Field trials to evaluate the acceleration and deceleration performance of heavy combination vehicles

By Rob Di Cristoforo, Engineer, Roaduser Systems Pty Ltd
Dr Peter F Sweatman, Managing Director, Roaduser Systems Pty Ltd
Brian Kidd, Road Safety Manager, Main Roads Western Australia

Enquiries: Rob Di Cristoforo (rob@advantia.com.au, M: 0409 525 959)

Abstract

This paper presents the findings of recent field trials to evaluate the acceleration and deceleration performance of a range of heavy combination vehicles typically operating in Western Australia. The acceleration and deceleration performance of heavy combination vehicles needs to be considered for the safe design of roads and traffic control systems. Particular design considerations such as clearance times and sight distance provisions at level rail crossings are primarily affected by the reduced performance of heavy combination vehicles in comparison with the performance of typical passenger cars. Tests carried out during the recent trials include acceleration from rest and deceleration from initial speed to determine performance measures such as time to travel distance, time to reach speed, distance to reach speed, stopping distance from initial speed and average acceleration/deceleration for a set of test vehicles ranging in gross mass from 44 to 166 tonnes.

Introduction

Roaduser Systems Pty Ltd was commissioned by Main Roads Western Australia to carry out field trials to evaluate the acceleration and deceleration performance of a range of heavy combination vehicles typically operating in Western Australia. The testing was carried out in Perth on 9 – 13 April, 2004. A section of the Great Eastern Highway Bypass 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 suitable for the acceleration and deceleration tests.

A set of heavy combination vehicles was assembled for the test program, which included various body types, prime mover makes, engines, gearboxes and gross combination masses (GCMs). Table 1 lists the details of the test vehicles in order of increasing GCM.

Table 1: Details of test vehicles

Vehicle configuration		Body type	Prime mover make	Engine power (HP)	Gearbox	GCM (tonnes)
1	Prime mover and semi-trailer	Livestock	Kenworth	600	18 speed	43.85
2	Prime mover and semi-trailer	End tipper	Mack	470	18 speed	47.00
3	Prime mover and semi-trailer	Side tipper	Kenworth	600	18 speed	47.85
4	B-double	Container	Volvo	420	14 speed	52.75
5	Truck-trailer	End tipper	Volvo	420	14 speed	60.30
6	B-double	Livestock	Kenworth	600	18 speed	61.90
7	Double road train	End tipper	Mack	470	18 speed	84.80
8	Double road train	Side tipper	Kenworth	600	18 speed	89.05
9	A+B (AB-triple)	Side tipper	Kenworth	600	18 speed	106.65
10	A+B3 (ABB-quad)	Container	Mack	600	18 speed	111.75
11	Triple road train	Livestock	Kenworth	600	18 speed	115.85
12	Triple road train	Livestock	Western Star	600	18 speed	117.90
13	Triple road train	Livestock	Western Star	600	18 speed	118.40
14	2A+B (AAB-quad)	Side tipper	Kenworth	600	18 speed	147.85
15	2A+B (AAB-quad)	Side tipper	Kenworth	600	18 speed	166.20

Test and analysis procedures

The test procedures adopted for the study were based on research previously conducted by Haldane [1] and comments from the Queensland Department of Main Roads, with certain differences as outlined in the following sections.

Acceleration tests

Drivers were instructed to engage first gear and wait for a verbal signal to begin accelerating. A 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 for subsequent analysis.

Deceleration tests

A test layout similar to that illustrated in Figure 1 was set up on the test site. 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.

