Transport Research Laboratory

The likely effects of permitting longer semi-trailers in the UK: vehicle specification performance and safety

Final Report

by I Knight, T Robinson, B Robinson, T Barlow, I McCrae (TRL) & A Odhams, R L Roebuck, C Cheng (Cambridge University)

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Background

Previous research (Knight *et al.*, 2008) investigated the likely effects of permitting longer and/or longer and heavier vehicles in the UK and found that it was uncertain whether the larger options assessed would produce a net benefit, with the potential to bring significant benefits within the road sector but also with the potential to require substantial investment in parking facilities and for adverse environmental effects as a result of modal shift from rail to road. However, the report did suggest that there could be worthwhile overall benefits from permitting a modest increase in the length of semi-trailers.

The DfT decided that as part of its overall work on freight strategy, further research would be undertaken to consider in detail the feasibility and likely effects of longer semi-trailers, if permitted. A consortium led by WSP and including MDS Transmodal, TRL, and Cambridge University was appointed to undertake the work, which included peer reviews by MIRA, VSRC, Heriot-Watt University and Preston Solutions.

The research was constrained to consideration of length increases up to a maximum of 2.05m and candidate vehicle configurations that would be capable of meeting all existing regulations (other than length). This would mean an increase in semi-trailer length from around 13.6m to no more than 15.65m, which would provide the same loading length as a rigid truck/drawbar trailer combination and represents the limit of what could be achieved under EU rules without the risk of having to accept longer combination vehicles. This would translate to an increase in overall length from 16.5m to around 18.55m. No increase in maximum permitted mass was to be considered.

Objectives

The primary objective of the study was to establish whether the introduction of longer semi-trailers would be likely to deliver overall economic, environmental and societal benefits or dis-benefits. In order to determine this, the work examined:

- The extent to which longer semi-trailers would be used by different freight sectors and journey types;
- What configuration of longer articulated vehicle would be most used and for which types of movements, taking into account any new safety risks;
- The effect on road networks and other modes;
- The overall environmental effect;
- The effects on injury accidents;
- Compatibility with existing infrastructure;
- The economic implications.

The work began in June 2009 and this report describes all of the findings related to vehicle specification, vehicle performance (manoeuvrability and dynamics), environmental effect (fuel consumption and emissions) and safety (target populations and accident involvement rates). Research to investigate the freight, logistics, and economics aspects has been reported separately.

Conclusions

The main conclusions of the research are:

1) The cost and mass implications of longer semi-trailers have been well defined in cooperation with the vehicle industry and increasing the length of semi-trailers to 15.65m would be likely to increase unladen mass by between approximately 575kg and 1,750kg. Capital costs could increase by between about £3,300 and £7,200.

Both would depend on the level of steering technology applied and cheaper, lighter solutions would be available for length increases of less than 2.05m.

2) Bridge loading and pavement wear effects have not been studied in detail because the previous study (Knight *et al*, 2008) confirmed that increased length without increased GVW or axle weight would cause no adverse bridge loading effects and would have only marginal effects on structural pavement wear from vertical loading. However, the review has identified theoretical evidence to suggest that steered trailer axles reduce pavement wear caused by turning HGVS, although there was insufficient data to allow this to be quantified.

3) Simulation results predicted that increasing the length of semi-trailers would produce a small increase in the fuel consumed (up to 1.8%) and consequent tail pipe emissions per vehicle km at full load. This is considered against an increase in pallet capacity of approximately 15% and a decrease in payload mass capacity of up to approximately 5%. There is also evidence to suggest that steered axles on trailers can substantially reduce tyre wear, which would reduce the emissions associated both with their manufacture (e.g. CO_2) and wear (e.g. particulates).

4) Increasing vehicle length by more than about 0.4m (to 16.9m) with fixed, closely coupled trailer axles is only possible within current axle load and manoeuvrability regulations if the maximum load carried is reduced (assuming uniformly distributed load). An 18.55m vehicle would be possible if the GVW were reduced from 44 to 38 tonnes. However, this is only possible because the existing legislation allows semi-trailer manoeuvrability to be approved by numerical methods and no tailswing limit is applied. Longer, fixed axle vehicles at reduced weight will have much greater tail swing than current vehicles (more than double, from 0.17m to 0.37m, for a 17.5m vehicle and approximately 4 times, from 0.17m to 0.67m for an 18.55m vehicle compared with the baseline).

5) The appropriate use of existing (non active) steering axle technology can allow vehicles to comply with all existing regulations at a GVW of 44 tonnes and a length of up to 18.55m (semi-trailer length 15.65m) but the tail swing produced in a “drive in”[1] roundabout manoeuvre will be much greater than for current vehicles (around 0.6m, depending on specific design, compared to the existing 0.17m). Prototype active steer systems have demonstrated the potential to allow 18.55m vehicles at 44 tonnes whilst reducing tail swing to near zero.

