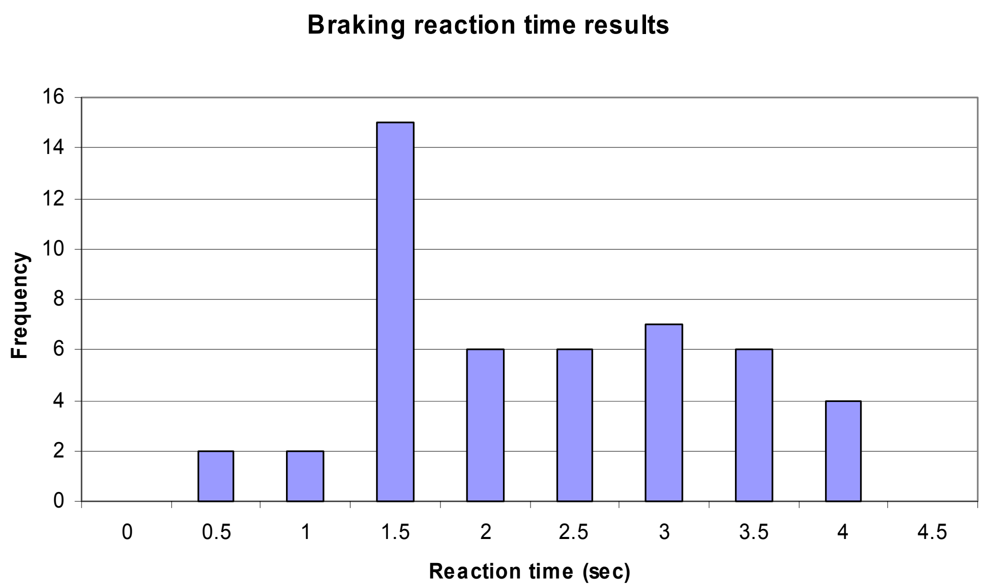

Figure 28 Braking reaction time histogram

With a mean reaction time of around 2 seconds, the stopping distance of a vehicle is significantly affected by driver reaction. For every second that the brakes are not applied, the stopping distance is increased according to the following formula:

$$\Delta S = \frac{Vt}{3.6}$$

where:

ΔS = Additional stopping distance (m)

V = Initial speed (km/h)

t = Reaction time (sec)

For an initial speed of 60 km/h and a driver reaction time of 2 seconds, this equates to an additional 33.3 m of stopping distance.

4.2.3 Stopping distance

Stopping distance was recorded for initial speeds of 60 km/h, 80 km/h and 100 km/h. All results are documented in Appendix C, Section C.2, with an example (60 km/h) shown in Figure 29. Distance due to driver reaction time has been incorporated using the formula in Section 4.2.2. It can clearly be seen that driver reaction time makes up a large proportion of the total stopping distance. This effect diminishes for higher initial speeds, because the stopping distance increases more than the distance due to driver reaction time.

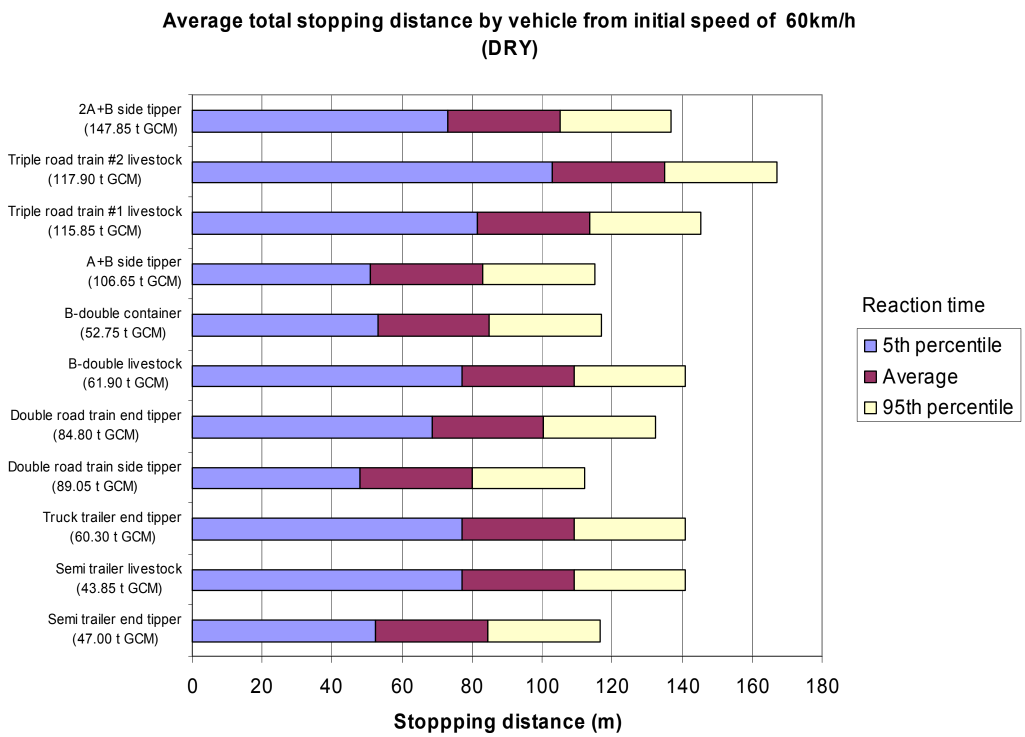

Figure 29 Stopping distance by vehicle from initial speed of 60 km/h (DRY)

4.2.4 Effect of grade

The calibrated simulation models were able to be used to determine speed-distance trajectories for various upgrades (+1%, +2%, +5%) and downgrades (-1%, -2%, -5%). Figure 30 and Figure 31 show examples of the results obtained for the semi-trailer side-tipper and 2A+B side-tipper braking from 100 km/h. All results are documented in Appendix C, Section C.3.

It can be seen that the speed-distance trajectories for these two extreme vehicle combinations are very similar. Grade does not have a large effect on the stopping distance.

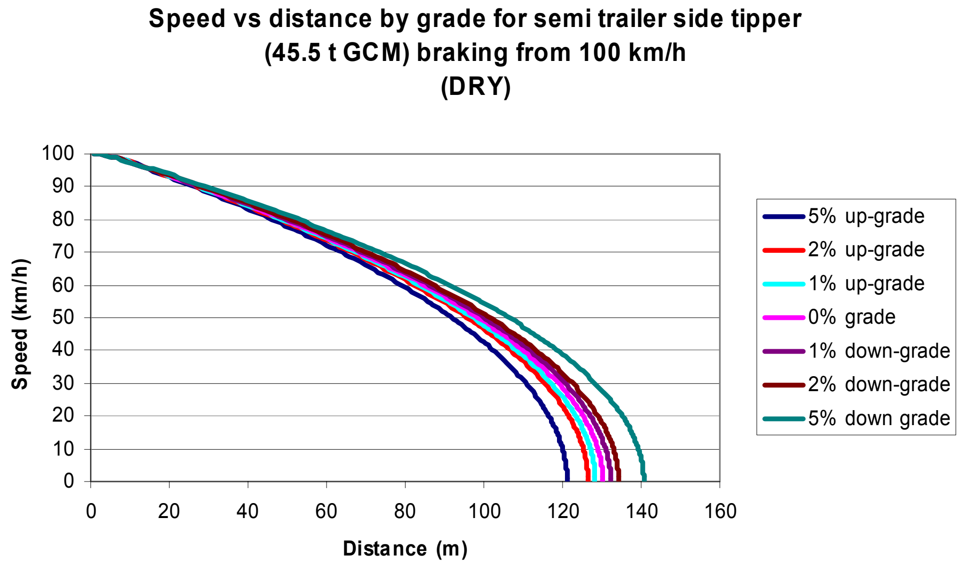

Figure 30 Semi trailer side tipper (45.5 t GCM) from 100 km/h (DRY)

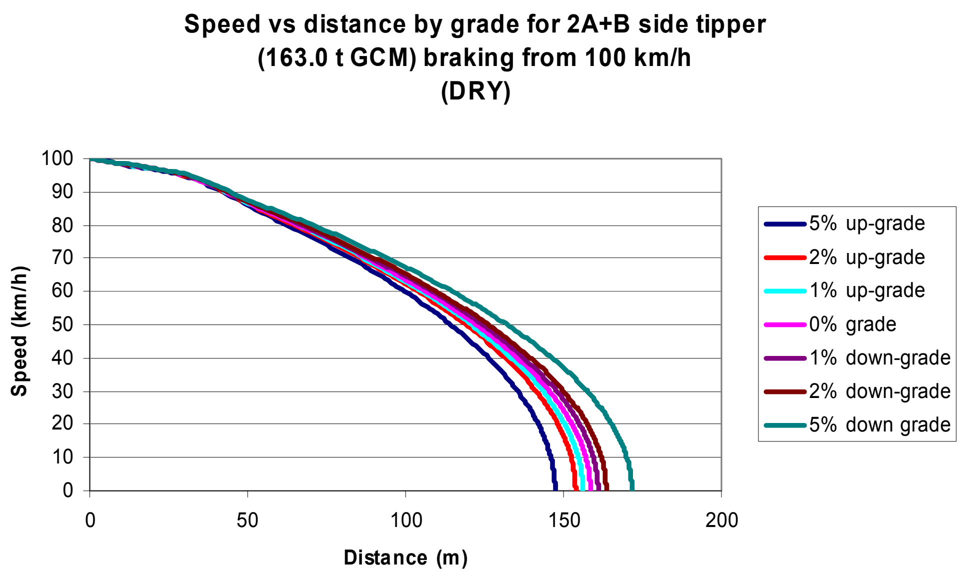

Figure 31 2A+B side tipper (163.0 t GCM) from 100 km/h (DRY)

4.2.5 Effect of available friction (wet road)

Stopping distances measured from both dry and wet road tests are documented in Appendix C, Section C.2. Further processing of these results, through comparison of dry and wet road stopping distances measured for each vehicle, led to the concept of "Wet Correction Factor" (WCF). WCF is the factor by which a dry stopping distance needs to be multiplied to obtain the associated wet stopping distance. WCF was determined by dividing wet stopping distances by dry stopping distances for the same initial test speed.

It was found that WCF varied significantly with initial speed, which is an indication that driver confidence in wet braking reduces with increasing speed. The effect of wet weather on stopping distance is therefore of greater concern in high-speed environments.

Figure 32 shows a plot of the average WCF obtained for each initial test speed. The relationship is linear with good correlation.

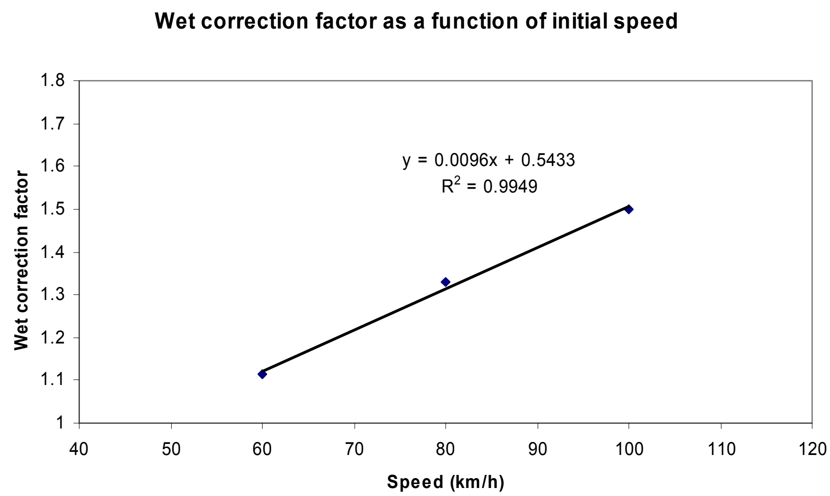

Figure 32 Wet correction factor as a function of initial speed

It can be concluded from Figure 32 that stopping distance from 60 km/h in the wet could be around 10% greater than in the dry, while stopping distance from 100 km/h in the wet could be around 50% greater than in the dry.

4.3 Benchmarking of results

4.3.1 Austroads literature

An Austroads publication on the geometric design of roads for trucks [3] uses truck acceleration and deceleration performance as a design basis for road geometry standards. This includes driver perception-reaction time as a key component of stopping distance.

A normal driver perception-reaction time in braking (hitherto termed “reaction time”) is quoted as being 2.5 seconds for rural road design. The reaction time is quoted to include 0.5 seconds of air transport delay in the braking system. Therefore, the standard value of 2.5 seconds is equivalent to 2.0 seconds when air transport delay is excluded. This compares perfectly with the average value obtained from the present study (2.0 seconds excluding air transport delay). However, significant variability was observed in reaction times, with a standard deviation of approximately 1 sec. There may be a case for utilising higher-percentile reaction times for heavy vehicles in road and traffic design standards.

Austroads presents stopping distance based on a simplified formula that contains two terms: (i) the distance travelled during driver reaction time, and (ii) the distance travelled during a constant deceleration stop. Austroads quotes a design deceleration of 0.29 g for a reference tractor-semi-trailer (42.5 t) in a 60 km/h speed environment. Appendix C, Section C.1 of this report presents a series of correlation charts showing linear equations relating deceleration performance to GCM. These equations were determined directly from the measured test data. The equation for stopping distance from 60 km/h gives a value of 83 m for a 42.5 t vehicle. By using the Austroads stopping distance equation to back-calculate for average deceleration, the average deceleration for this case is 0.29 g, which compares perfectly with the Austroads design value.

Austroads quotes acceleration performance in terms of the distance required to reach a certain speed (for the design of acceleration lanes). Two examples for the design tractor-semi-trailer (42.5 t) accelerating on zero grade are (i) 910 m to accelerate to 80 km/h, and (ii) 2400 m to accelerate to 100 km/h. Appendix B, Section B.1 of this report presents a series of correlation charts showing linear equations relating acceleration performance to GCM. These equations were determined directly from the measured test data. Using the above two Austroads examples as a means of testing these equations for comparison, we get: (i) 972 m to accelerate to 80 km/h, and (ii) 2164 m to accelerate to 100 km/h.

It is considered that the findings of the present study are in line with the basis of the design guidelines in the Austroads publication. However, the scope of data quoted in the Austroads publication is limited, and the present study provides much more comprehensive information with regard to GCM, vehicle configuratuion and road conditions.

4.3.2 Other research

A study by Haldane [2] documents the results of recent acceleration tests carried out on a range of combination vehicles in Queensland.

Significant discrepancies were noted between the results of the two studies. It was found that the measured acceleration performance of the vehicles in the present study was generally not as good as the measured acceleration performance of the vehicles in the Haldane study. Table 8 demonstrates the difference by comparing a selection of comparable vehicles from the two studies.

Table 8 Performance comparison – time to cover distance

Vehicle	GCM (t)	Engine power (HP)	Time to travel 250 m (sec)	Difference
Present study: B-double	61.9	600	45	Haldane study: 31% less time
Haldane study: B-double	62.1	550	31	
Present study: Double road train	89.1	600	47	Haldane study: 32% less time
Haldane study: Double road train	79.9	550	32	
Present study: Triple road train	115.9	600	48	Haldane study: 25% less time
Haldane study: Triple road train	115.0	550	36	

Engine horsepower is in favour of the vehicles in the present study, with each having 600 HP in comparison with 550 HP for the Haldane vehicles. Although mass was very similar for the B-doubles and triple road trains, performance proved to be better for the Haldane vehicles.

A possible reason for these discrepancies is that the drivers of the present study were requested to accelerate in a manner typical of normal day-to-day operation (ie. not necessarily to accelerate at the vehicle's maximum capability). The driver in the Haldane study was requested to accelerate as though he/she was the first vehicle in a line of cars stopped at a signalised intersection. It is possible that the driver perceived this as a request to accelerate with maximum effort. Seeing that the Austroads design guidelines are most likely conservative in nature, the good match between those guidelines and the results of the present study indicate that perhaps the drivers in the present study were in fact accelerating in a conservative manner.

5 Conclusions

The comprehensive acceleration and deceleration test program provided a high degree of confidence in the results presented. Repeated tests on a reasonably large sample of vehicles and drivers provided enough data to determine the relationship between performance and GCM, and to determine average reaction times in braking and also in starting a vehicle moving from rest. The following average driver perception-reaction times are suitable for acceleration and deceleration:

- Acceleration reaction time: 3.25 sec
- Deceleration reaction time: 2.00 sec

The acceleration reaction time includes the driver's physical reaction time and the vehicle's mechanical delay in beginning to move forward (due to clutch slip time, etc).

It was found that reaction times varied significantly between drivers, and this should perhaps be considered in road and traffic design standards for heavy vehicles. 95th percentile values for acceleration and deceleration reaction times were found to be 5.42 sec and 3.95 sec respectively. There was no evidence that reaction times vary systematically with vehicle factors or road conditions.

The strong relationships observed between GCM and acceleration/deceleration performance provided linear equations that can be used to calculate acceleration time and stopping distance for a given GCM. These equations were used to fill the schedules in Table 9 and Table 10, showing acceleration times and stopping distances respectively for the range of GCMs tested (40 – 160 t). Also shown for each scenario is the associated average acceleration or deceleration. Stopping distance in wet weather braking can be determined by application of the appropriate Wet Correction Factor in Table 10. The reaction time component is then added if it is required to account for reaction time effects in either acceleration or deceleration. The reaction time component in stopping distance is calculated using the expression in Section 4.2.2.

Table 9 Schedule of acceleration time and average acceleration

GCM	Acceleration time (sec)				Average acceleration (g)			
(t)	0 – 100 m	0 – 60 km/h	0 – 80 km/h	0 – 100 km/h	0 – 100 m	0 – 60 km/h	0 – 80 km/h	0 – 100 km/h
40	19.3	55	78	99	0.054	0.031	0.029	0.029
50	20.1	60	92	150	0.050	0.028	0.025	0.019
60	20.9	65	106	201	0.047	0.026	0.021	0.014
70	21.7	71	121	252	0.043	0.024	0.019	0.011
80	22.5	76	135	303	0.040	0.022	0.017	0.009
90	23.3	82	149	354	0.038	0.021	0.015	0.008
100	24.1	87	163	405	0.035	0.019	0.014	0.007
110	24.9	93	177	457	0.033	0.018	0.013	0.006
120	25.6	98	192	508	0.031	0.017	0.012	0.006
130	26.4	103	206	559	0.029	0.016	0.011	0.005
140	27.2	109	220	610	0.028	0.016	0.010	0.005
150	28.0	114	234	661	0.026	0.015	0.010	0.004
160	28.8	120	248	712	0.025	0.014	0.009	0.004
	Reaction time component + 3.25 sec							

Table 10 Schedule of stopping distance and average deceleration

GCM	Stopping distance (m)			Average deceleration (g)		
(t)	60 – 0 km/h	80 – 0 km/h	100 – 0 km/h	60 – 0 km/h	80 – 0 km/h	100 – 0 km/h
40	44.7	78.2	121.2	0.317	0.322	0.325
50	46.0	80.2	124.1	0.308	0.314	0.317
60	47.3	82.3	127.1	0.300	0.306	0.310
70	48.6	84.3	130.0	0.291	0.298	0.302
80	49.9	86.4	133.0	0.284	0.291	0.296
90	51.2	88.4	135.9	0.277	0.285	0.289
100	52.5	90.5	138.9	0.270	0.278	0.283
110	53.8	92.6	141.8	0.263	0.272	0.277
120	55.1	94.6	144.8	0.257	0.266	0.272
130	56.4	96.7	147.7	0.251	0.260	0.266
140	57.7	98.7	150.7	0.245	0.255	0.261
150	59.0	100.8	153.6	0.240	0.250	0.256
160	60.3	102.8	156.6	0.235	0.245	0.251
	Wet Correction Factor					
	x 1.12	x 1.31	x 1.50			
	Reaction time component					
	+ 33.3 m	+ 44.4 m	+ 55.5 m			
Example: Stopping distance of 140 t road train from 80 km/h on wet road (including driver reaction time)						
Stopping distance = (98.7 x 1.31) + 44.4 = 173.7 m						

It is particularly important to note that acceleration from rest through a distance of 100 m is very difficult to achieve within the time allotted by the performance levels in the PBS standard *Acceleration Capability*. Once the reaction time is included (which accounts for unavoidable clutch slip time), the performance levels required to meet the Acceleration Capability standard become impossible to achieve. It is likely that these performance levels will need to be revised so that combination vehicles utilising standard engine/transmission specifications can satisfy the requirement. Alternatively, much larger and heavier engines will need to be specified, which will lead to increased steer axle loads and higher emissions.