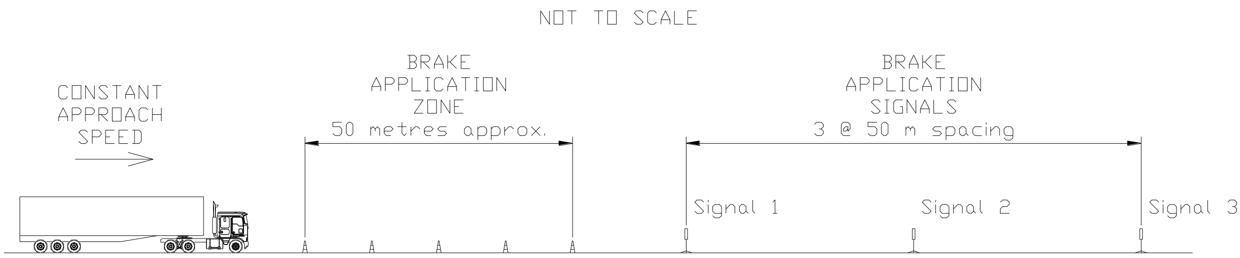

Figure 1: Layout of test site

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.

Simulation modelling

For each test vehicle, a computer simulation model was constructed and calibrated to match 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. The calibrated simulation models could then be used to generate results for various upgrades and downgrades.

Analysis of results

Acceleration tests

Correlation analysis

The effect of GCM on acceleration performance was first examined in terms of its effect on:

- 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. The analysis showed that there are vast differences in the sensitivity to GCM for the range of measures. A summary of GCM-sensitivity is provided in Table 2.

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.

Table 2: Sensitivity of performance measures to GCM

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

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 to 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, which is summarised in Table 3.

Table 3: Acceleration reaction time summary

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**

The average reaction time of 3.24 seconds is not to be confused with driver perception-reaction time; acceleration reaction time, as defined in this paper, includes the time delay due to clutch engagement.

Time to cover distance

Time to cover distance was found to be the measure least sensitive to GCM. The acceleration performance measure in the national Performance-Based Standards project [2] is a specified distance-time trajectory, which has been quantified simply in this study as the time to travel 100 m from rest.

Figure 2 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. The acceleration performance levels required by PBS are also shown on the chart, however the performance-based standard requires that acceleration reaction time is not included.