6) Longer vehicles that make use of steering axles to achieve manoeuvrability and axle load compliance will tend to have longer wheelbases. Those using fixed axles and reduced weight will have wheelbases similar to existing articulated vehicles.

7) The stability of vehicles travelling at speed is more sensitive to wheelbase than to length:

   a) Vehicles that achieve increased length by increasing their wheelbase will be more susceptible to crosswinds than existing vehicles (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 10% increase in load transfer ratio during crosswinds compared to a 16.5m, 8m wheelbase vehicle). They will also have a slightly worse rollover threshold in steady state cornering than those with shorter wheelbases (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 0.75% poorer steady state rollover threshold compared to a 16.5m, 8m wheelbase vehicle). However, vehicles with a longer wheelbase will tend to have better dynamic performance (e.g. path error, rearward amplification etc.) than existing vehicles in transient manoeuvres such as a lane change.

[1] Two manoeuvrability “roundabout” tests are defined in Directive 97/27/EC. The “Drive In” test involves starting while moving forward in a straight line and then turning into a circular path. The “Steady State” test involves starting from rest with the wheels so directed that the vehicle is travelling on the circular path as soon as it moves away from rest. The latter typically produces much larger values of measured tail swing.

b) Vehicles that achieve increased length with shorter wheelbases similar to existing articulated vehicles (i.e. increasing rear overhang) will tend to be significantly less stable in transient manoeuvres such as a lane change (e.g. an 18.55m vehicle with 8m wheelbase would display a 40% increase in path error and a 15% increase in rearward amplification compared with the standard vehicle). However, the steady state rollover threshold and susceptibility to cross winds would be comparable to existing vehicles

8) The analyses suggest that it would be very difficult for a longer vehicle to provide an improved performance than an existing vehicle in every metric considered and that there are no combinations where the performance is reduced in all metrics at the same time – there is a trade-off based on wheelbase such that the metrics which are adversely affected are often accompanied by metrics where there is an improvement. This means that overall there can be net performance improvements relative to existing vehicles. Where individual reductions in performance are predicted these can be mitigated or improved by the imposition of design restrictions or new performance standards that force the use of new technology. For example, a height limit of around 4.6m would allow 18.55m vehicles to have approximately the same high speed stability performance as a 16.5m vehicle at 4.9m height, while electronic stability control would be expected to mitigate the risk associated with reduced rollover stability.

9) The findings of the simulation work helped identify three regulatory possibilities:

   i) Retain existing length limits (do nothing)

   ii) Increase length, require compliance with all other existing regulations

   iii) Increase length, require longer vehicles to match or exceed actual performance of existing vehicles

10) Within the regulatory constraints of possibility number ii) it would be possible for industry to react in a number of different ways:

   a) Low tech – A maximum length of up to 18.55m would be possible with a wheelbase of approximately 8m without steering axles. However, the maximum load carried would need to be limited to 38 tonnes to avoid trailer axle overload. Forty tonnes would be possible at a length of up to around 17.8m. Both configurations would exhibit reduced stability in dynamic manoeuvres such as lane changes, for example, the path error exhibited by the 18.55m configuration would be in excess of 33% greater than for an existing 16.5m vehicle. Tail swing would be increased by approximately 215% for a 17.8m vehicle and by approximately 400% for an 18.55m vehicle.

   b) Medium tech – Vehicles could be up to 44 tonnes GVW and up to 18.55m overall length if existing steer axle technology was to be used. Such vehicles would increase tailswing by approximately 350% (in a “drive in” manoeuvre), suffer a small increase in the susceptibility to cross winds of approximately 5% at 17.5m and approximately 10% at 18.55m, with a reduction of just under 2% in steady state rollover threshold, compared with a 16.5m vehicle. However, the other vehicle dynamics parameters would match or better those of the standard 16.5m vehicle, for example a reduction of 7% in the rearward amplification and a slight reduction in cut-in during low speed manoeuvring. The high speed performance assumes that like all existing systems the steer axles are locked at speed. New regulation may be required to enforce this condition.