Acceleration from rest to a target speed has been found to be sensitive to GCM. The effect of starting reaction time is very small in comparison with the total time required to reach a high speed. Regardless of starting reaction time, the effect of vehicle GCM becomes more important when considering acceleration performance in high-speed environments.

Analysis of stopping distances found that there was very little sensitivity to GCM. This is due to the higher GCM vehicles generally having a greater number of axles, and therefore a greater amount of stopping power. There was, however, a small increase in stopping distance observed for the longer combination vehicles. This could be attributed to the driver's perception of vehicle stability under braking causing him/her to brake with less force when driving a long combination vehicle. The theoretical stopping distance of a long combination vehicle is similar to that of a shorter combination having similar axle loads.

Stopping distance was found to be made up of a considerable amount of distance travelled due to driver reaction time (ie. the distance travelled before the driver reacts to the signal to stop). At a speed of 100 km/h, for example, a 2 second reaction time adds 55.5 m to the stopping distance.

As initial speed increases, the distance travelled during driver reaction time increases proportionally. However, stopping distance from the onset of braking increases with the square of speed. Subsequently, the proportion of stopping distance attributable to driver reaction reduces with increasing initial speed.

The analysis presented herein would be greatly enhanced by the testing of a greater number of innovative high productivity road trains in the 120 – 180 tonne GCM range. As many of these vehicles are fitted with high performance disc brakes and may have superior dynamic stability, it may be beneficial to produce additional schedules, such as those shown in Table 9 and Table 10, based purely on the test results of innovative vehicles in the 120 – 180 tonne GCM range.

6 References

[1] National Road Transport Commission, *PBS Safety Standards for Heavy Vehicles*, January 2003.

[2] Haldane, M.J., *Assessing the impacts of multi-combination vehicles on traffic operation*, Master of Engineering Thesis, Queensland University of Technology, 2002.

[3] Austroads, *Geometric design for trucks – when, where and how?*, Austroads publication AP-R211, 2002.

Appendix A Simulation model directory

Acceleration Simulations **Z:\Jobs\JobsInprogress\J1075\Engineering\Simulations\Runs\Acceleration\XXXX(vehicle combination)**		
Manoeuvre	**Results**	**Input files**
Acceleration from stand still 0% grade	0-60km/h, 0-80 km/h 0-100 km/h	Flat xxxx.in
Acceleration from stand still on ±1%, ±2% and ±5% grades	Distance vs time	±1%.in ±2%.in ±5%.in

Braking simulations **Z:\Jobs\JobsInprogress\J1075\Engineering\Simulations\Runs\Braking\XXXX(vehicle combination)\60-0**		
Manoeuvre	**Results**	**Input files**
Braking from 60 km/h on ±1%, ±2% and ±5% grades	Stopping distance, stopping time and braking diagrams	XXXX.in

Braking simulations **Z:\Jobs\JobsInprogress\J1075\Engineering\Simulations\Runs\Braking\XXXX(vehicle combination)\80-0**		
Manoeuvre	**Results**	**Input files**
Braking from 80 km/h on ±1%, ±2% and ±5% grades	Stopping distance, stopping time and braking diagrams	XXXX.in

Braking simulations **Z:\Jobs\JobsInprogress\J1075\Engineering\Simulations\Runs\Braking\XXXX(vehicle combination)\100-0**		
Manoeuvre	**Results**	**Input files**
Braking from 100 km/h on ±1%, ±2% and ±5% grades	Stopping distance, stopping time and braking diagrams	XXXX.in