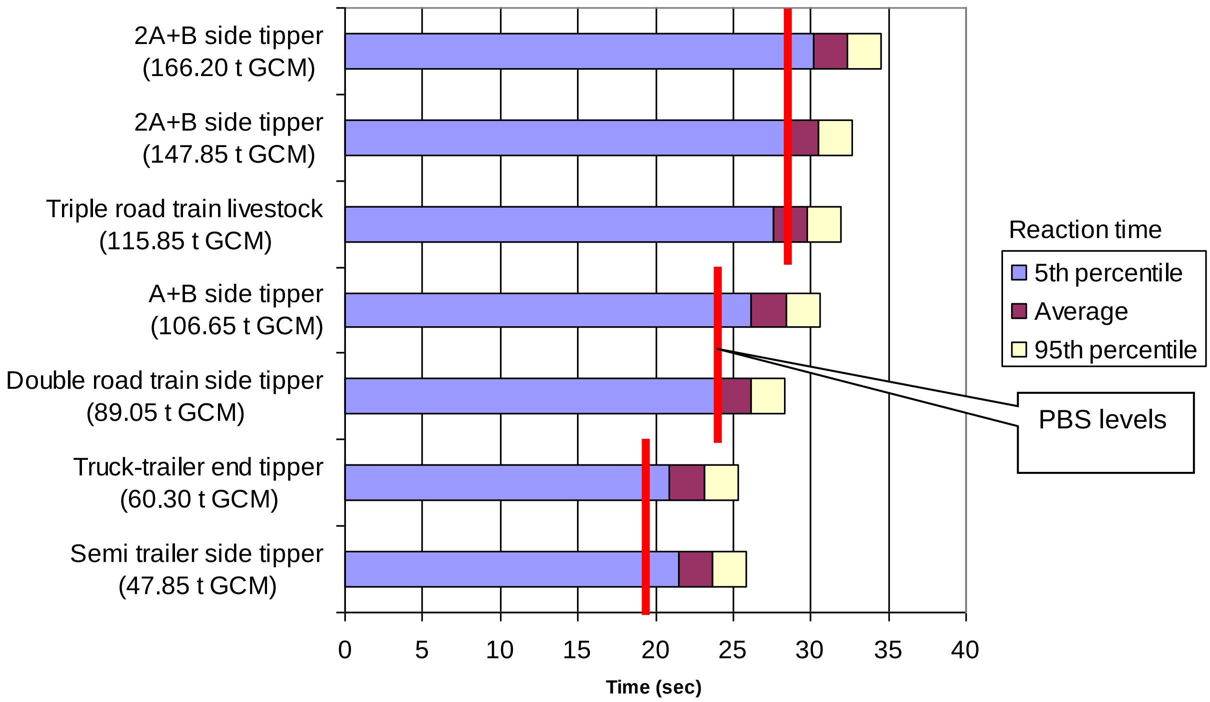

Figure 2: Time to travel 100 m by vehicle

Time to reach speed

Figure 3 shows the results obtained for time to reach 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.

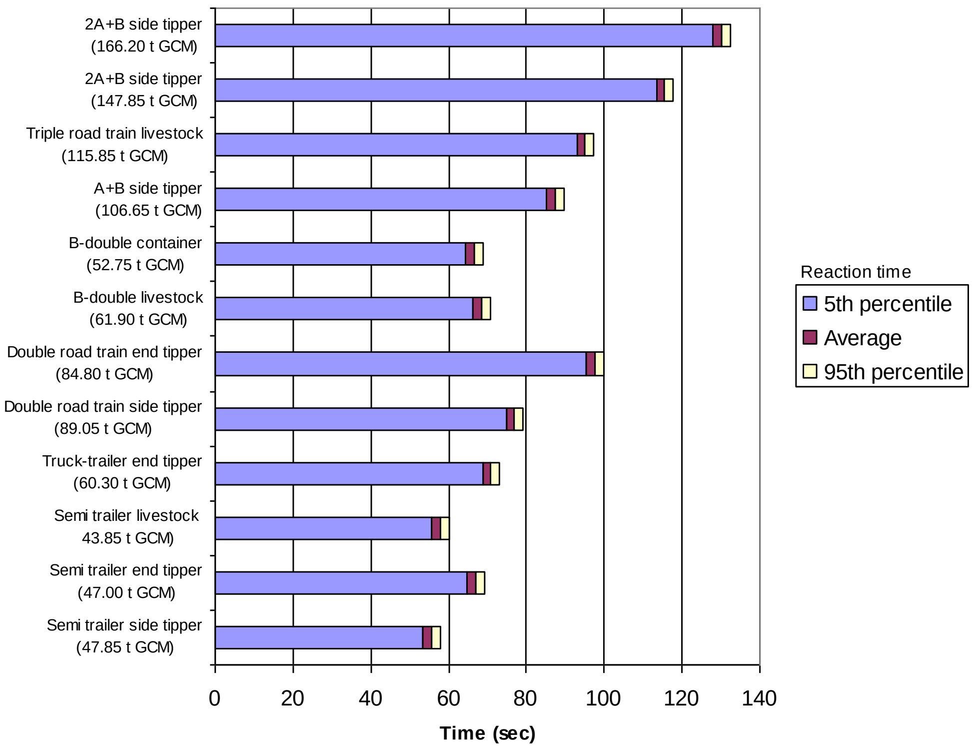

Figure 3: Time to reach speed of 60 km/h by vehicle

Distance to reach speed

Figure 4 shows the results obtained for distance to reach 60 km/h. This measure is not affected by starting reaction time, but is affected significantly by GCM.