11) There are possible deficiencies in current regulation, for example, manoeuvrability regulations are intended to limit tailswing for all vehicle types but trailers are approved by calculation. This produces existing vehicle combinations that exhibit tailswing well within the limits applied for rigid trucks and buses. However, if the formula were applied to longer semi-trailers it would prevent an increase in

wheelbase limiting industry to the low tech approach described above. These low tech vehicles could exceed the tailswing limits applied to other vehicle types. If it was considered desirable to allow the medium tech approach and to enforce the spirit of the existing legislation then it would be necessary to introduce a specific test for an articulated combination with an appropriate tailswing limit (either 0.6 for a drive in test, comparable to buses, or 0.8 in a steady state test comparable to rigid trucks) and to prescribe the test speed for evaluation (e.g. 6km/h). Similarly, all existing steered trailer axles are locked at high speed but this is not a regulatory requirement. If it was considered necessary to ensure that this could not change it would be necessary to introduce either a technology limiting requirement that steered axles were locked at high speed or a performance based requirement that the vehicle remained stable in a lane change (or similar dynamic) manoeuvre based on parameters such as load transfer ratio or rearward amplification.

12) Under regulatory possibility number iii), only one approach would be possible:

   a) High tech - Vehicles would need to be fitted with a new generation of active trailer steering systems, such as those described by Jujnovich et al (2008). Vehicles of up to 44 tonnes and 18.55m overall length (15.65m semi-trailer length) could be considered. Maximum length vehicles would have a 10% increase in load transfer during crosswinds and slightly less than 2% reduction in steady state rollover threshold compared with a 16.5m vehicle. However, tailswing could be almost eliminated and cut-in could be reduced, thus substantially improving low speed manoeuvrability in comparison with existing 16.5m vehicles, and it is possible that tuning the system could improve performance in high speed transient manoeuvres such as lane changes by around 20%.

13) If it was decided that regulatory possibility number iii) were to be implemented, this could be achieved by implementing a more stringent tail swing limit for an articulated combination (around 0.2m in a drive-in test at 6 km/h). Regulatory possibility iii) allows vehicles that match or exceed existing performance in all regulatory tests and in terms of overall net performance, including unregulated high speed stability metrics. However, within this some individual metrics, for example cross wind stability, can still be of a reduced standard compared with existing vehicles. Enforcing a condition where all individual metrics matched or exceeded existing performance would require either a height limit of around 4.6m (design prescriptive) or a dynamic stability and cross wind sensitivity test (performance based) evaluated in terms of parameters such as load transfer ratio.

14) It should be noted that the active steer system likely to be required for regulatory possibility iii) (high tech) may take in the region of 18 months to two years to develop for production and currently it appears that the system is outside the scope of the technical requirements of UNECE Regulation 79. Although Type Approval could possibly still be granted via an exemption for new technology, provided equivalent levels of safety can be demonstrated, an amendment to Regulation 79 may ultimately be required.

15) A conservative analysis has been undertaken to assess the potential casualty effects of these changes. This analysis has suggested that:

   a) Regulatory possibility ii) would be likely to result in a very small increase in the casualty risk per vehicle km but so small as to be immeasurable in casualty data after implementation. Introducing a limit that reduced slightly the height of the tallest vehicles would be enough to eliminate this increase in risk.

   b) Regulatory possibility iii) would be likely to result in a small reduction in the casualty risk per vehicle km but again this is likely to be so small as to be immeasurable.

1 Introduction

Previous research (Knight et al., 2008) investigated the likely effects of permitting longer and/or longer and heavier vehicles in the UK and found that the overall benefits of the larger options assessed were uncertain, with the potential to bring significant benefits within the road sector but also with the potential for adverse environmental effects, principally as a result of modal shift from rail to road, and potentially very large investments in improved parking facilities. However, the report did suggest that there could be worthwhile benefits from permitting a modest increase in the length of semi-trailers.

When this previous research was published, the Secretary of State for Transport announced that so-called *"super lorries"* would not be permitted *"for the foreseeable future"* but that further consideration would be given to allowing longer semi-trailers. The DfT, therefore, decided that as part of its overall work on freight strategy, further research would be undertaken to consider in more detail the feasibility and likely effects of longer semi-trailers, if permitted. A consortium led by WSP and including MDS Transmodal, TRL, and Cambridge University was appointed to undertake the work, which included peer reviews by MIRA, VSRC, Heriot-Watt University and Preston Solutions.

The main constraints applied to this research were that it should consider a length increase up to a maximum of 2.05m and that any candidate vehicle configurations must be capable of meeting all existing regulations (other than length). This would mean an increase in semi-trailer length from around 13.6m to no more than 15.65m, which would provide the same loading length as a rigid truck/drawbar trailer combination and represents the limit of what could be achieved under EU rules without the risk of having to accept longer combination vehicles. This would translate to an increase in overall length from 16.5m to around 18.55m. The effects of intermediate length increases, based on pallet size, were also considered. However, an increase in maximum permitted mass was not considered at any vehicle length.