Appendix B Acceleration test results

B.1 Correlation

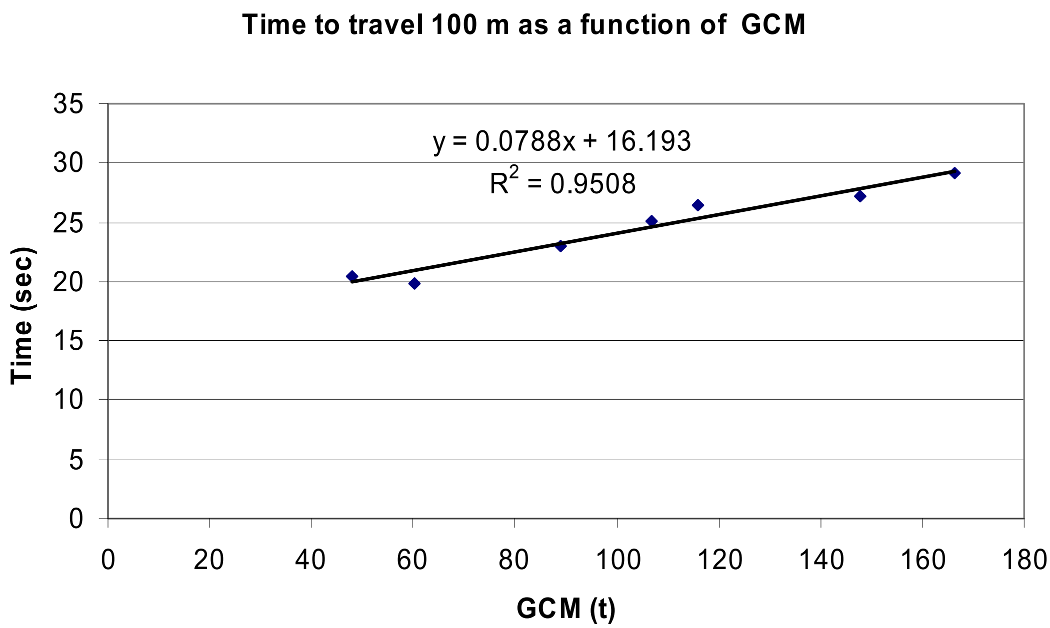

Figure 33 Time to travel 100 m as a function of GCM

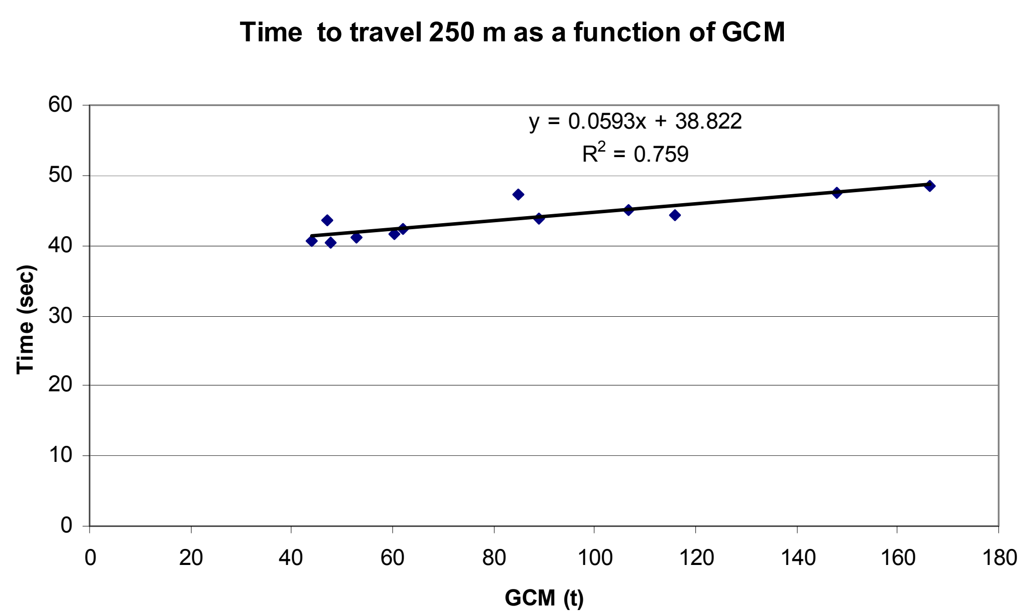

Figure 34 Time to travel 250 m as a function of GCM

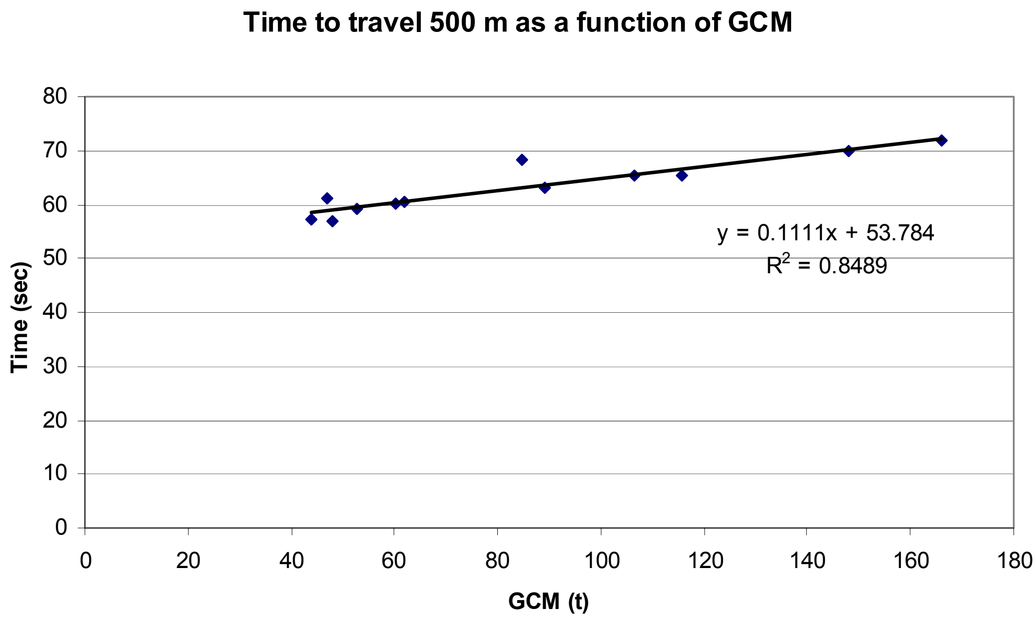

Figure 35 Time to travel 500 m as a function of GCM

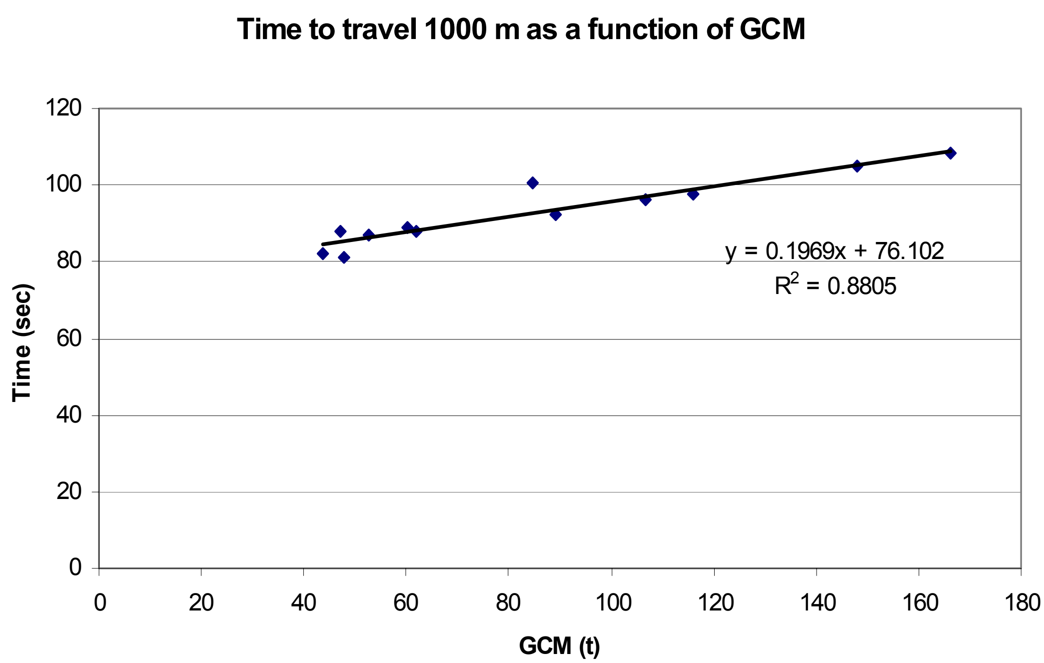

Figure 36 Time to travel 1000 m as a function of GCM

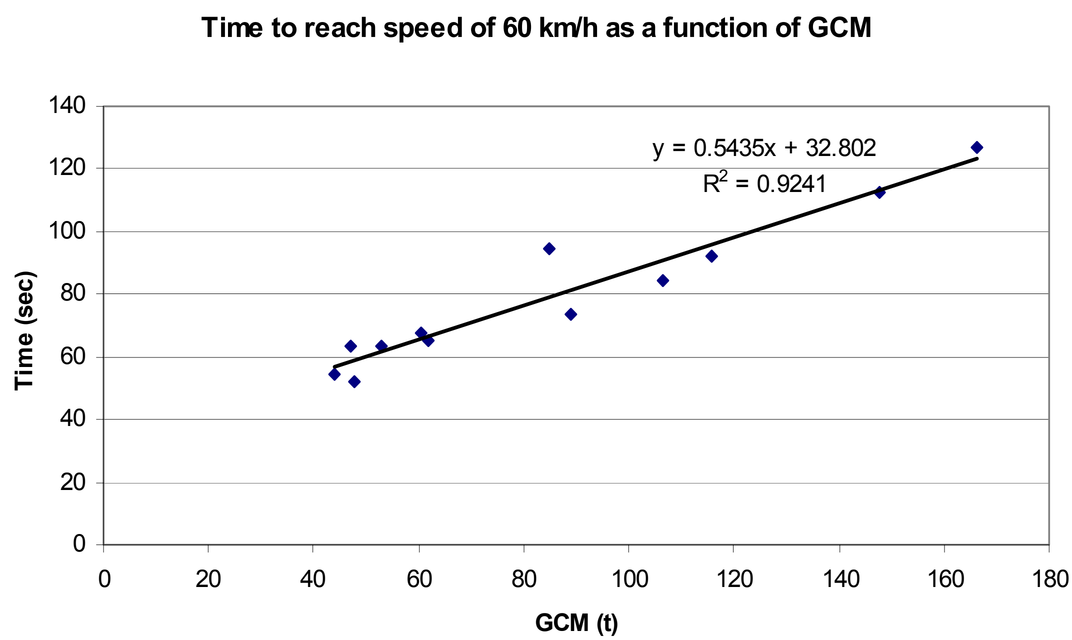

Figure 37 Time to reach speed of 60 km/h as a function of GCM

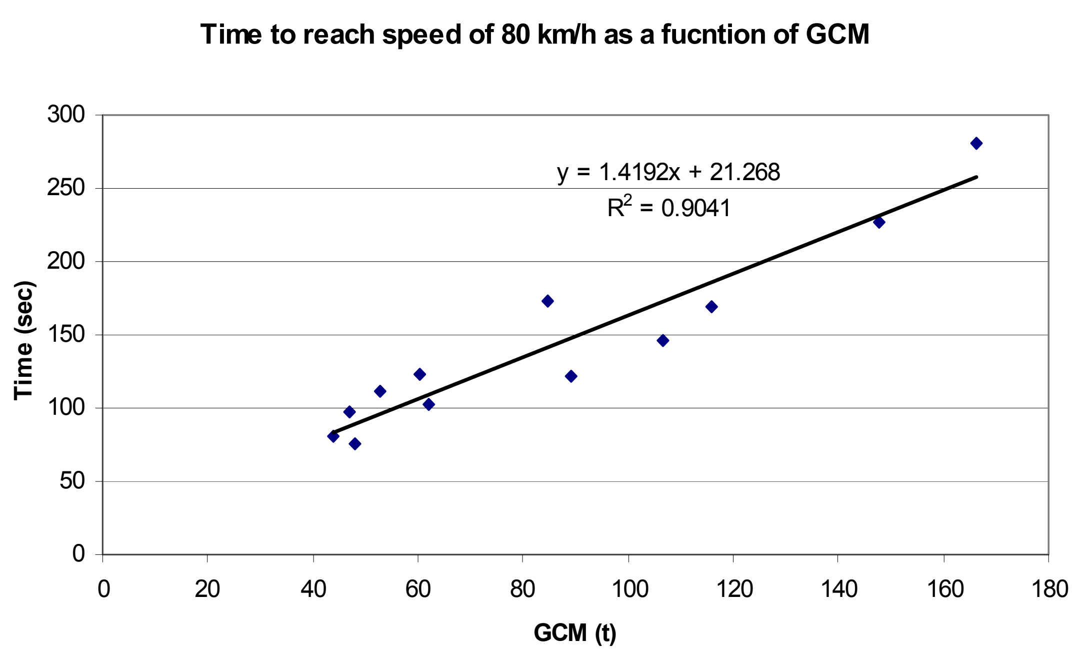

Figure 38 Time to reach speed of 80 km/h as a function of GCM

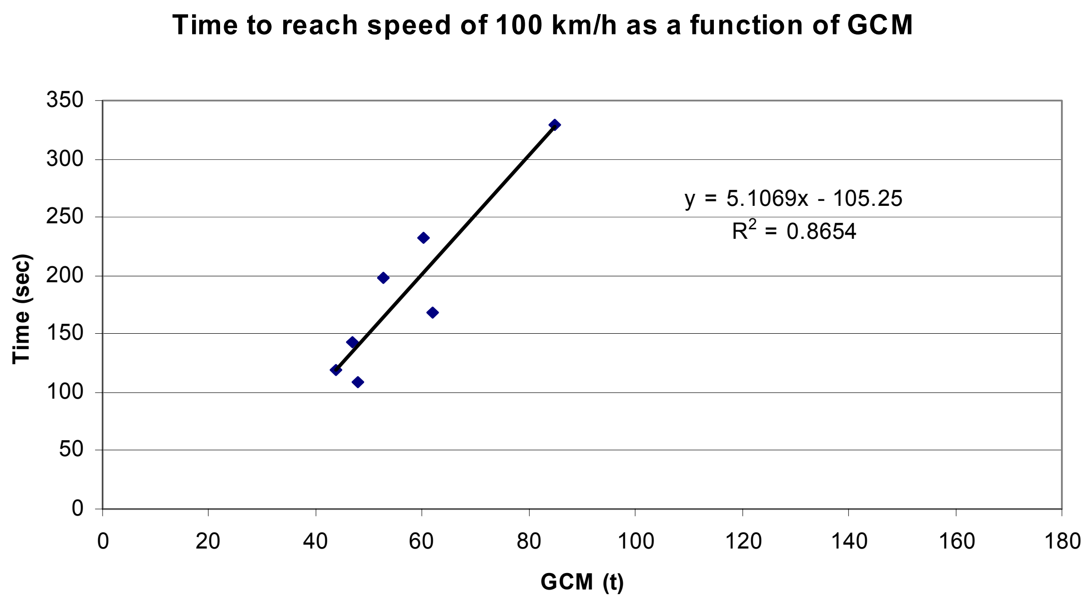

Figure 39 Time to reach speed of 100 km/h as a function of GCM

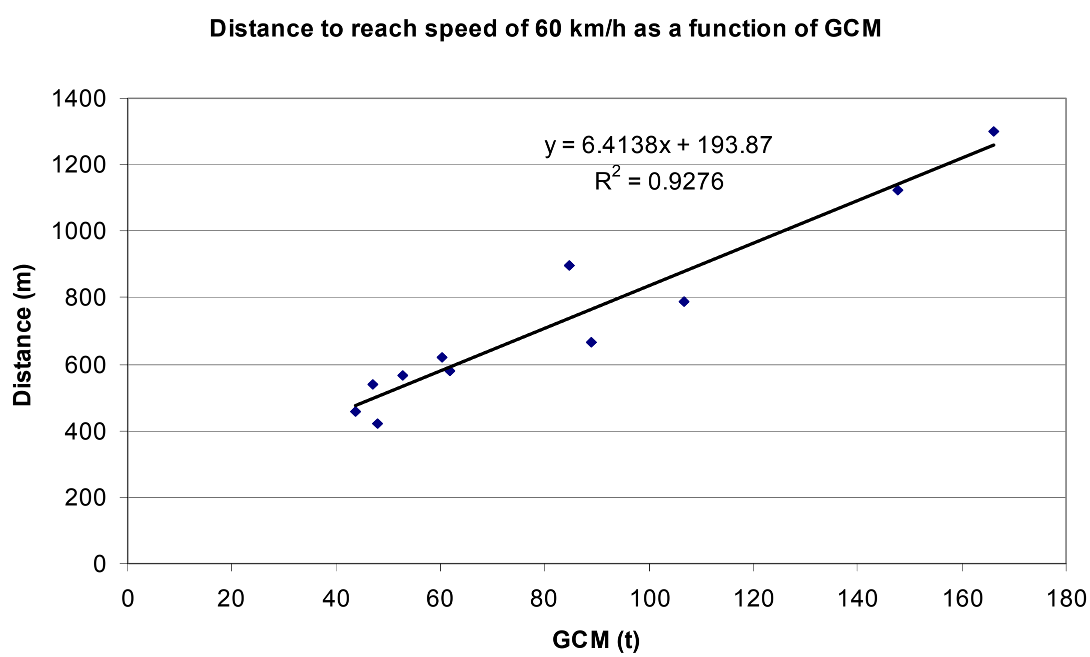

Figure 40 Distance to reach 60 km/h as a function of GCM

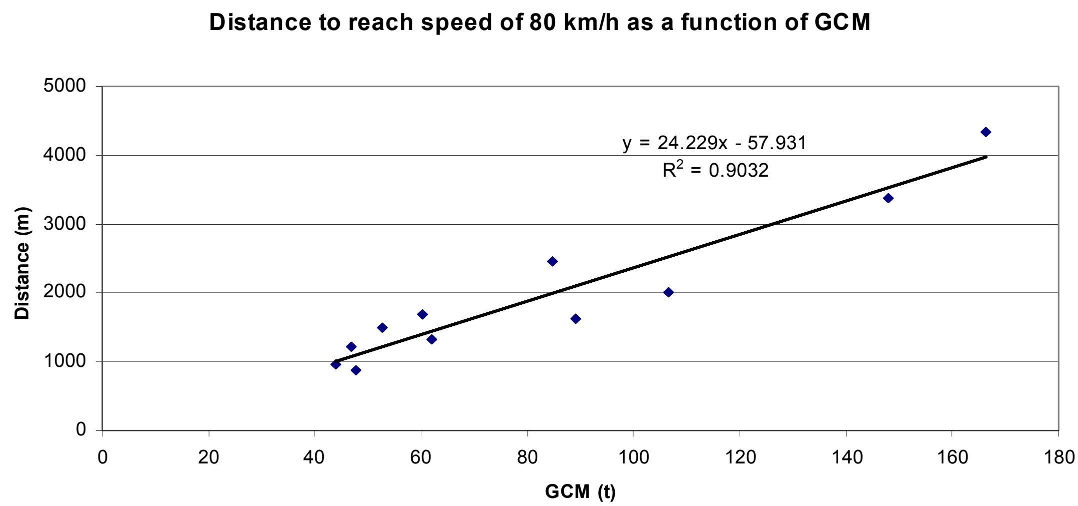

Figure 41 Distance to reach speed of 80 km/h as a function of GCM

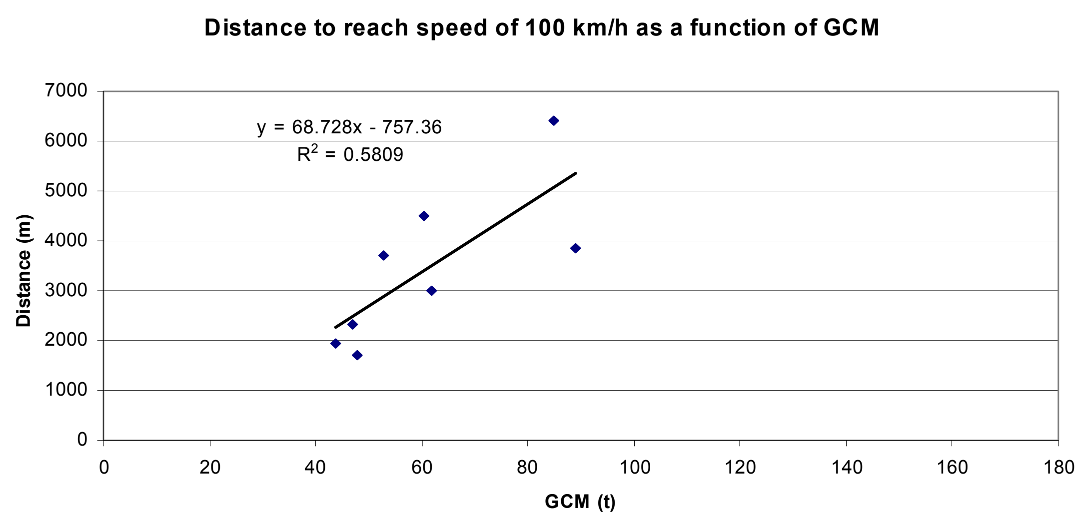

Figure 42 Distance to reach speed of 100 km/h as a function of GCM

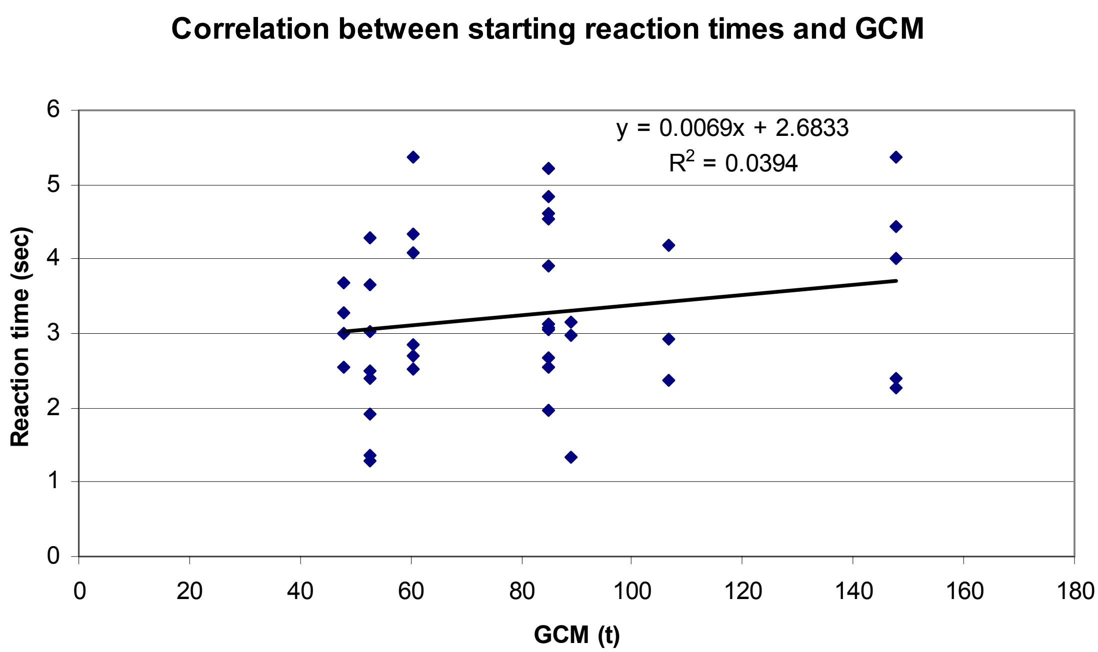

Figure 43 Correlation between starting reaction times and GCM