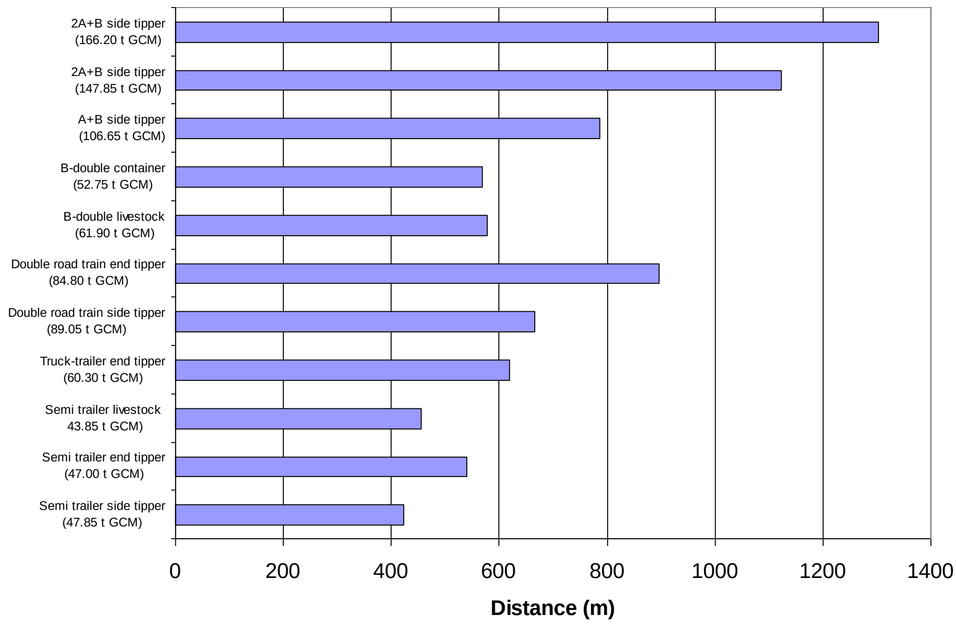

Figure 4: Distance to reach speed of 60 km/h by vehicle

Deceleration tests

Correlation analysis

The effect of GCM on deceleration performance was observed using the same methods as for the acceleration tests.

Figure 5 shows an example (stopping from 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.

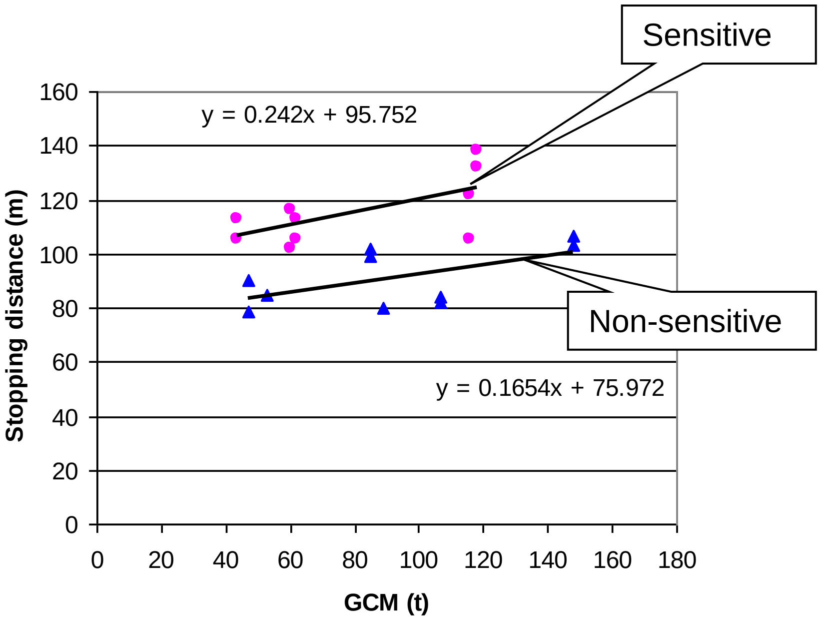

Figure 5: Stopping distance from initial speed of 60 km/h vs GC

Provided all axles are laden with similar mass, 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.