The primary objective of the study was to establish whether the introduction of longer semi trailers would be likely to deliver overall economic, environmental and societal benefits or dis-benefits. In order to determine this, the work examined:

- The extent to which longer semi-trailers would be used by different freight sectors and journey types (e.g. primary, secondary and tertiary distribution);
- What configuration (e.g. magnitude of length increase, wheelbase, overall height, need for steering axles etc) of longer articulated vehicle would be most used and for which types of movements taking into account any new safety risks (e.g. tail-swing and stability);
- The effect on road networks and for the current and potential use of non-road modes;
- The overall environmental effect including but not restricted to CO_2 emissions across freight modes as a whole;
- The effects on fatal, serious and slight injury accidents;
- Compatibility with existing infrastructure – including all of the road network, distribution centres and retail outlet loading bays;
- The effect on the cost of transporting goods by road and any wider economic effect.

The work began in June 2009 and this report describes all of the findings related to vehicle specification, vehicle performance, environmental effect and safety.

Research to investigate the freight, logistics, and economics aspects has been reported separately.

2 Vehicle specification

2.1 Research methods

A very wide diversity of semi-trailers exists in the UK, featuring a wide range of mass, length, axle configurations, and steering characteristics. A two stage approach was used in order to allow a simple comparison of the performance of longer vehicles in terms of manoeuvrability, stability, safety and economy. First, the properties of “typical” existing vehicles were defined. Second, the ways those properties would change if the length were to be increased were identified (while continuing to comply with all other regulatory requirements).

The properties were defined by a combination of a review of scientific and sales/promotional literature and directly gathering evidence from the trailer and axle manufacturing industries. The exercise of directly gathering evidence from the industry was focussed on obtaining objective vehicle data wherever possible in preference to general opinion on likely effects. A total of 11 trailer manufacturers, 3 axle/steering system manufacturers and one vehicle design consultancy were contacted. The questions asked varied according to the recipient but they were typically asked to provide the following information:

- Basic vehicle/trailer mass and geometric information (e.g. unladen/laden mass, wheelbase, axle spacing, tyre sizes etc) for existing vehicles including single deck, double deck and hi-cube. The focus should be on curtain-sided, box and refrigerated vehicles.
- Examples of the “typical” cost of those trailers.
- Where possible, data on the centre of gravity position and moments of inertia.
- Equivalent information for longer semi-trailers (up to 2.05m longer than standard), if manufactured.
- If no longer semi-trailers are manufactured, then an estimate of the increase in unladen weight and cost expected if the length of a standard 13.6m semi trailer were increased by 2.05m, with no other significant changes (i.e. same number of axles, no additional steering axles, same GVW etc).
- For respondents involved in manufacturing steering axles for trailers, or fitting such axles to their trailers, the following additional information was requested:
    - what type(s) do you use (e.g. self steer, command steer passive (e.g. mechanically linked to articulation angle), command steer active (e.g. computer controlled), steered bogie)?
    - A technical description of their characteristics.
    - How much cost do they add in comparison to standard fixed axles (all other variables being equal)?
    - How much do they add to the trailer unladen weight in comparison to standard fixed axles (all other variables being equal)?
    - Any available evidence of the effect of the steered axles on tyre wear, tyre life and fuel consumption.

Constructive replies were received from 7 of the 14 companies contacted and a face to face meeting was held with one trailer manufacturer who was constructing a prototype longer semi-trailer. In addition to this, informal discussion with industry representatives took place at Freight Transport Association (FTA) and Road Haulage Association (RHA) events.

2.2 Defining the baseline vehicles

In line with the scope of the research, as defined in the original tender documents, the main baseline vehicles for comparison were considered to be 6 axle articulated vehicles that would typically have box or curtain-sided bodies for use in volume constrained sectors such as fast moving consumer goods (FMCG). The scope allowed for consideration of standard height vehicles, assumed to be 4m tall in line with EU regulation, and double decked vehicles, assumed to be 4.9m tall approximating the practical maximum that can be achieved within UK bridge infrastructure constraints. Mass data was obtained for 8 standard vehicles and 8 double decked vehicles. All were tri-axle semi-trailers and none had steered axles. The results are shown Table 1.

Table 1. Unladen mass of existing tri-axle, 13.6m semi-trailers

Trailer type		Unladen mass (kg)		
		Mean	Min	Max
Single deck		6,343	5,200	6,910
Double deck	Fixed deck	9,843	7,150	16,500
	Lifting deck	12,735	9,000	15,500
	Overall	11,835	7,150	16,500

Compared with the variety of different semi-trailers in use, the sample included here is small, so the results cannot be expected to be perfectly representative of the whole sector. However, it is considered that the mean results are sufficiently representative of typical vehicles to provide a robust examination of the relative performance of longer vehicles.