B.2 Time to cover distance

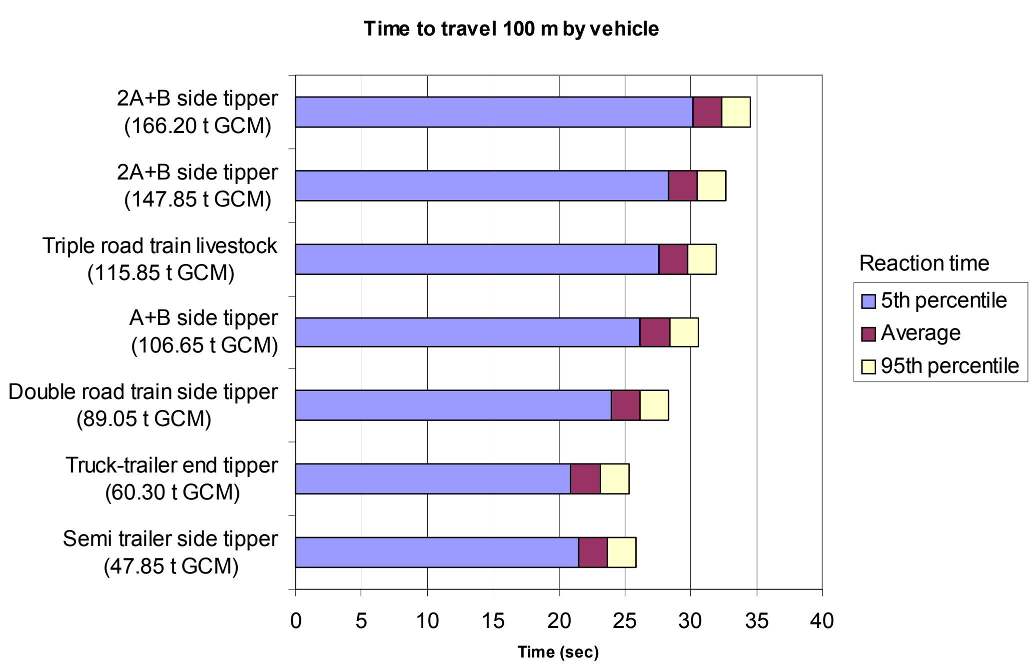

Figure 44 Time to travel 100 m by vehicle

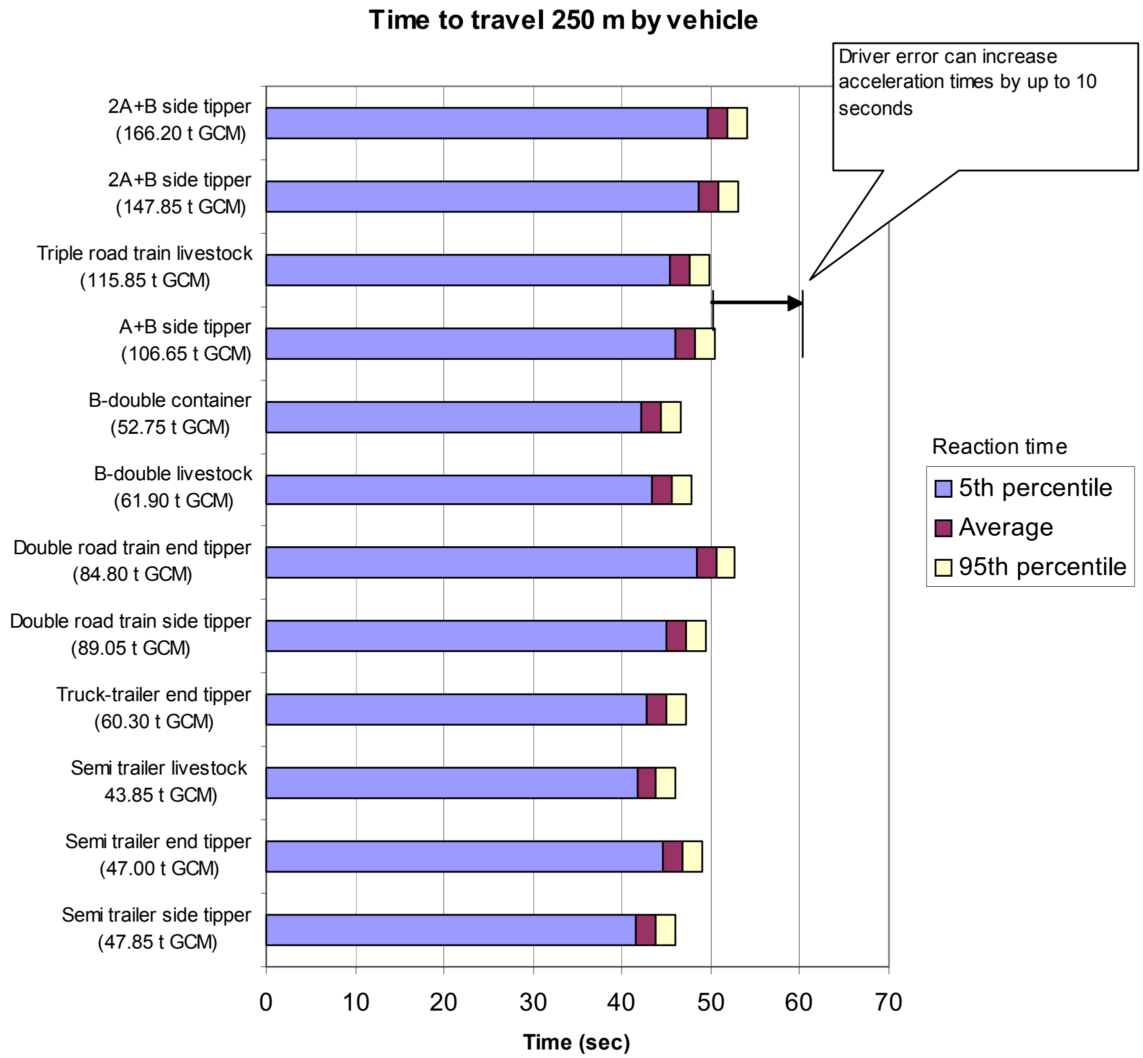

Figure 45 Time to travel 250 m by vehicle

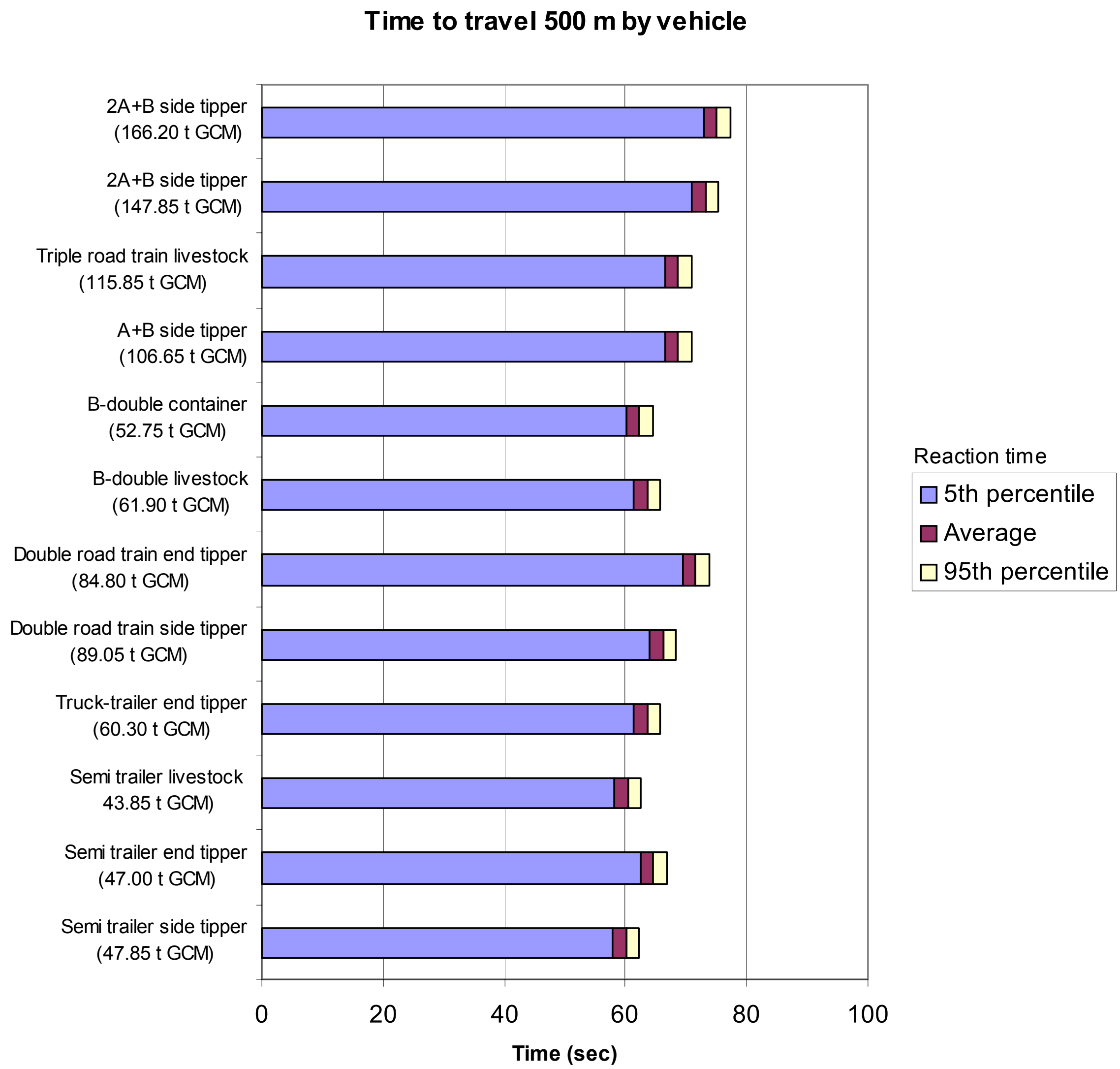

Figure 46 Time to travel 500 m by vehicle

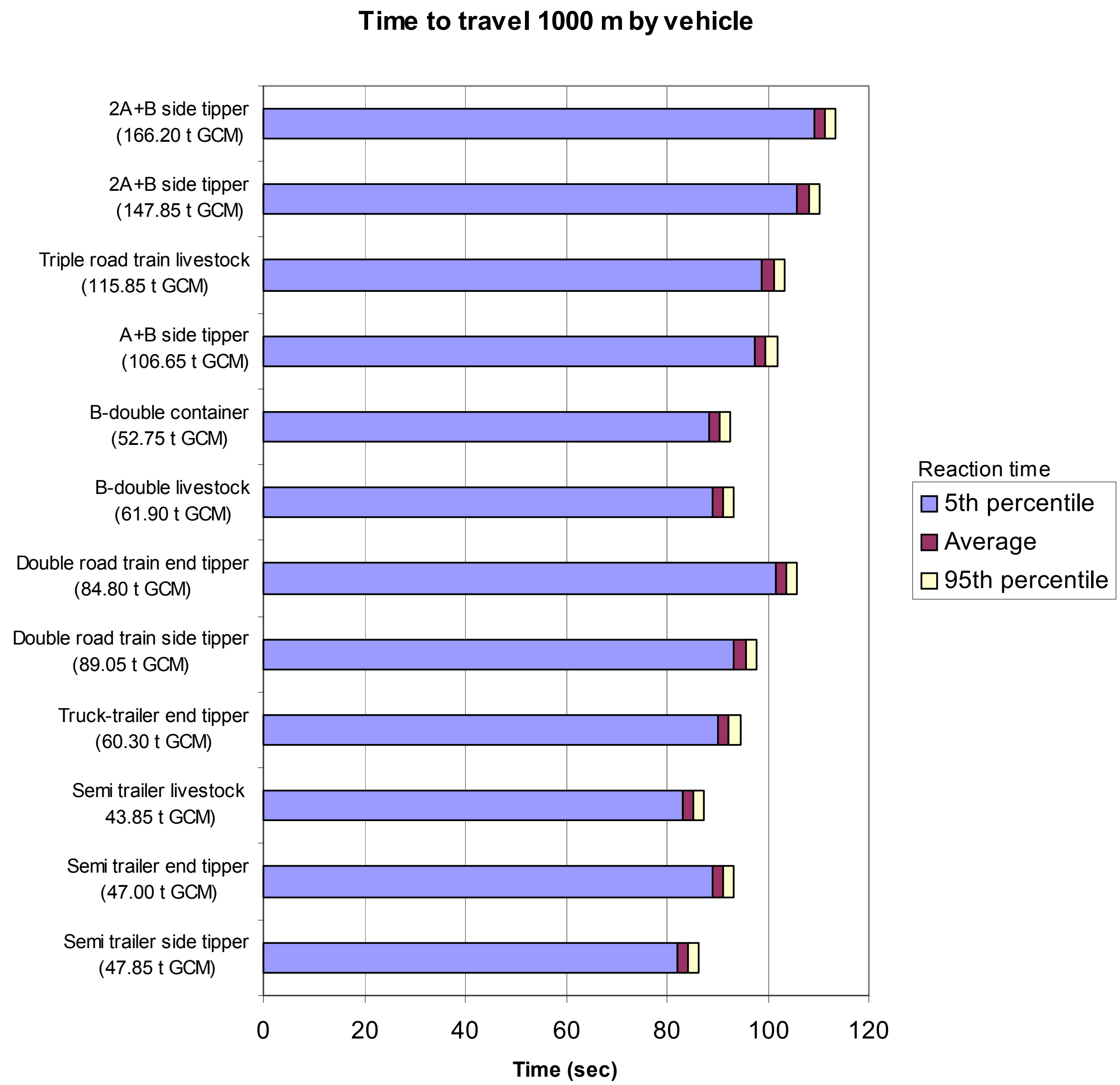

Figure 47 Time to travel 1000 m by vehicle

B.3 Time to reach speed

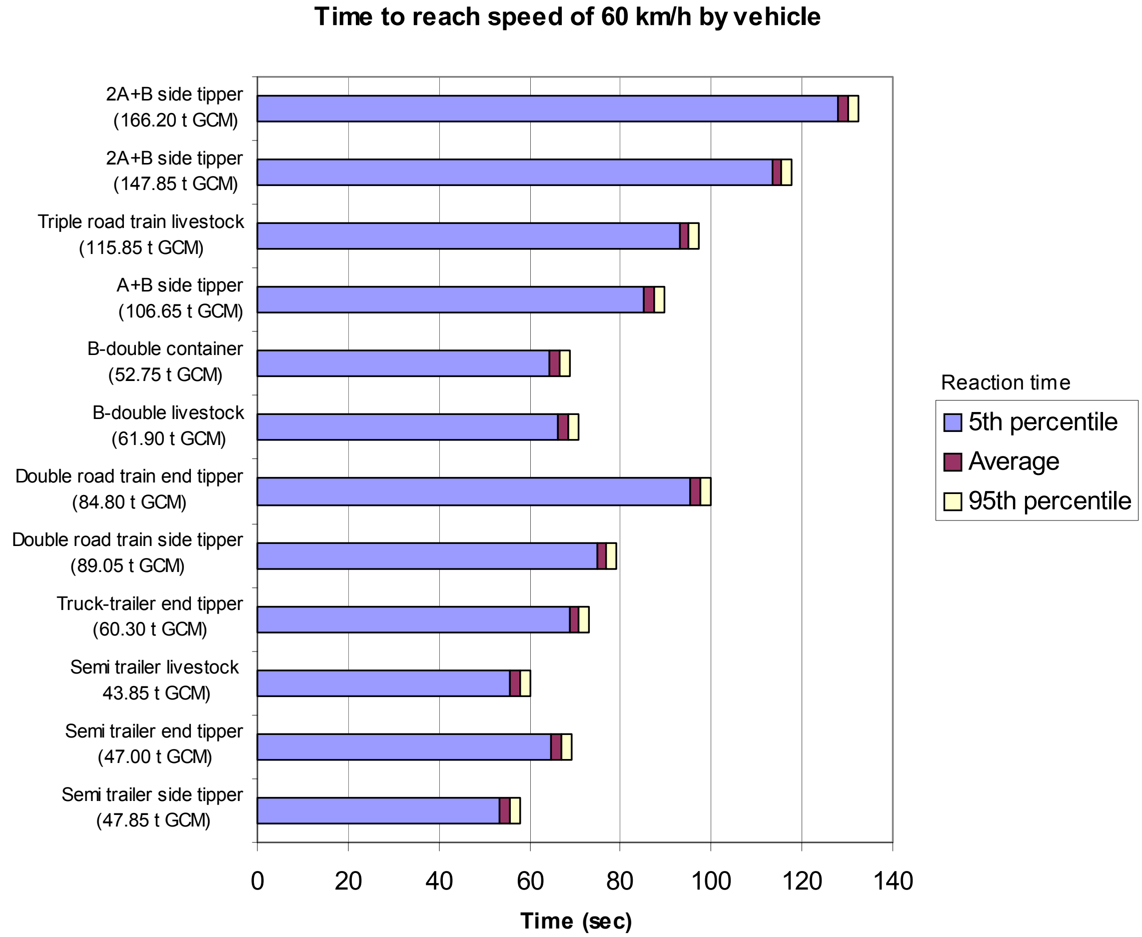

Figure 48 Time to reach speed of 60 km/h by vehicle

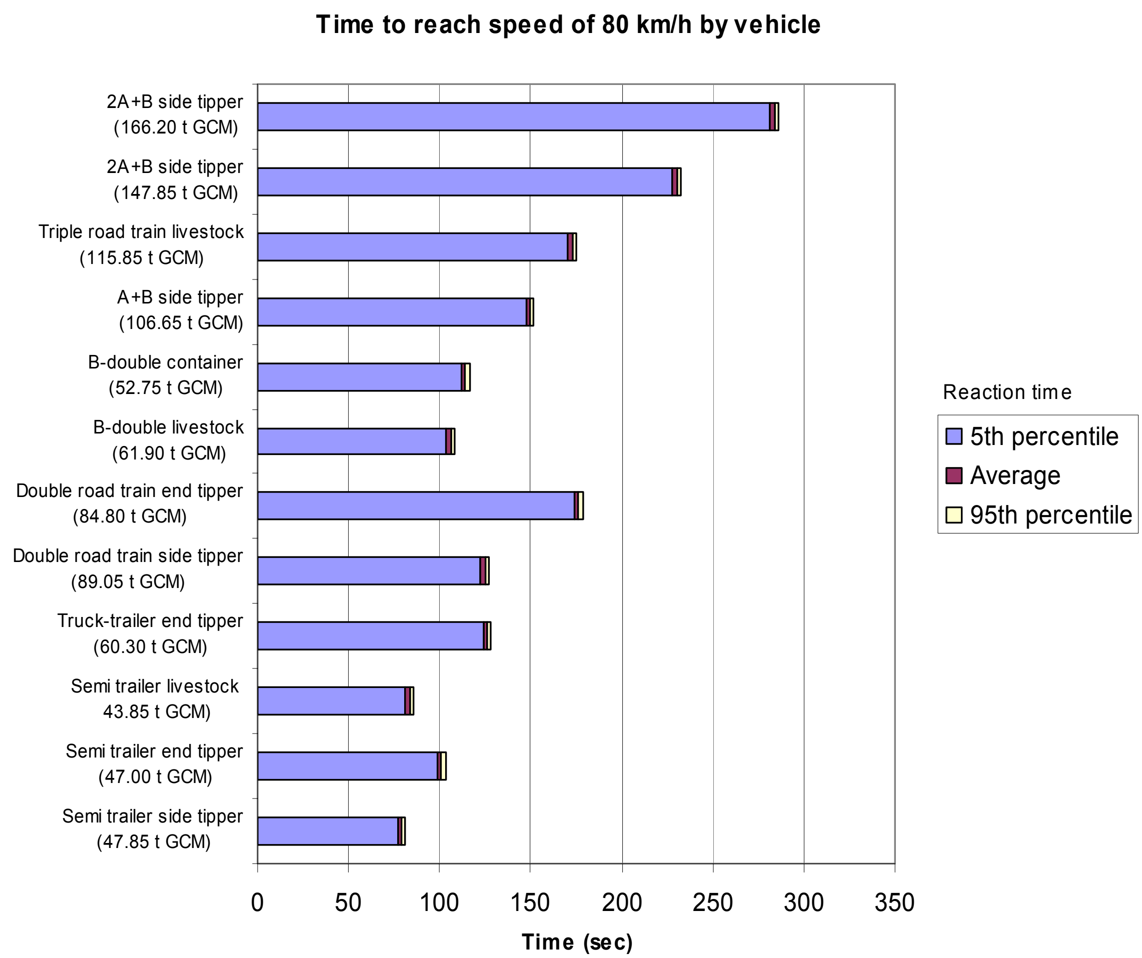

Figure 49 Time to reach speed of 80 km/h by vehicle

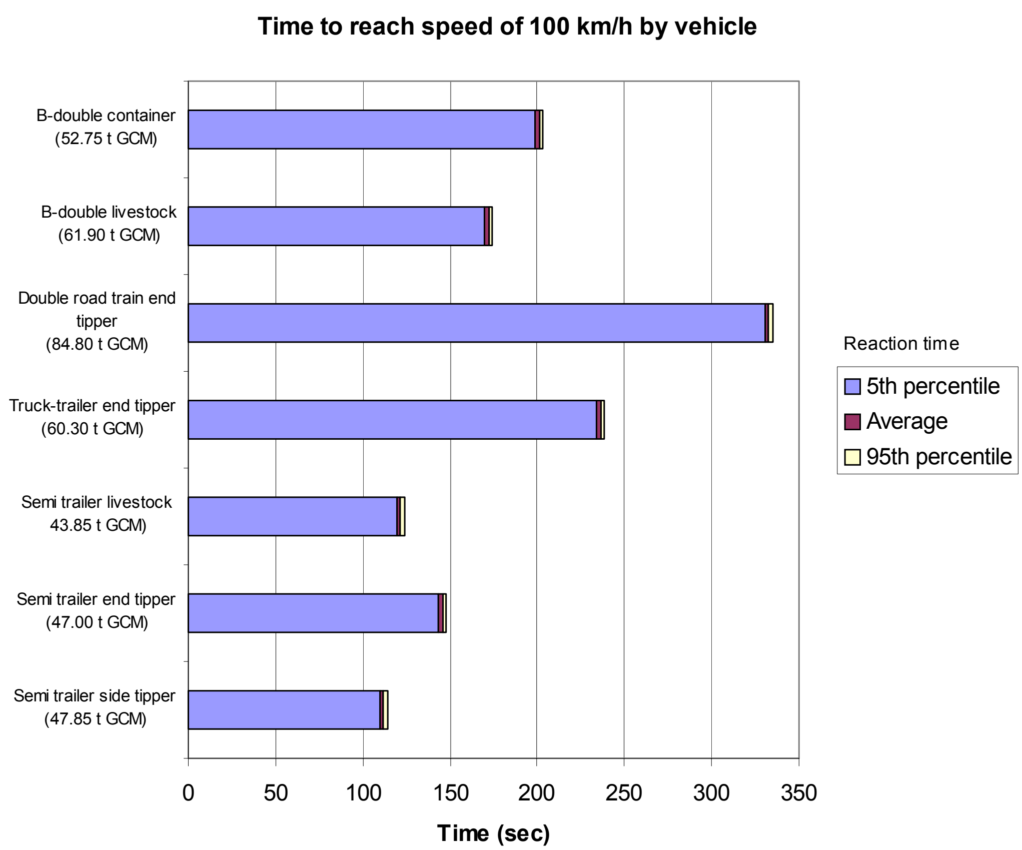

Figure 50 Time to reach speed of 100 km/h by vehicle

B.4 Distance to reach speed

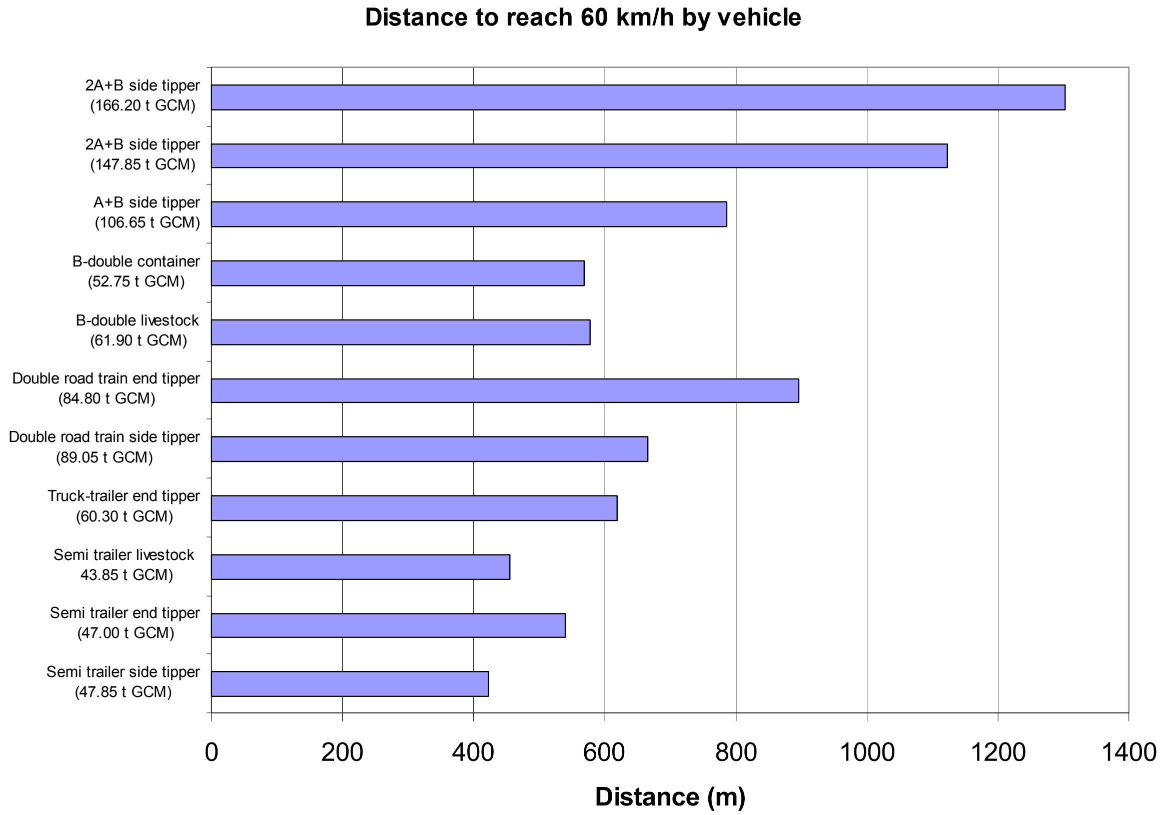

Figure 51 Distance to reach 60 km/h by vehicle

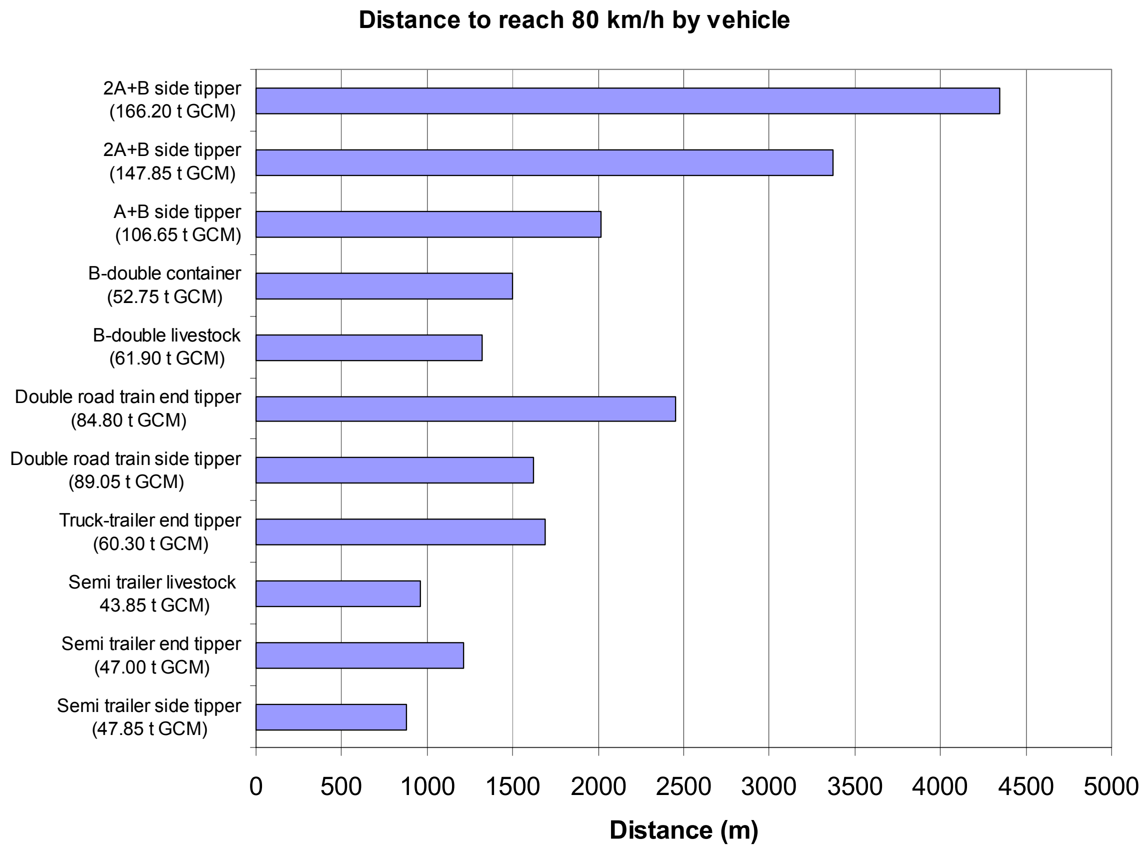

Figure 52 Distance to reach 80 km/h by vehicle

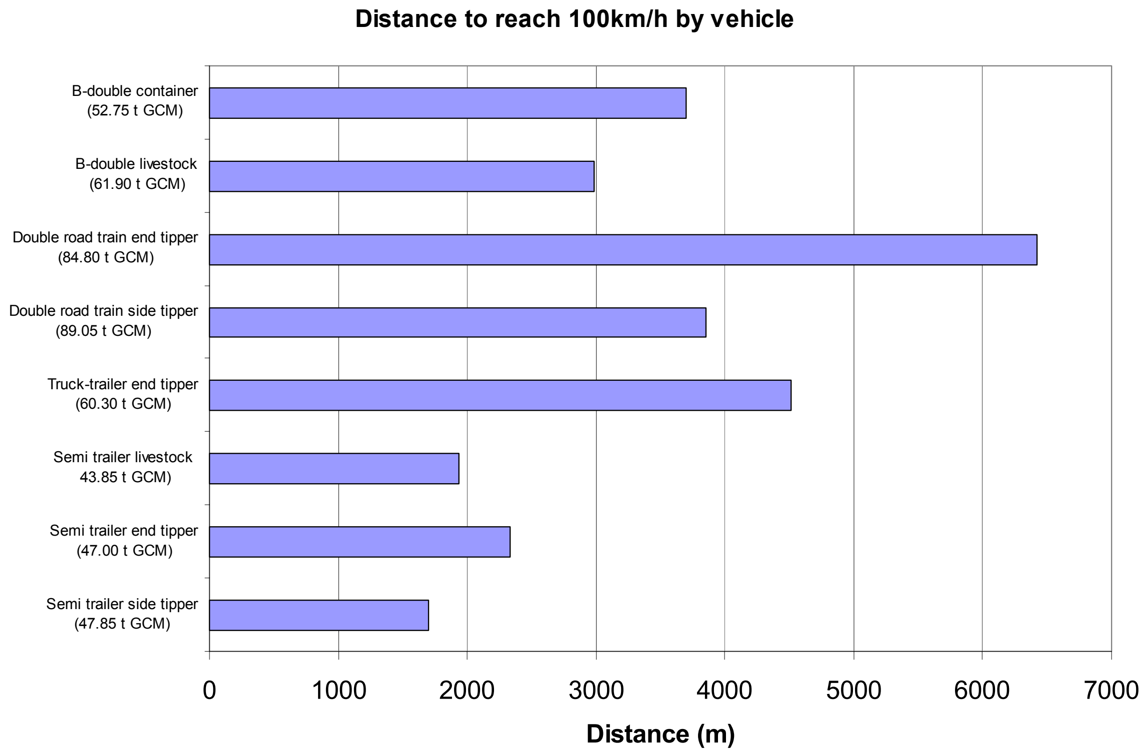

Figure 53 Distance to reach 100 km/h by vehicle

B.5 Effect of grade

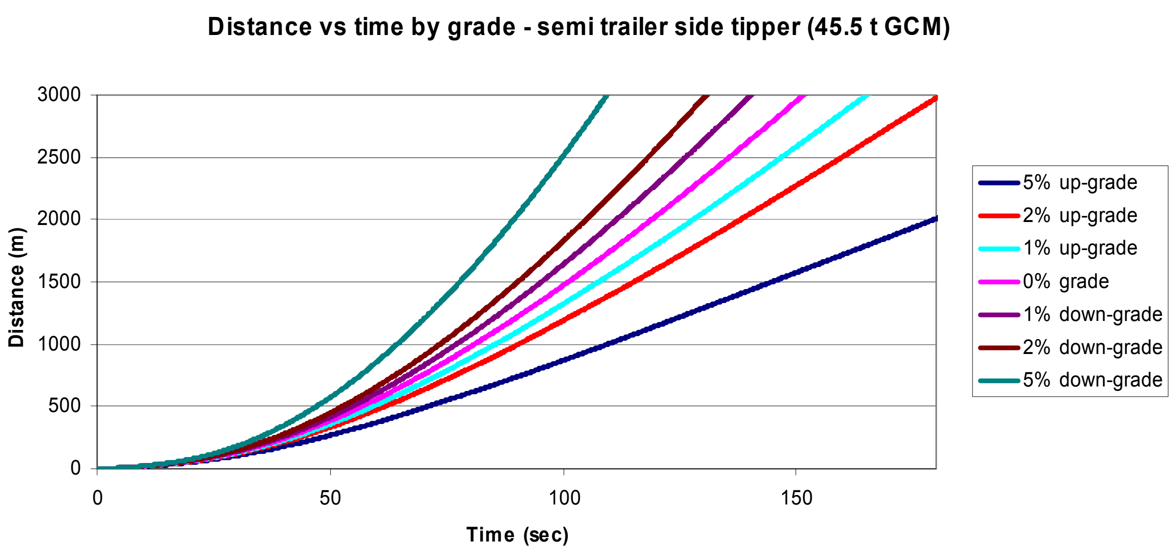

Figure 54 Distance vs time by grade – semi trailer side tipper (45.5 t GCM)