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 4.

Table 4: 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**

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.

Stopping distance

Figure 6 shows the results for stopping distance from 60 km/h. 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.

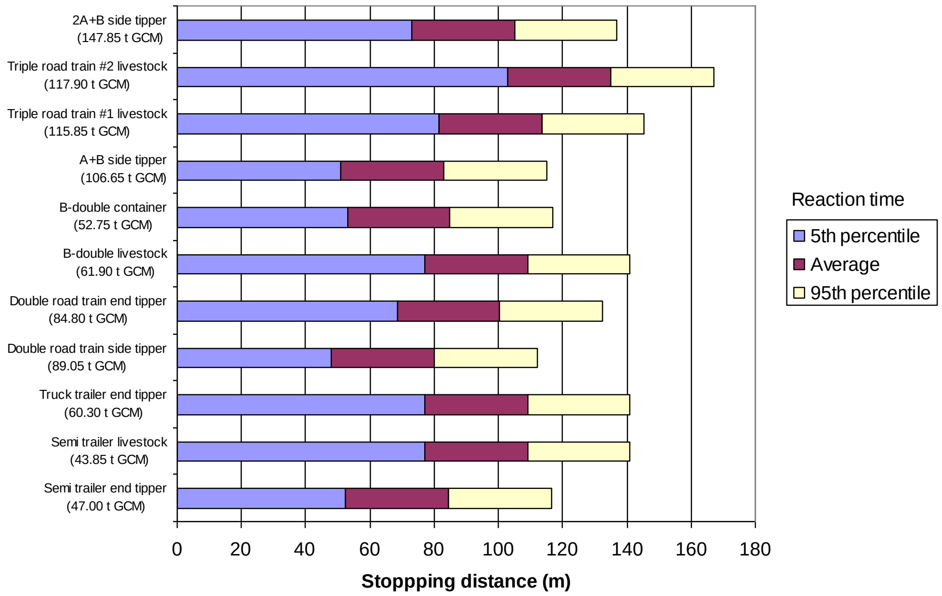

Figure 6: Stopping distance by vehicle from initial speed of 60 km/h (DRY)

Effect of available friction (wet road)

Stopping distances measured from both dry and wet road tests were compared to arrive at a “Wet Correction Factor” (WCF) for each test. 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 7 shows a plot of the average WCF obtained for each initial test speed. The relationship is linear with good correlation.

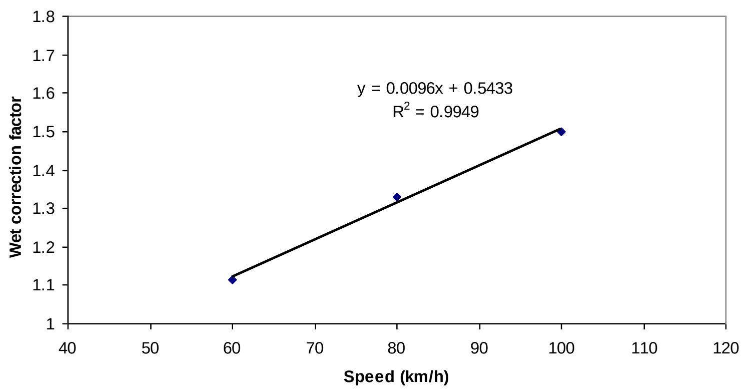

Figure 7: Wet correction factor as a function of initial speed

It can be concluded from Figure 7 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.

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 perception-reaction time and the vehicle's mechanical delay in beginning to move forward (due to clutch slip time, etc).

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 5 and Table 6, 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 6. The reaction time component is then added if it is required to account for reaction time effects in either acceleration or deceleration.

Table 5: 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 6: 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						

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.

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 5 and Table 6, based purely on the test results of innovative vehicles in the 120 – 180 tonne GCM range.

References

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

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