It should be noted that the unladen mass of a double decked vehicle can vary widely, particularly depending on the manner of implementing the extra deck. This can range from simply adding a uniform deck in a single fixed position (referred to above as fixed deck) and incorporating moveable decks. Moveable decks can range from simple sections that can fold away to allow operation as a single deck where required, through to complex multiple sections equipped with hydraulic lifts to allow the vehicle to be loaded from a standard single height loading dock without additional equipment at the depot. Such systems can carry a substantial payload weight penalty, in some cases sufficient to double the unladen weight of the trailer.

A similar exercise was undertaken to investigate the typical mass for a 6x2 tractor unit, based on 5 existing vehicles. The results are shown in Table 2.

Table 2. Unladen mass for a 6x2 tractor unit

Mean unladen mass (kg)	8,190
Minimum unladen mass (kg)	7,860
Maximum unladen mass (kg)	8,685

Rounding the means, and assuming that fixed and lifting double decks are used in equal numbers, results in estimated unladen combination weights for the reference vehicles of approximately 14.5t (single deck) and 20t (double deck).

The typical capital cost of a tri-axle semi trailer was identified based on the Road Haulage Association's standard cost tables (DFF International, 2009) as £19,000. No distinction is made between single and double decked semi-trailers.

2.3 Cost and mass implications of increasing length

The modelled cost and mass implications are shown in Table 3. The mass implications of increased length were derived by a combination of direct comparison of otherwise identical trailers (e.g. the Kogel Maxx and Big Maxx ranges) and estimates provided by trailer manufacturers. The price of new trailers is based only on estimates provided directly by the manufacturers.

Table 3. Cost and mass implications of increased length

		Mean	Min	Max
Single deck	Mass (kg/m)	192	77	231
	Cost (£/m)	514	150	942
Double deck	Mass (kg/m)	250	250	250
	Cost (£/m)*	590	-	-

* Estimated.

Only one company separately identified the mass implications for double decked variants and none separately identified the costs. Therefore, an initial estimate of cost effects has been made based on the best available other data. These estimates assume that increasing the length will not add any requirements in terms of lifting equipment for moveable decks and, therefore, will only involve the extra materials for the increased upper deck length and the additional 0.9m height at the top. This is supported by the mass information from one company suggesting only a small difference compared with single deck vehicles. It has, therefore, been assumed that the additional cost per metre for double decked vehicles would be approximately 15% greater than the industry estimate for single deck vehicles.

2.4 Characteristics of steered trailer axles

A wide range of steering systems is available for semi-trailers. These can be broadly categorised as follows:

- Fixed axle – no steering system
- Self steer
- Command steer
- Pivotal bogie
- Active steer

The basic principle governing the use of steered rear axles is that they reduce the effective wheelbase, thus reducing the "cut in" or swept path of the vehicle but increasing the out swing at the rear of the trailer. However, the exact effects of any individual implementation will depend on the position of the steered bogies and axles and the relationship between steer angle at the front axle and steer angles at the trailer axles.

2.4.1 Self steer

Jujnovich and Cebon (2002) state that self steering axles are the most widely used form of trailer steering and that the main advantages are their relative simplicity and low cost. The basic principle of self steer axles is that the centre line of the steered tyre is offset from the centre line of the king pin which is free to pivot, as shown in Figure 1, below.