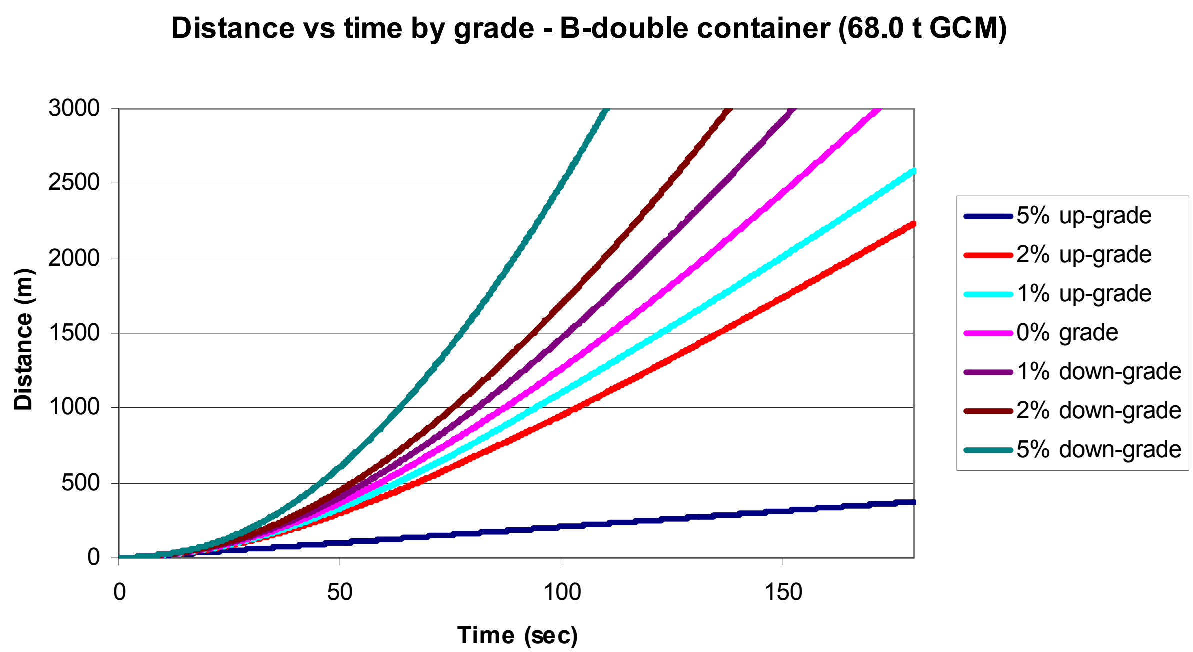

Figure 55 Distance vs time by grade – B-double container (68.0 t GCM)

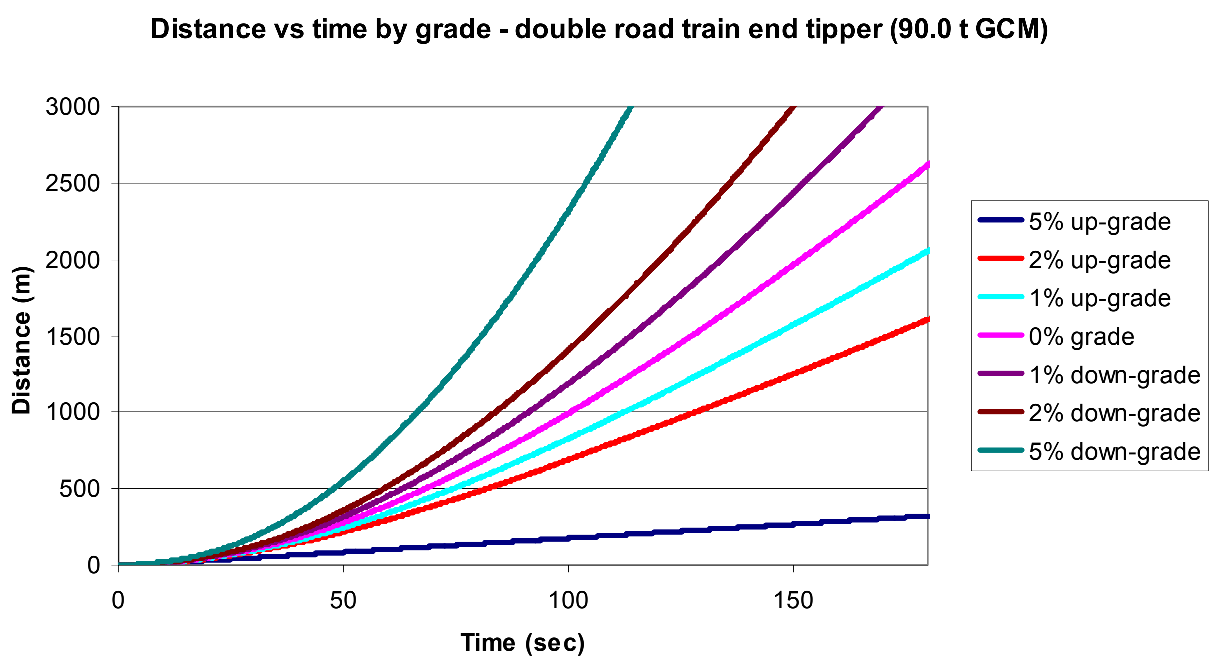

Figure 56 Distance vs time by grade – double road train end tipper (90.0 t GCM)

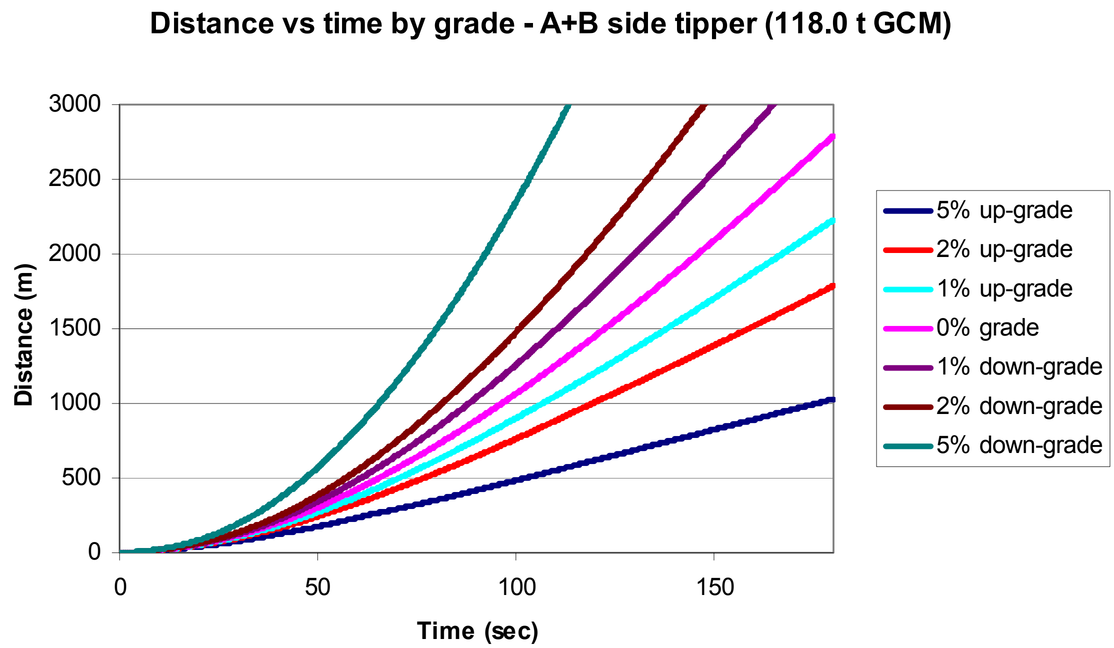

Figure 57 Distance vs time by grade – A+B side tipper (118.0 t GCM)

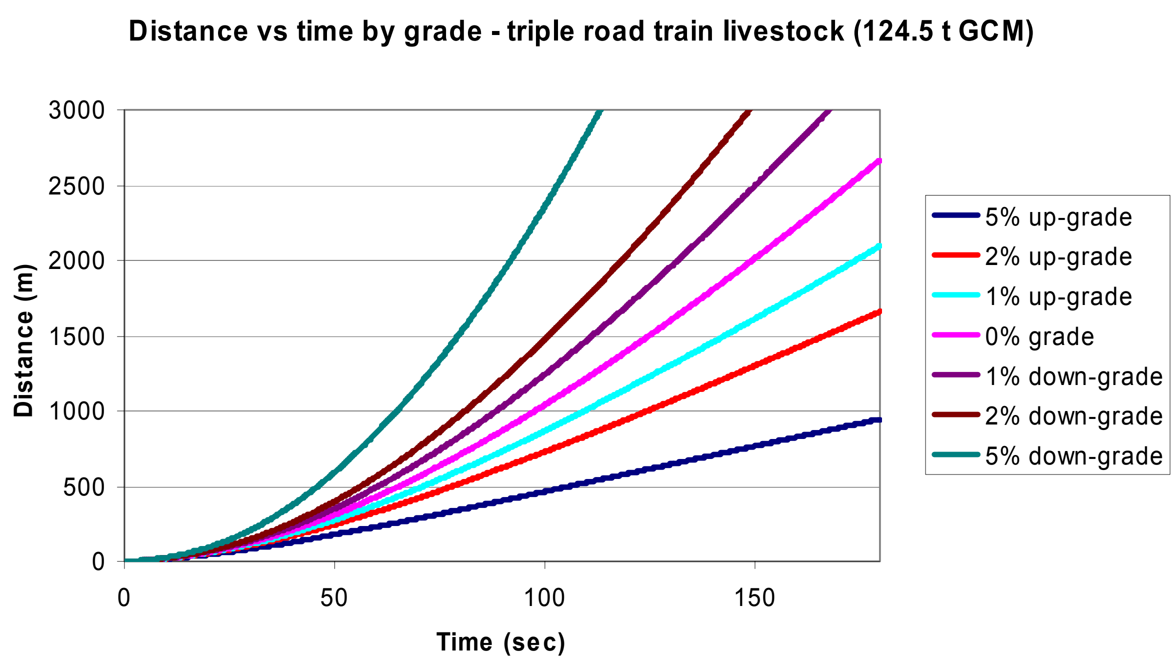

Figure 58 Distance vs time by grade – triple road train livestock (124.5 t GCM)

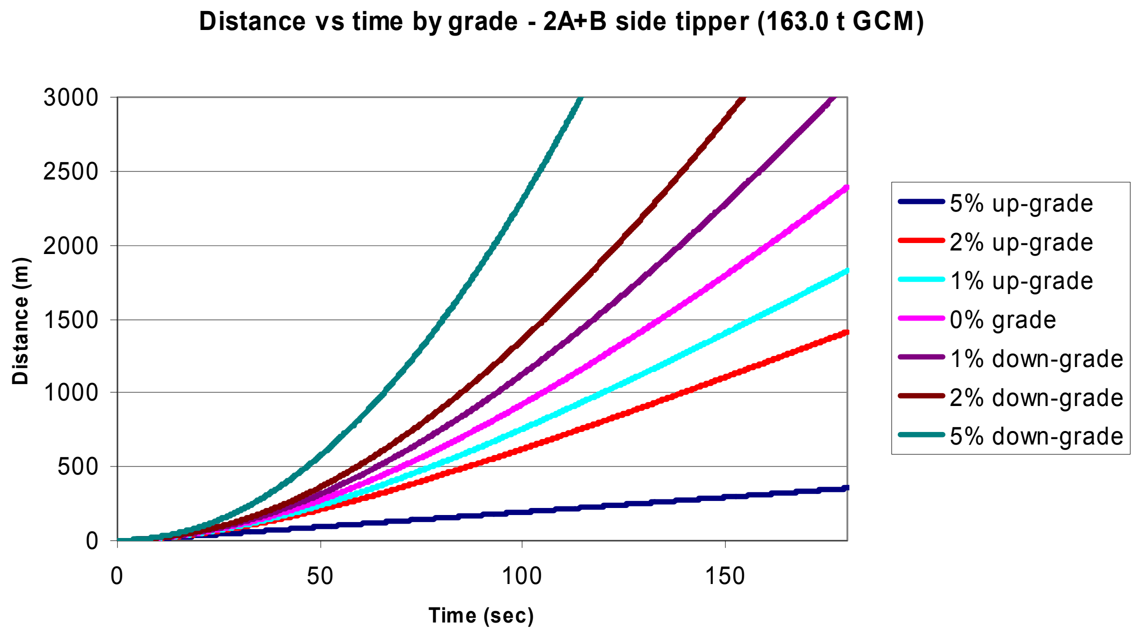

Figure 59 Distance vs time by grade – 2A+B side tipper (163.0 t GCM)

B.6 Top speeds in urban travel

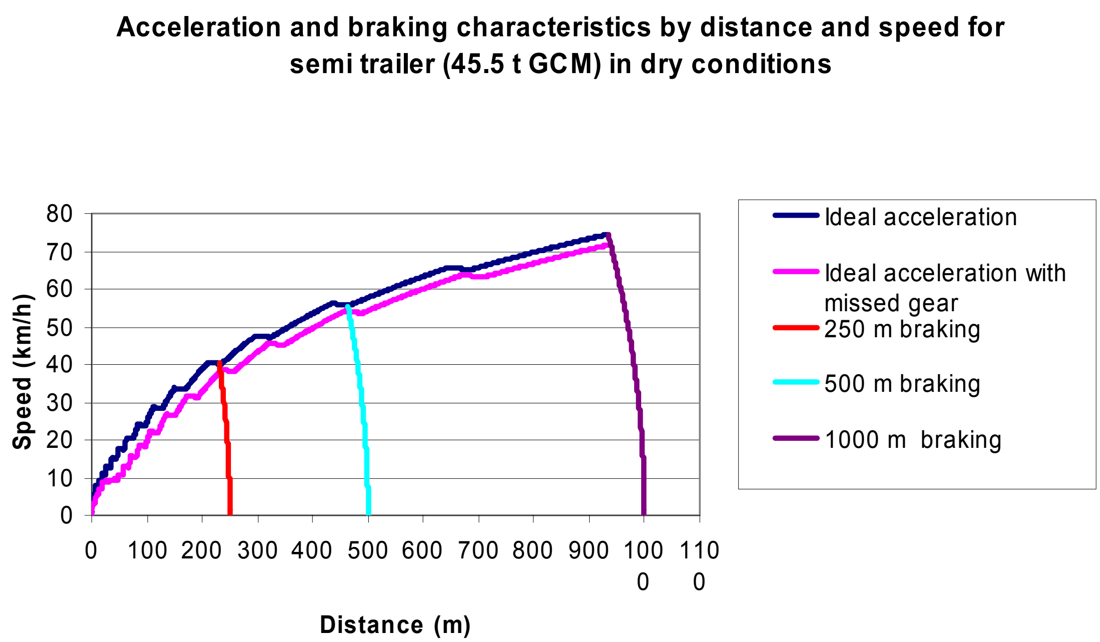

Figure 60 Speed profile for semi trailer (45.5 t GCM)

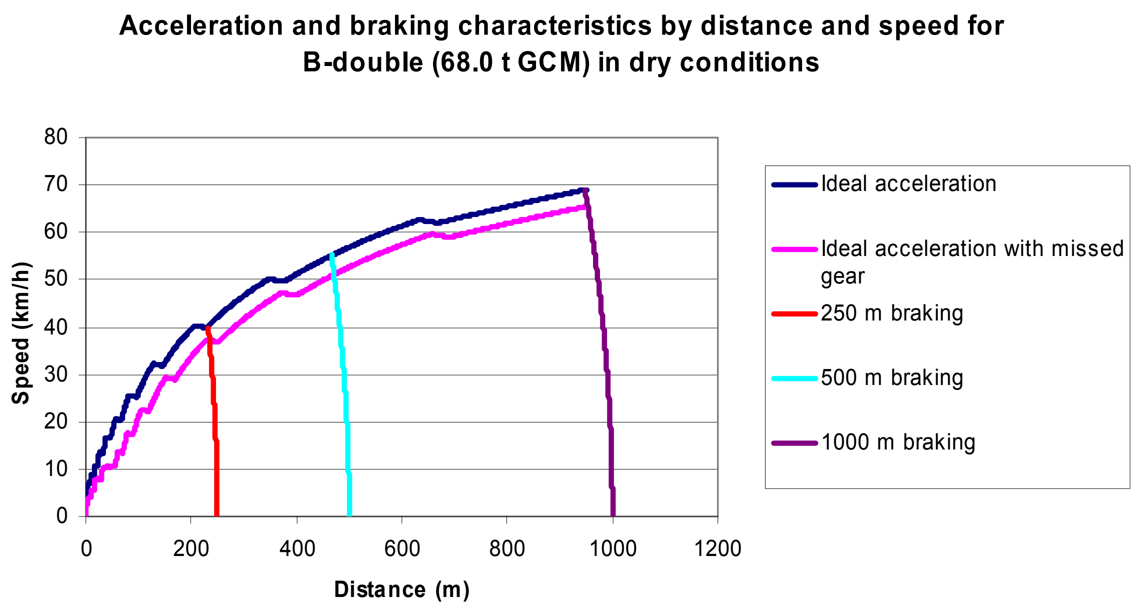

Figure 61 Speed profile for B-double (68.0 t GCM)

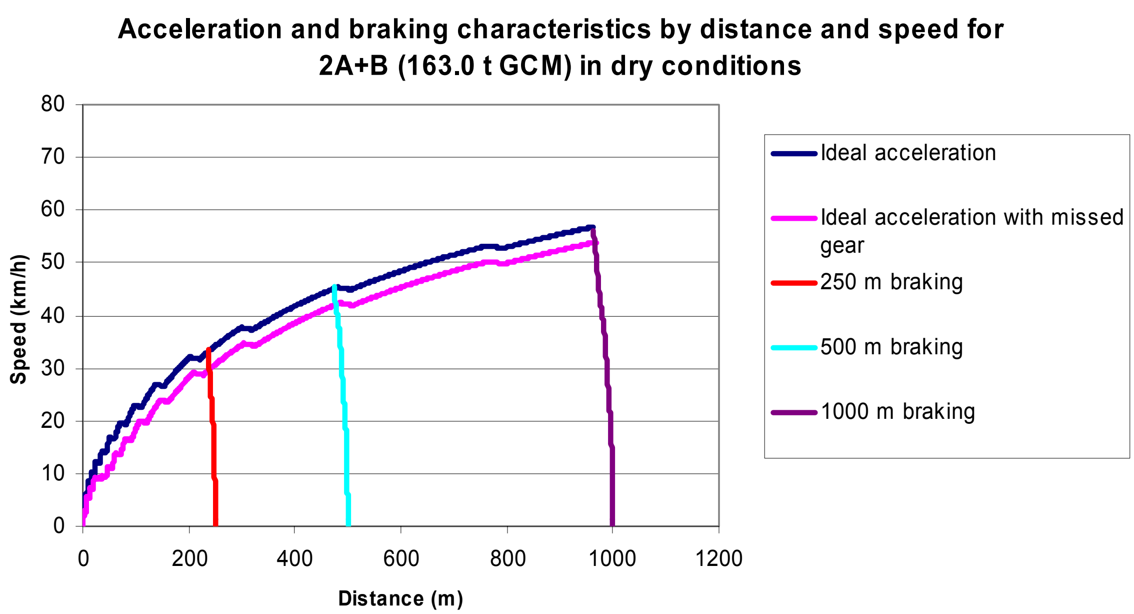

Figure 62 Speed profile for 2A+B (163.0 t GCM)