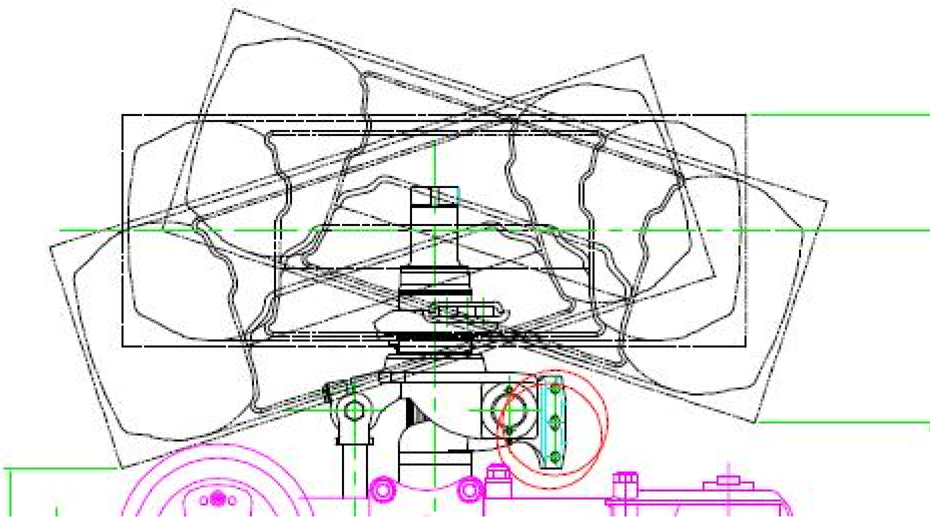

Figure 1. Self steer axle

This means that the tyre forces cause the wheel to align with the direction of travel. A predetermined level of resistance is typically built in such that the tyre forces have to exceed a certain threshold level before the wheel turns. The mechanism to achieve this varies and can include, for example, various pre-loaded springs, dampers or pressure bearings. The effect of this is that the tyres will generate the side forces required at low steer angles to maintain stability. Most systems will also include a locking function to prevent steering when reversing. The maximum steering angles that can be achieved do vary; 20 degrees is common (see for example, BPW (2007)) but up to 30 degrees is claimed by some manufacturers (e.g. http://kgi.ca/products/steeraxles.htm).

2.4.2 Command steer

Command steer systems steer the trailer in proportion with the articulation angle between tractor and semi-trailer. This can be achieved in a number of ways. The simplest (passive) systems are mechanical and involve fitting a moveable plate to the semi-trailer king pin. This turns with the relative movement of the fifth wheel and uses pushrods to translate that rotation into a steering action at the trailer axles. Typically where installation is difficult (e.g. space or geometric restrictions), the mechanical pushrods can be replaced by hydraulic systems. Examples of command steer systems are shown in Figure 2, below.

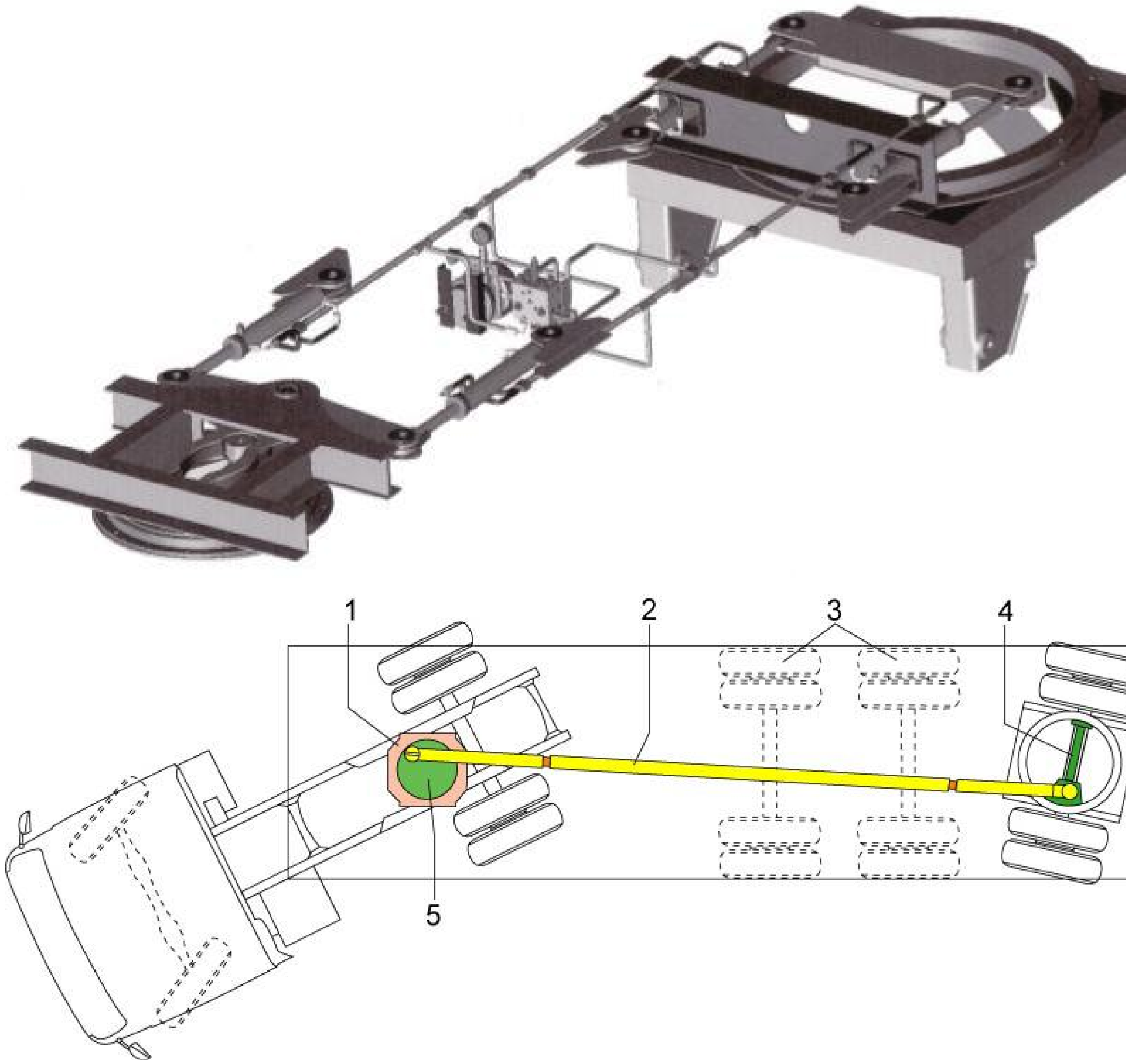

Figure 2. Examples of command steer systems, (Top Muldoon[2], bottom Tridec[3])

There is a single fixed relationship between the articulation angle and the steering angle at the road wheel and this is usually linear up to a maximum. However, the relationship varies. For example, one system might reach a maximum steering angle of 30 degrees at an articulation angle of 80 degrees but another system reaches a maximum of almost 25 degrees steering at an articulation angle of just 40 degrees. In general, command steer systems can achieve greater steering angles than self steer systems and the tyre side forces during low speed manoeuvring will also be lower because there is no “pre-load” to overcome in order to commence steering. However, the additional equipment tends to increase complexity, weight and cost. In order to maintain stability at higher speeds all systems feature some form of locking. This can either be a direct system interlock that acts to prevent steering above a certain speed threshold but can also be achieved by preventing any trailer steering at the small articulation angles that will be typical at higher speeds.

[2] http://www.muldoon.com/psteer-manual.pdf
[3] http://www.tridec.nl

2.4.3 Pivotal bogie

One significant variation on the command steer principle is to steer not only individual axles but the whole bogie set. This is known as a pivotal bogie and examples can be seen in Figure 3, below.

Figure 3. Examples of pivotal bogie systems from Trackaxle (left)[4] and Don-Bur / Silvertip design (right)[5].

Such systems typically operate on the same principle of linearly increasing the trailer steer angle in proportion to an increasing articulation angle. However, the revised geometry can have a greater effect in terms of moving the effective wheelbase relative to the bogie position. This tends to offer further reductions of cut in but tends to increase outswing (for a given bogie position) and represents additional complexity.

2.4.4 Active steer

All of the steering systems discussed above involve trade-offs between axle loads/load distribution, cut-in and rear out swing. A small number of researchers (e.g. Hata *et* al., 1989, Notsu *et al.*, 1991, Cheng & Cebon, 2007, Kharrazzi *et al.,* 2008) have been investigating the potential of active steering systems to offer further improvements in cut-in, without adverse effects on out swing, while also improving high speed stability. In this context, active steering means a command steer system where the linear relationship between articulation angle and semi-trailer steer angle, typically provided mechanically or hydraulically, is replaced by a more sophisticated non-linear control function provided electronically.

All of the research agrees that adopting such an approach can provide substantial improvements in low speed manoeuvrability (cut-in and out swing) while also improving stability at higher speed. Jujnovich & Cebon (2008) describe the development of control algorithms for active steering systems for articulated vehicles and found that systems could be developed that allowed the rear of the vehicle to track the path of the front of the vehicle at any speed and on any path. These could also be applied to multiple trailer vehicles. Jujnovich *et al.* (2008) describe implementing the active steering system on a prototype articulated vehicle[6]. The basic principle of the system is illustrated below, where it can be

[4] http://www.trackaxle.com.au/docs/Brochure.pdf
[5] http://www.silvertipdesign.com/
[6] Research and development of this novel technology was part funded by The Engineering and Physical Sciences Research Council (EPSRC) and UK industry (via the Cambridge Vehicle Dynamics Consortium)

seen that all three trailer axles are individually steered to different degrees in order to achieve perfect path following.