Appendix C Deceleration test results

C.1 Correlation

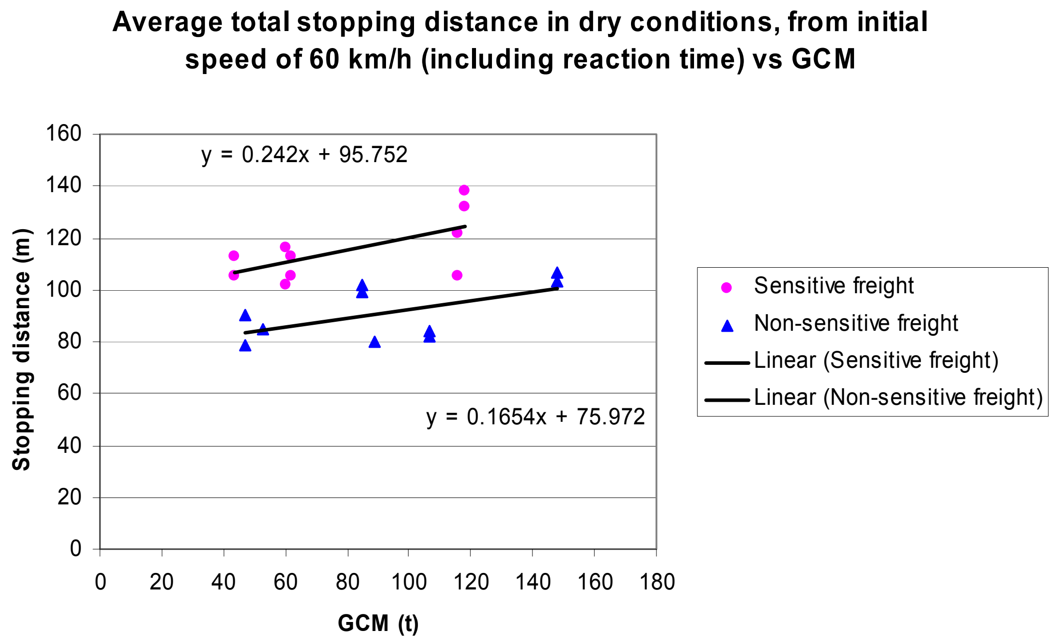

Figure 63 Stopping distance from initial speed of 60 km/h vs GCM

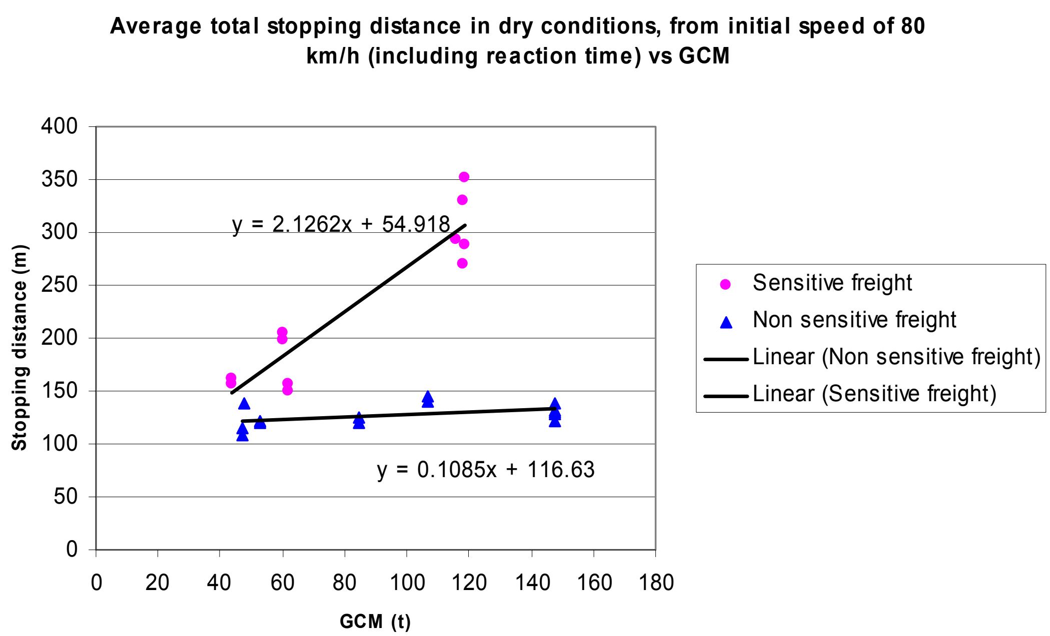

Figure 64 Stopping distance from initial speed of 80 km/h vs GCM

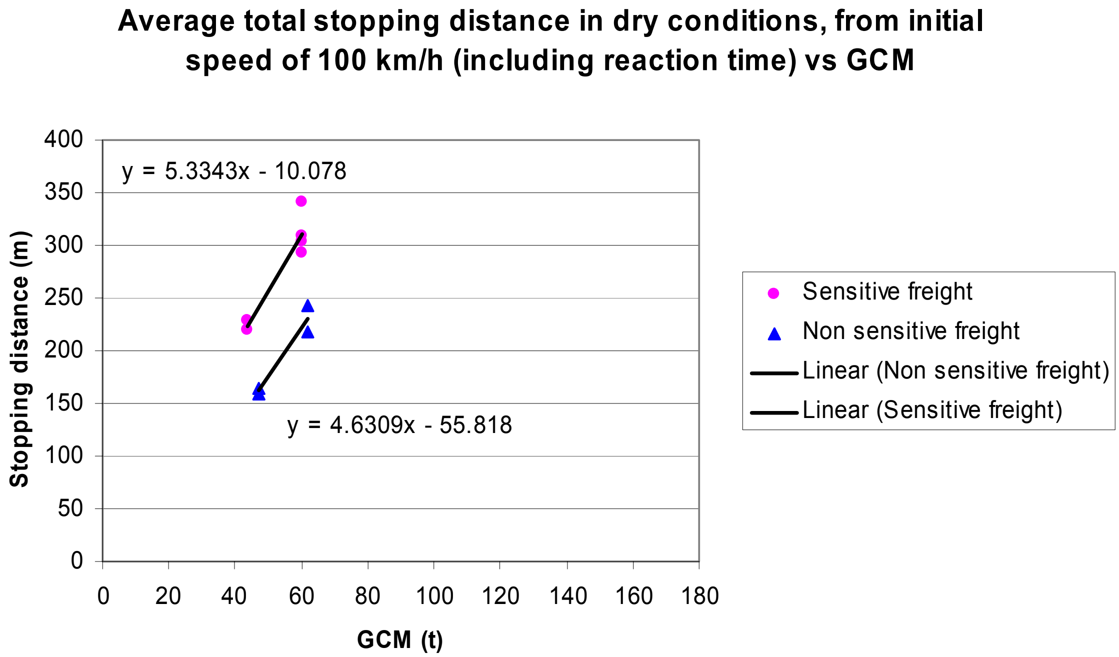

Figure 65 Stopping distance from initial speed of 100 km/h vs GCM

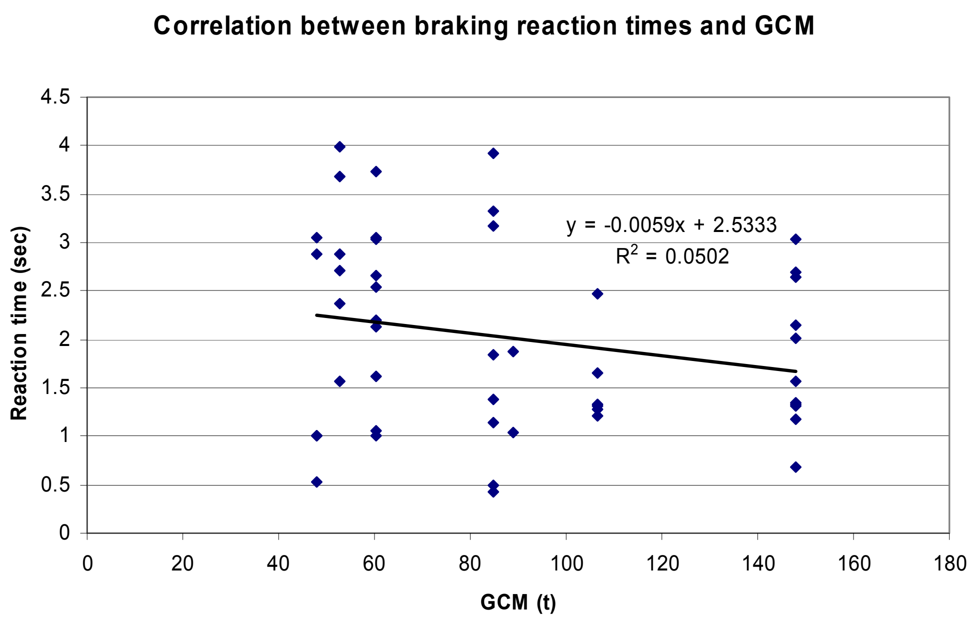

Figure 66 Correlation between braking reaction times and GCM

C.2 Stopping distance

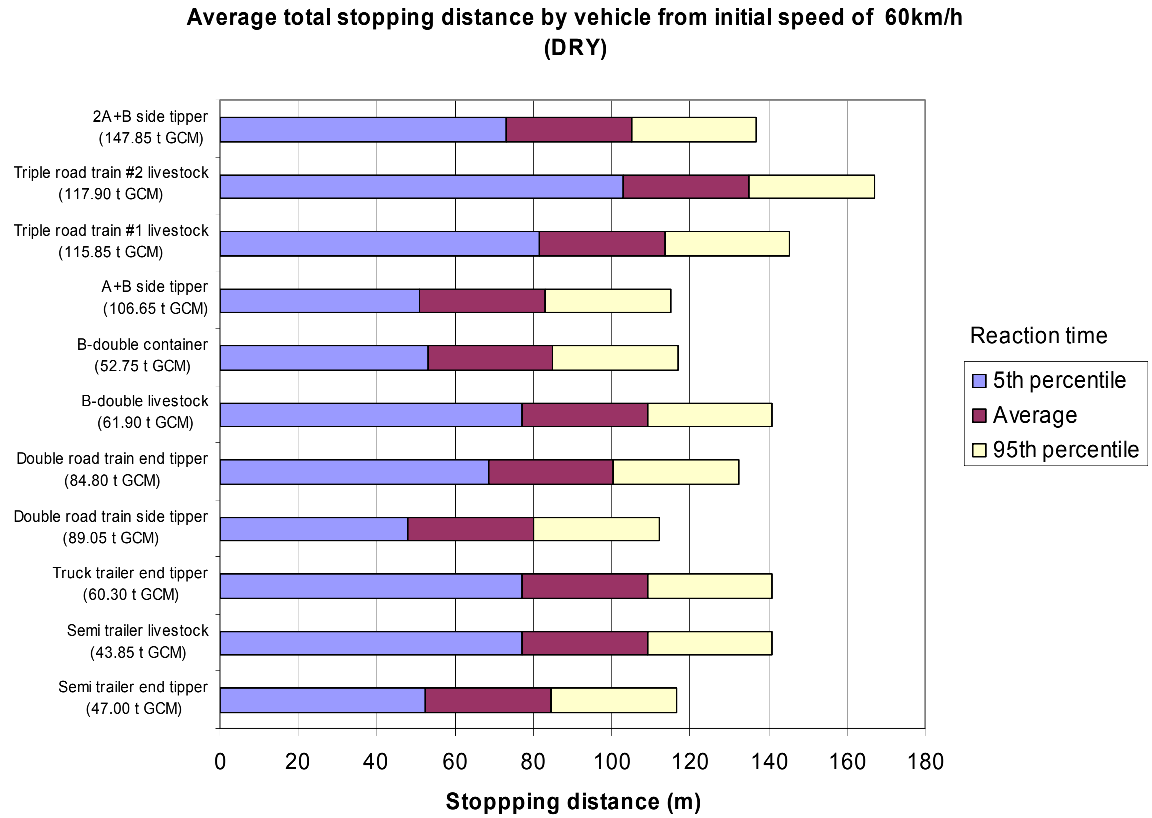

Figure 67 Stopping distance by vehicle from initial speed of 60 km/h (DRY)

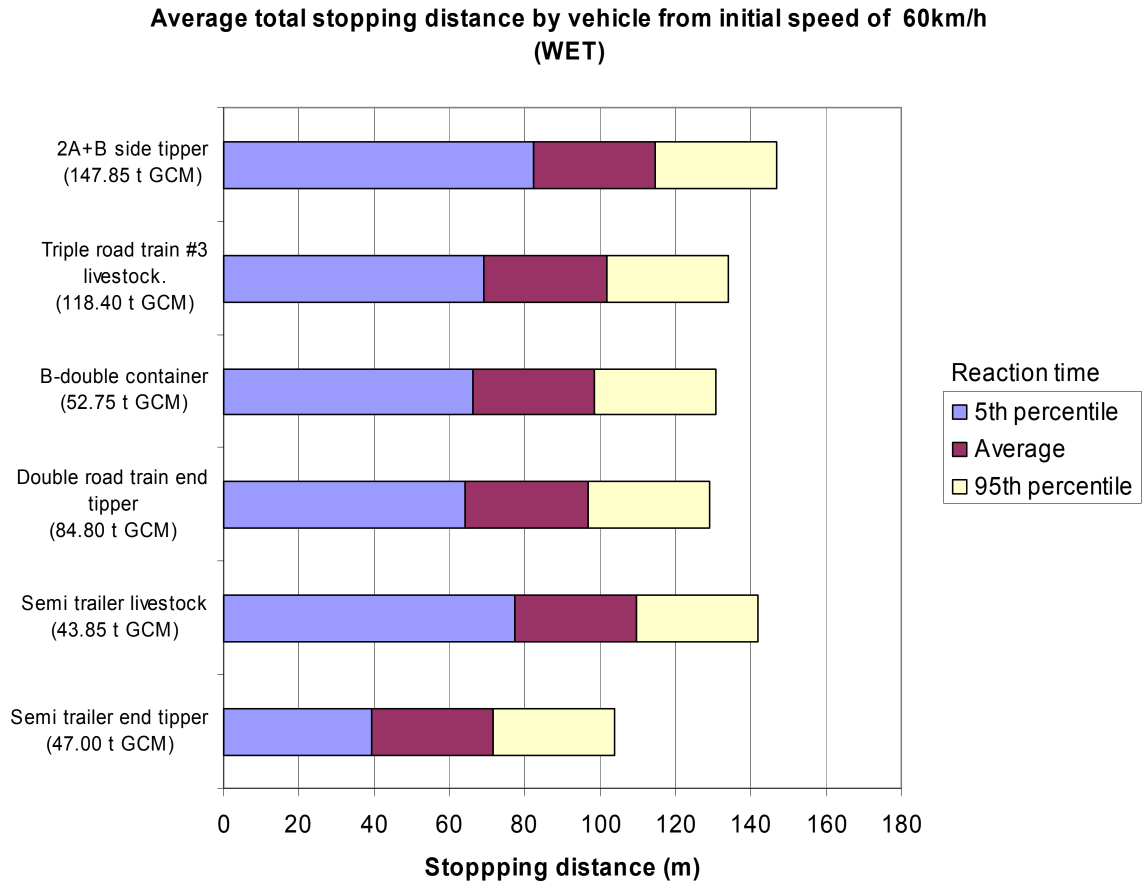

Figure 68 Stopping distance by vehicle from initial speed of 60 km/h (WET)

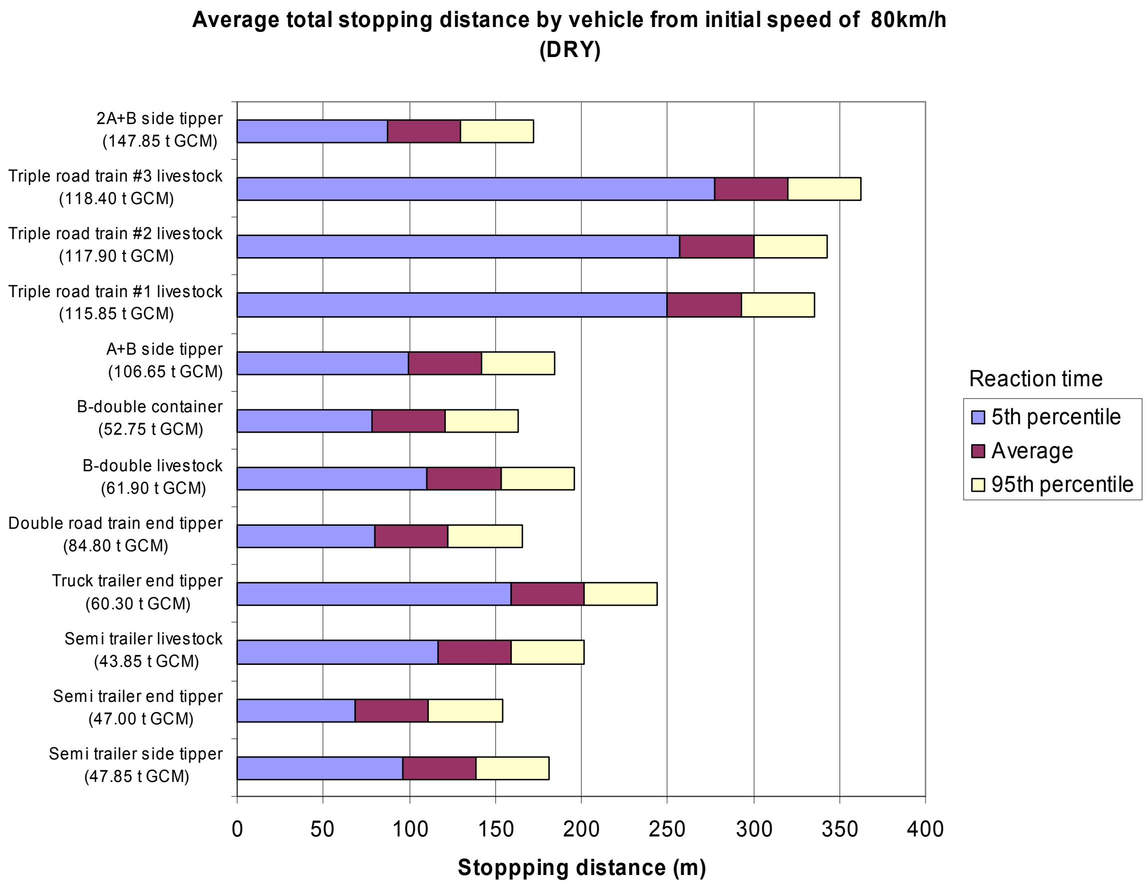

Figure 69 Stopping distance by vehicle from initial speed of 80 km/h (DRY)

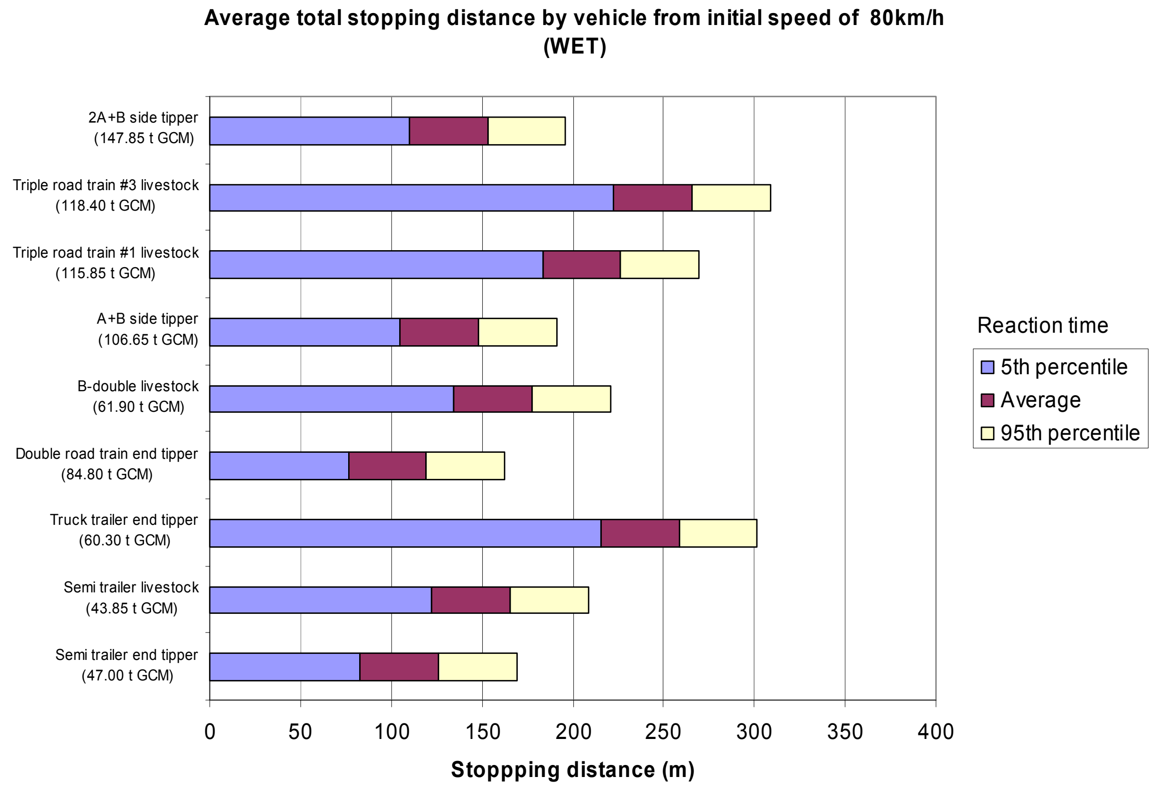

Figure 70 Stopping distance by vehicle from initial speed of 80 km/h (WET)

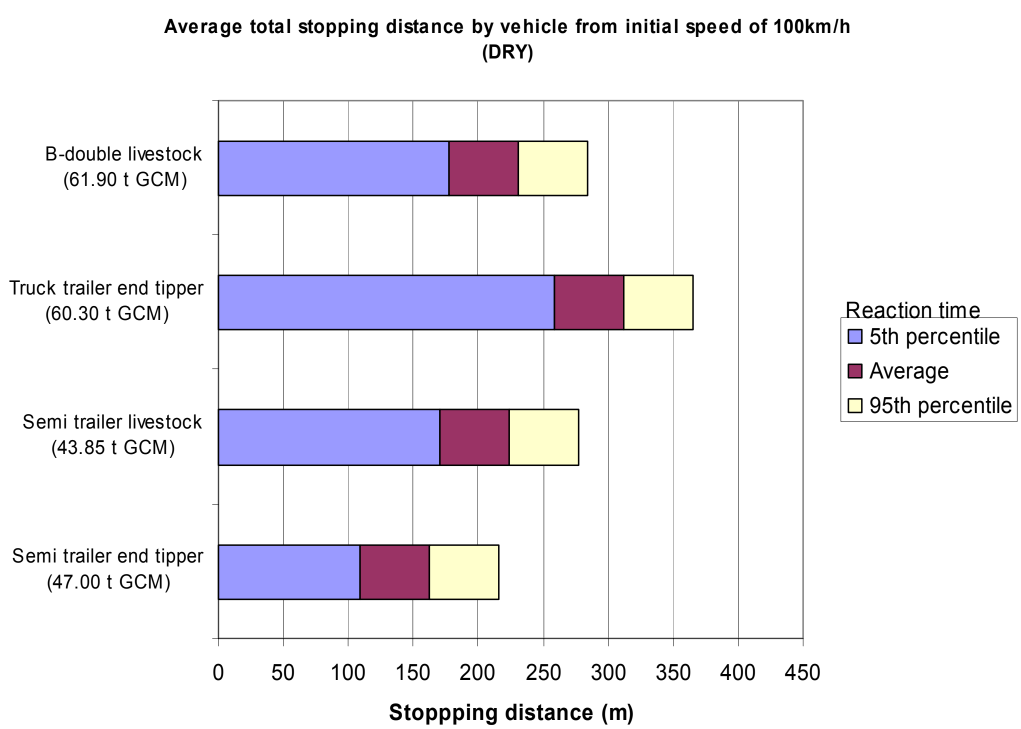

Figure 71 Stopping distance by vehicle from initial speed of 100 km/h (DRY)

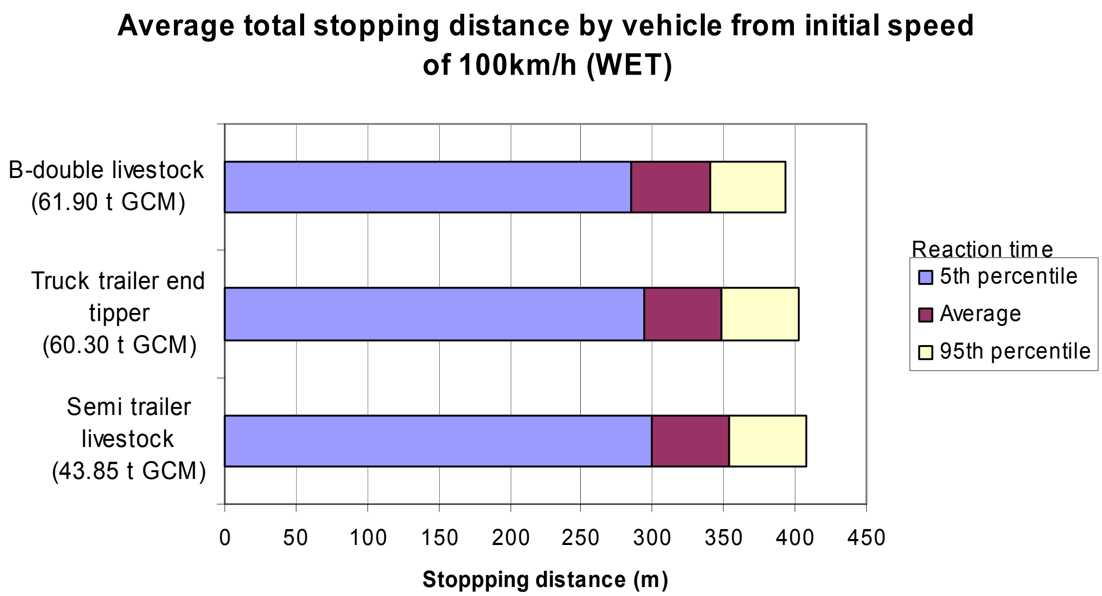

Figure 72 Stopping distance by vehicle from initial speed of 100 km/h (WET)

C.3 Effect of grade

Speed vs distance by grade for semi trailer side tipper (45.5 t GCM) braking from 60 km/h (DRY)

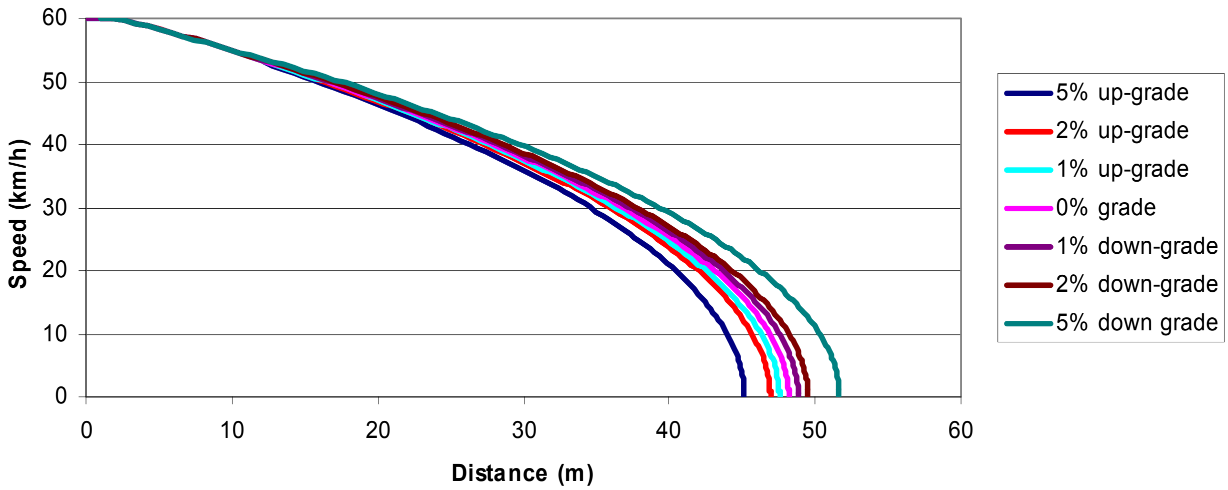

Figure 73 Semi trailer side tipper (45.5 t GCM) from 60 km/h (DRY)

Speed vs distance by grade for semi trailer side tipper (45.5 t GCM) braking from 80 km/h (DRY)

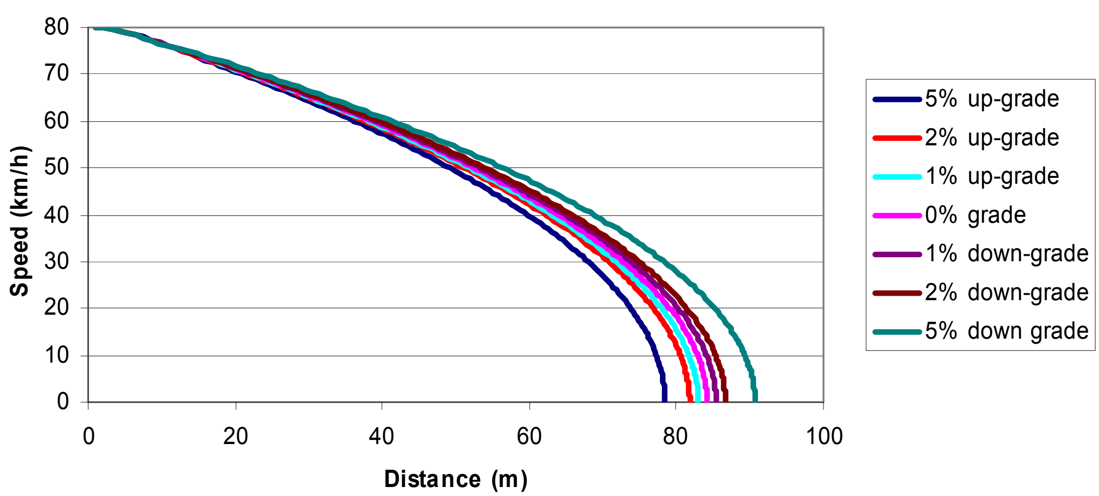

Figure 74 Semi trailer side tipper (45.5 t GCM) from 80 km/h (DRY)

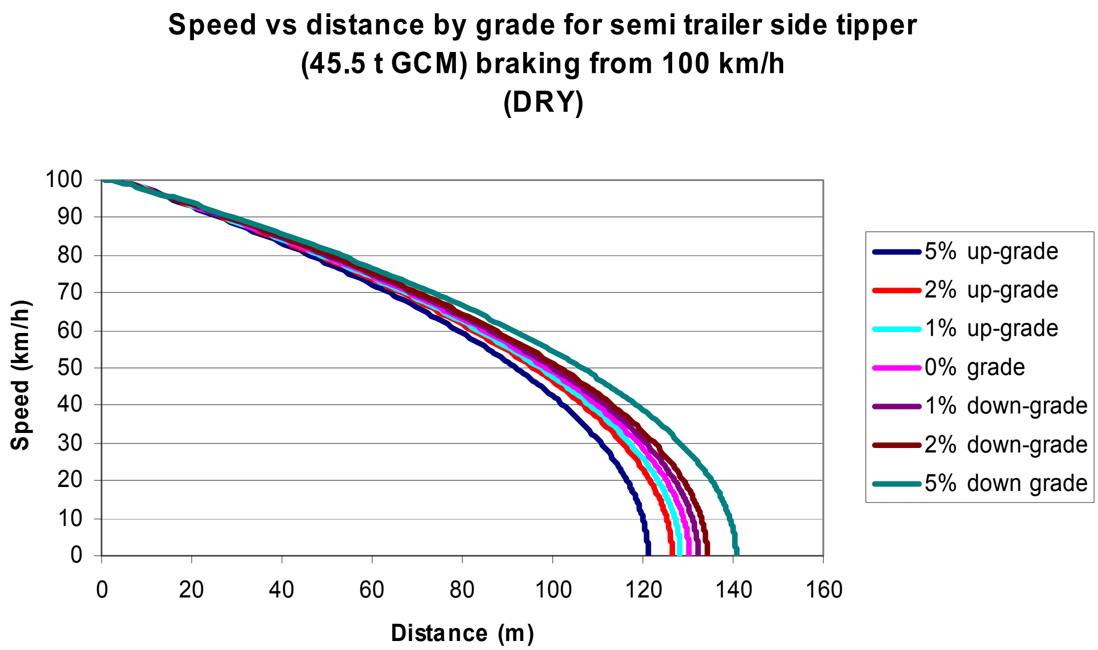

Figure 75 Semi trailer side tipper (45.5 t GCM) from 100 km/h (DRY)

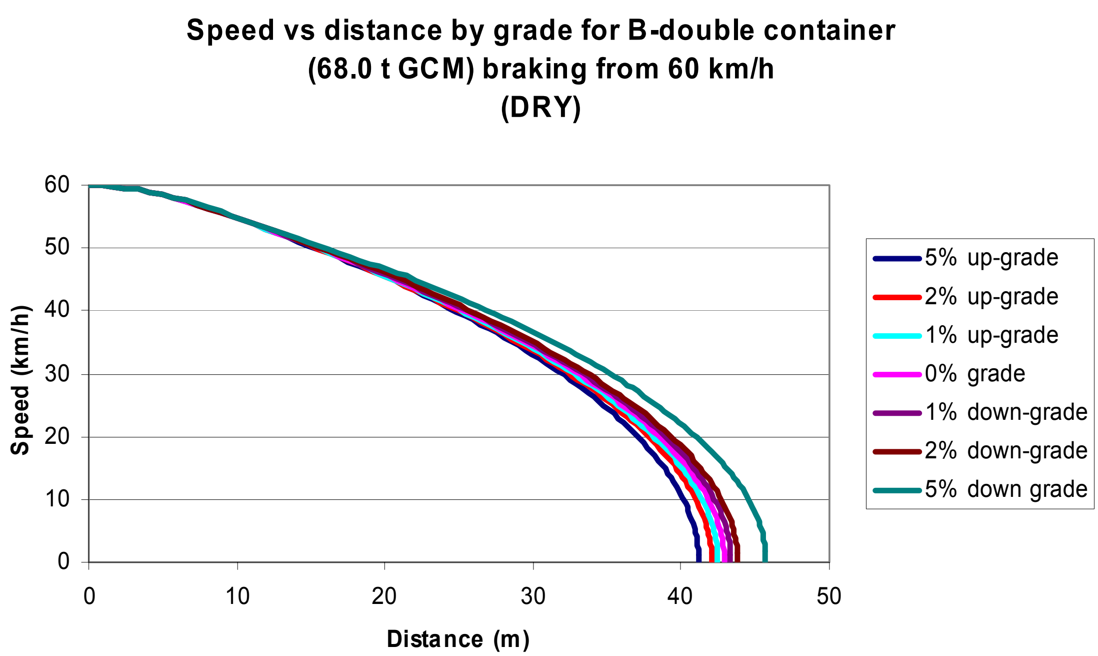

Figure 76 B-double container (68.0 t GCM) from 60 km/h (DRY)

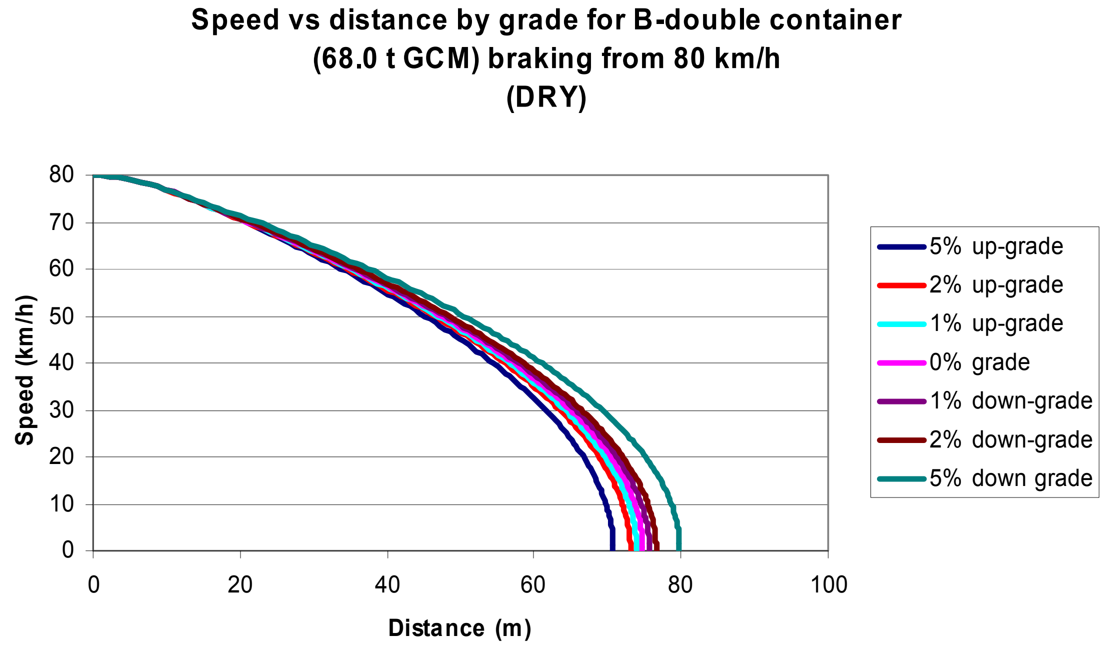

Figure 77 B-double container (68.0 t GCM) from 80 km/h (DRY)

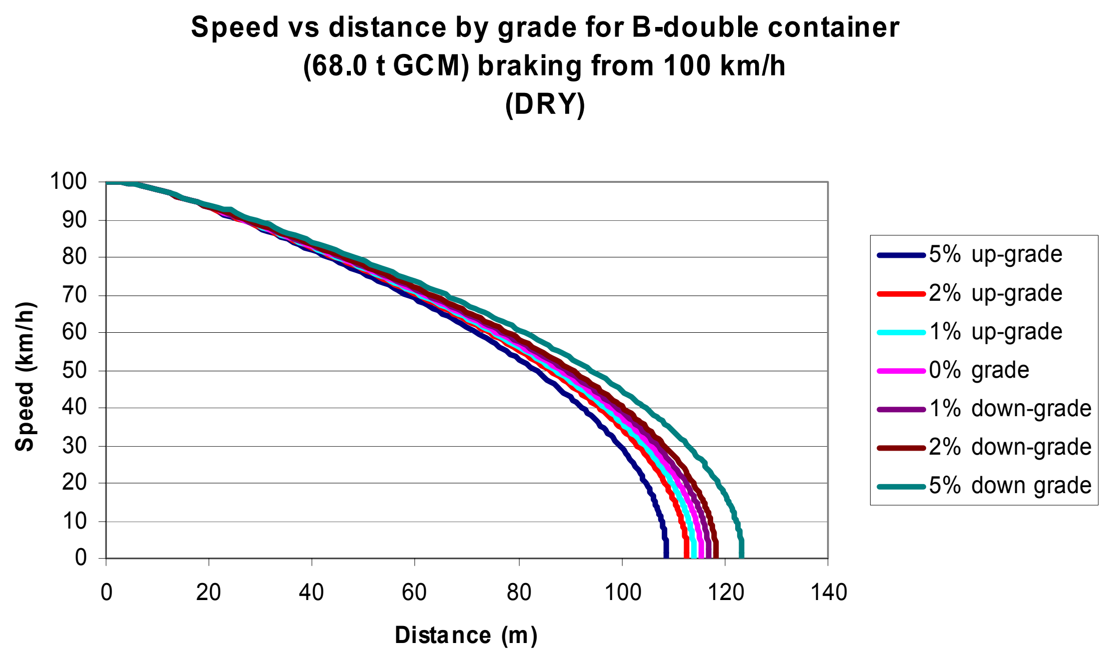

Figure 78 B-double container (68.0 t GCM) from 100 km/h (DRY)

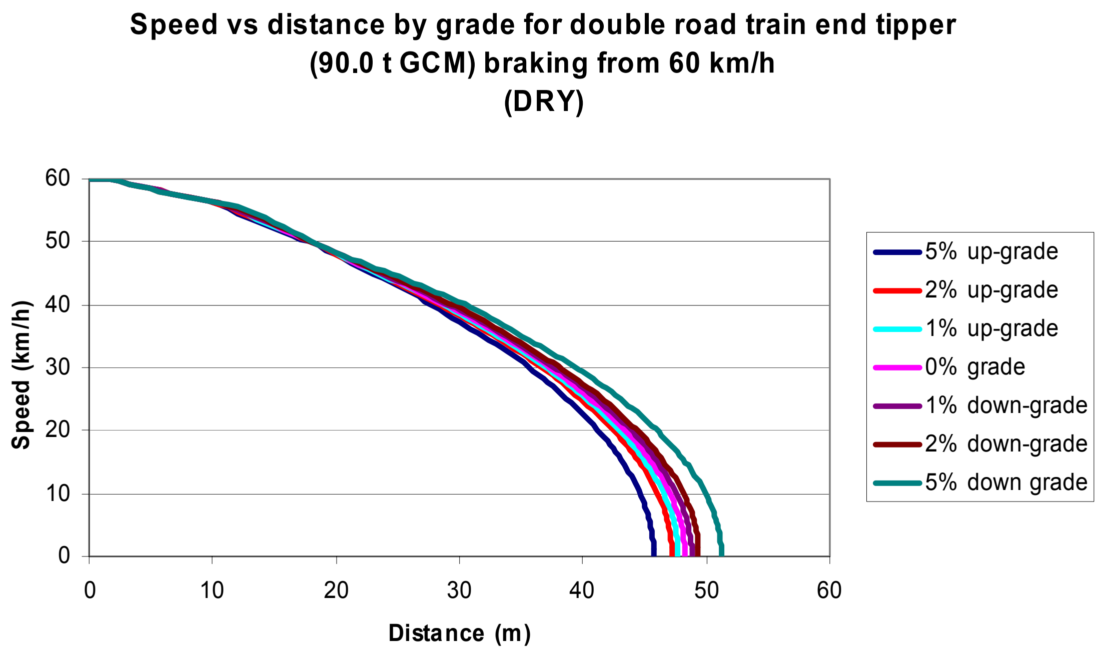

Figure 79 Double road train end tipper (90.0 t GCM) from 60 km/h (DRY)

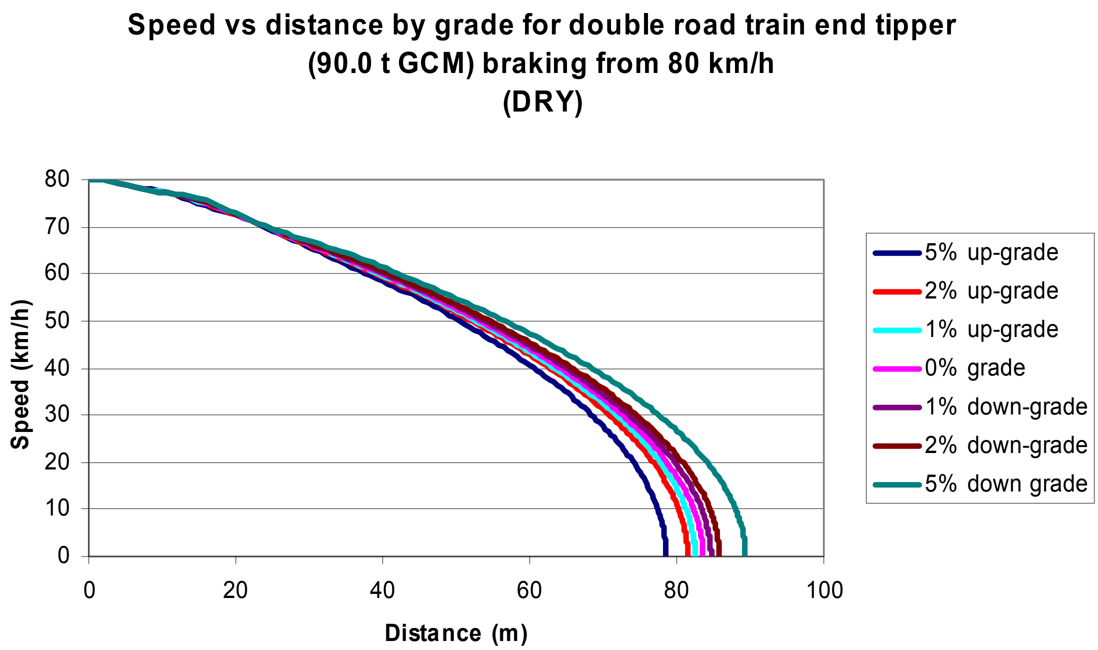

Figure 80 Double road train end tipper (90.0 t GCM) from 80 km/h (DRY)

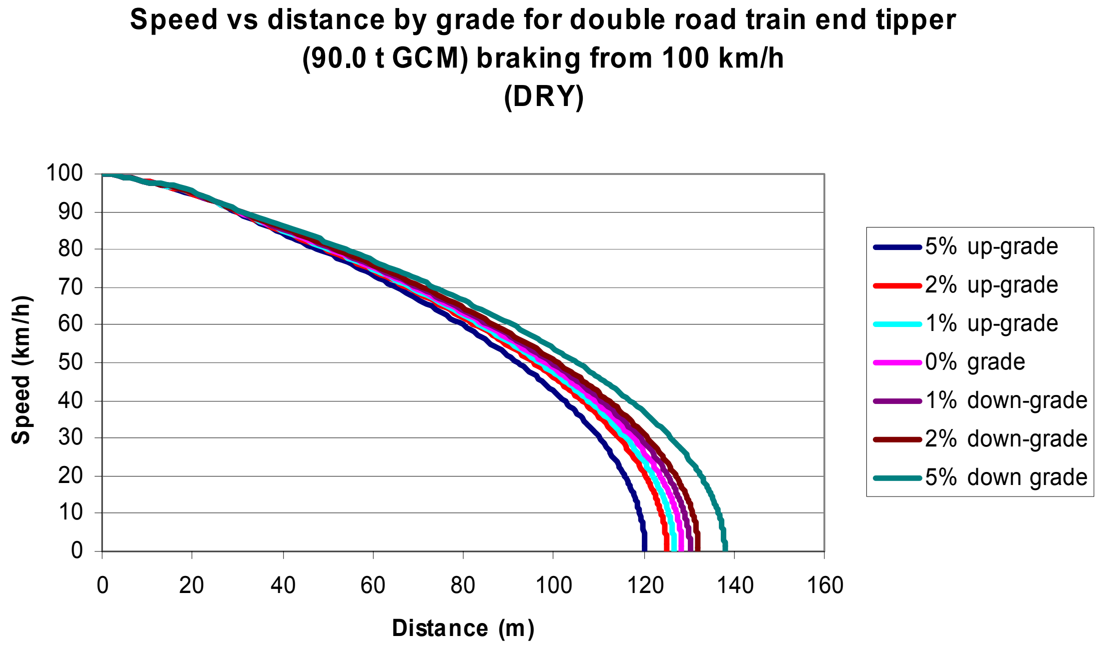

Figure 81 Double road train end tipper (90.0 t GCM) from 100 km/h (DRY)

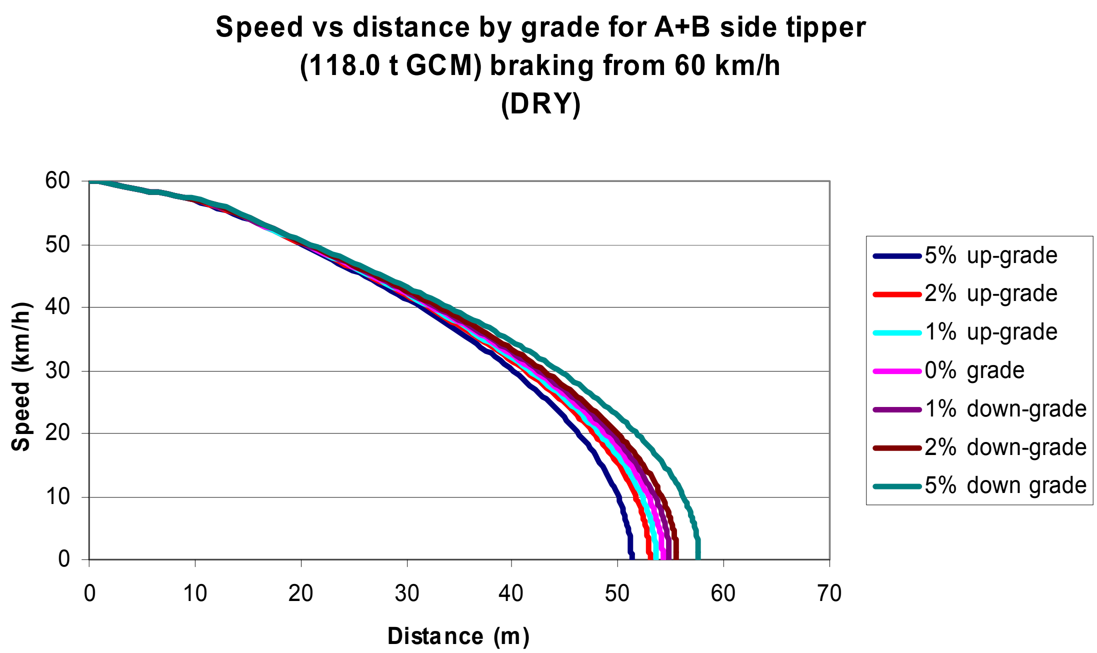

Figure 82 A+B side tipper (118.0 t GCM) from 60 km/h (DRY)

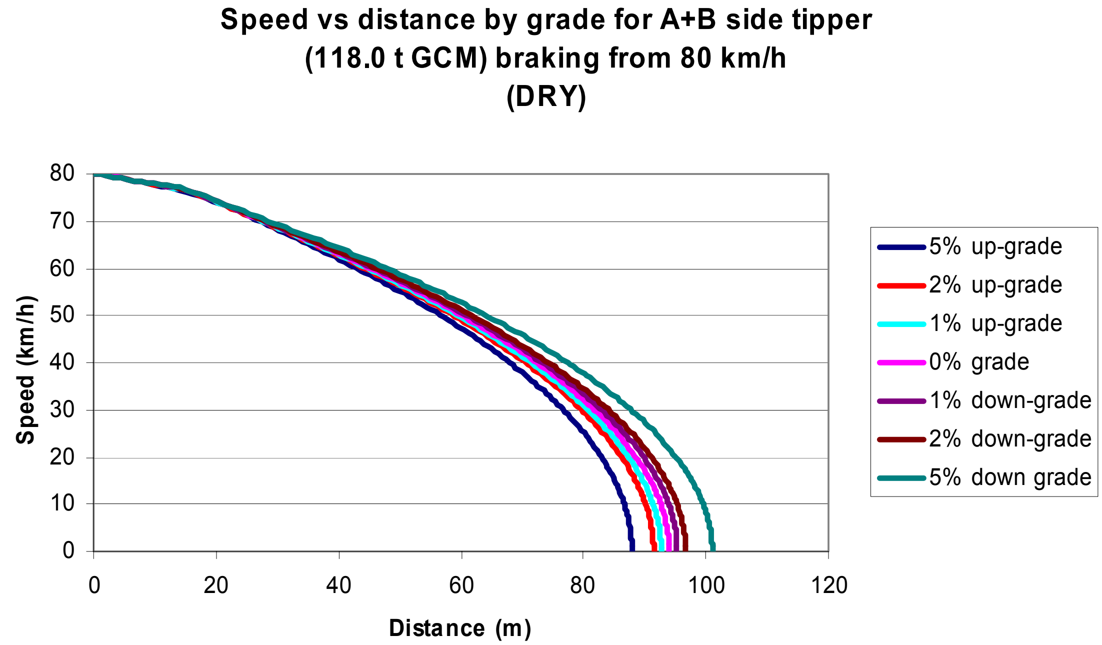

Figure 83 A+B side tipper (118.0 t GCM) from 80 km/h (DRY)

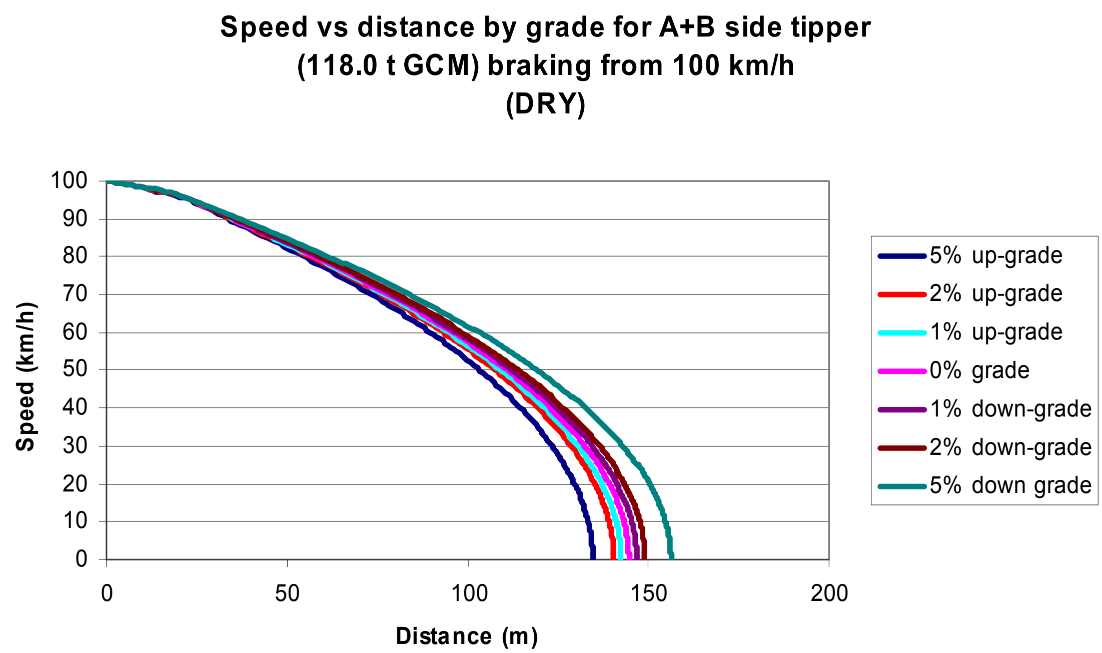

Figure 84 A+B side tipper (118.0 t GCM) from 100 km/h (DRY)

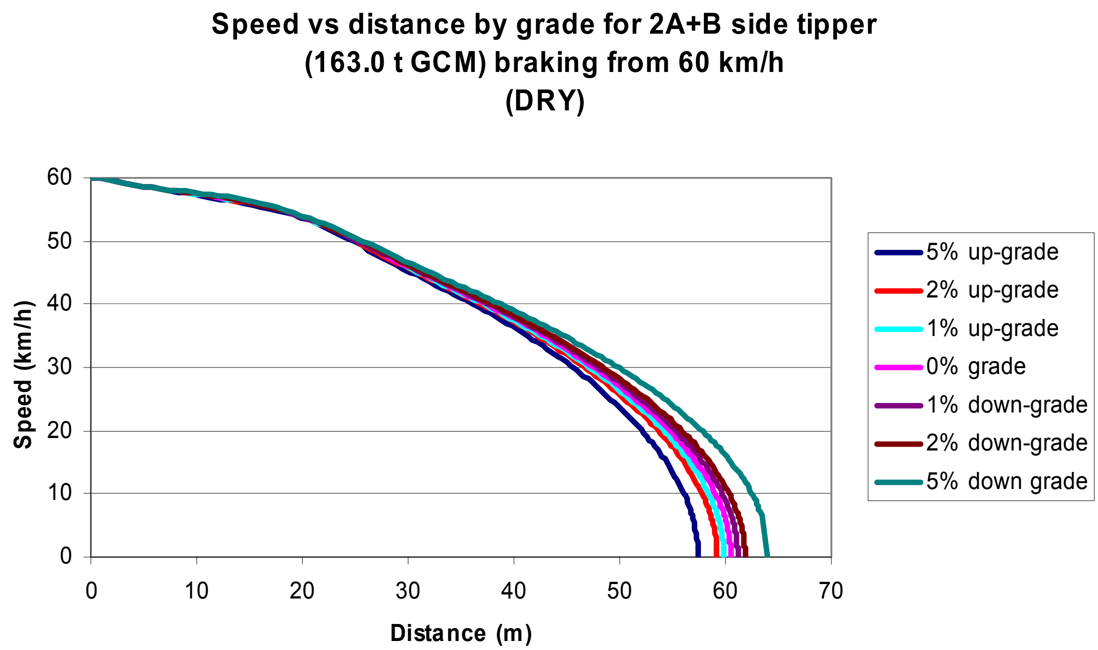

Figure 85 **2A+B side tipper (163.0 t GCM) from 60 km/h (DRY)**

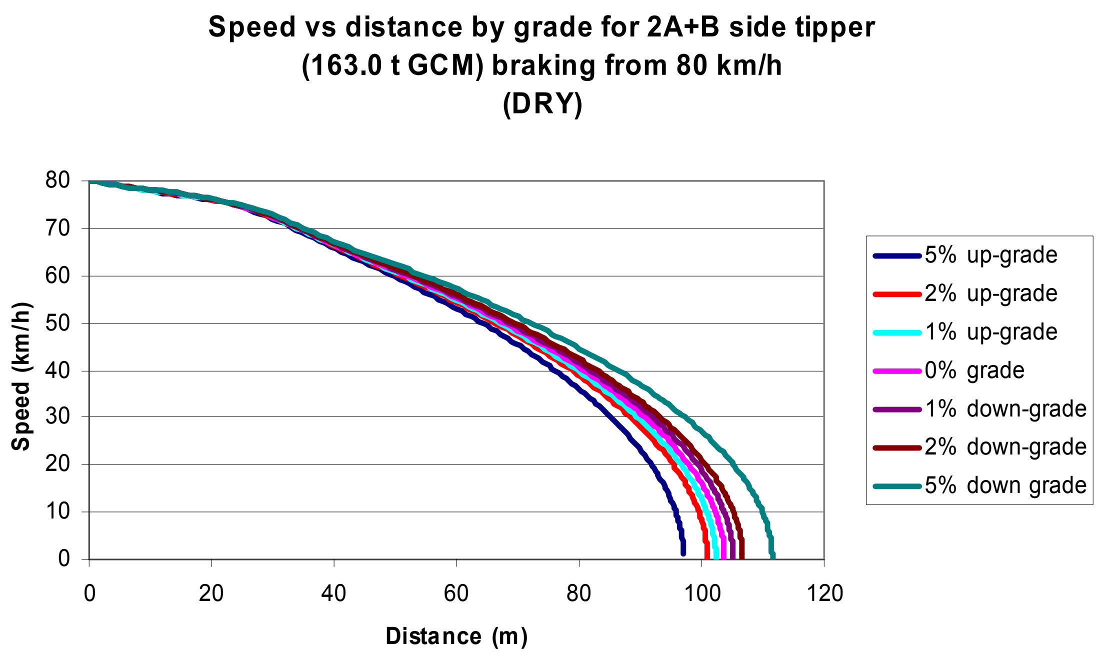

Figure 86 **2A+B side tipper (163.0 t GCM) from 80 km/h (DRY)**

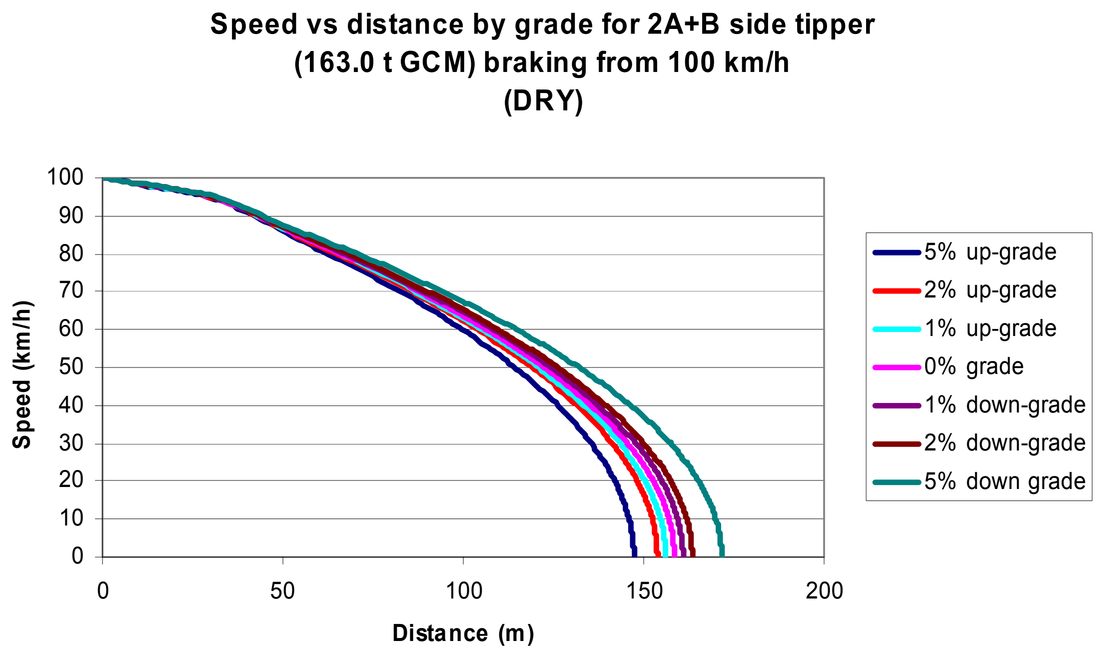

Figure 87 2A+B side tipper (163.0 t GCM) from 100 km/h (DRY)