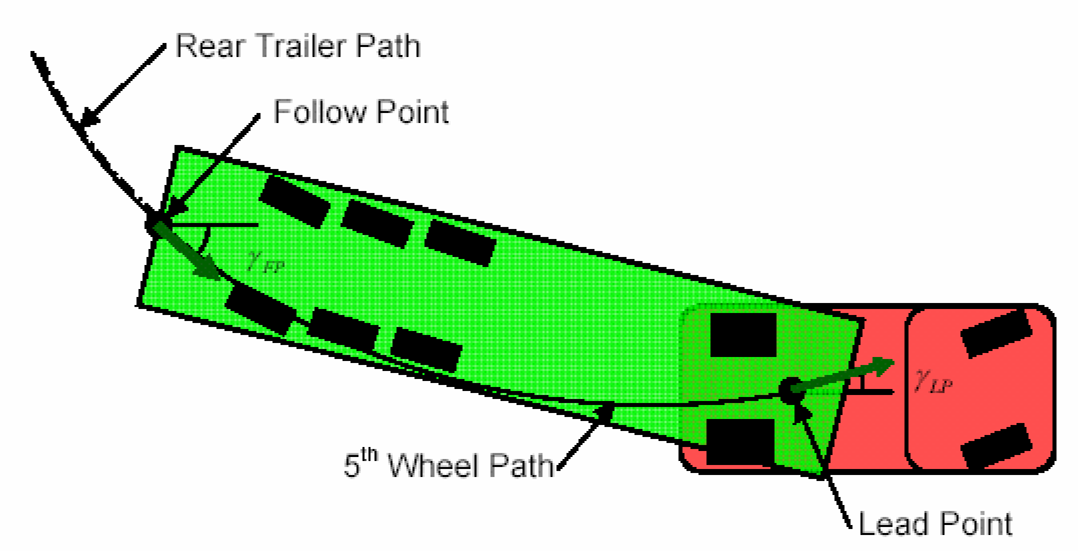

Figure 4. Active steering system (Jujnovich et al, 2008)

The active steering is achieved by electronically controlling separate electro-hydraulic actuators that act on each individual axle. It is understood that work is in progress to develop this concept into production systems, which could take somewhere in the region of two years, depending on the extent of predicted demand. In particular, trade-offs between performance and the number of actively controlled axles are being examined to investigate whether the cost and mass of the system can be reduced.

One potential barrier to implementation of this technology is that it appears that it could not gain the necessary approval to European steering regulations (UNECE R79), which states that the regulation does not apply to "*the electrical control of full power steering systems fitted to trailers*". It is possible that type approval could still be gained by using clauses in the framework Directive (2007/46/EC) intended to allow the approval of new technology where it can be demonstrated to offer at least equivalent levels of safety. If such technology is to be permitted or required, further investigation and possibly amendment of the regulations would be required.

2.5 Cost and mass implications of rear steer axles

The additional function and complexity of steered axle systems currently adds both mass and capital cost to a new semi-trailer. The typical effect on the mass of the vehicle has been estimated based both on published technical data for different axles and information provided directly by manufacturers and developers. The results are shown in Table 4.

Table 4. Additional mass for steering axles

System type	Additional mass (kg), compared with standard fixed axle		
	Mean	Min	Max
Self steer (one axle)	190	140	250
Command steer (One axle)	688	300	900
Command steer (Two axles)	1,145	1,040	1,280
Pivotal bogie	-	-	-
Active steer (Three axles)	1,250	1,250	1,250

It can be seen that the mass implications for steered axles span a considerable range depending on type. In fact this range could be greater because little information has been identified to date for the pivotal bogie system which might be expected to be the heaviest type. Sweatman *et al* (2003) cite a 12.3 tonne unladen weight for a flat-bed tridem semi-trailer equipped with a pivotal bogie being used as part of their tests. This implies a considerable additional weight, although it must be considered that this was for an Australian semi-trailer in excess of 15m long.

The active steering system currently refers only to the prototype system discussed previously and is, thus, a single sourced estimate of the likely mass in production form. The logic supporting this estimate was that the hardware of the system was broadly similar to the heavier command steer systems and that the mass would be toward the upper end of the range found for command steer. The main difference between the systems is in the control algorithm which is an electronic control with very low mass.

The estimated additional costs of steering axles are shown in Table 5.

Table 5. Additional capital costs of steered axles.

System type	Additional cost (£), compared with standard fixed axle		
	Mean	Min	Max
Self steer (one axle)	2,300	1,650	2,700
Command steer (One axle)	4,000	4,000	4,000
Command steer (Two axles)	6,600	-	-
Pivotal bogie	-	-	-
Active steer (Three axles)	6,000	-	-

For single command steer axles only one source of the capital cost was identified. It should also be noted that no information has been provided regarding the additional cost of a twin command steer system. It has, therefore been assumed that it will be approximately 1.65 times the single steer equivalent, which is the ratio between the masses of the twin and single steer systems.

The active steer system has again been estimated on the basis that it will fall toward the upper end of the range found for the command steer systems. In this case the value added part of the active steer system is in the control algorithm which will imply only relatively small additional unit costs if spread over significant production volumes. The only other change in cost is replacing some mechanical or hydraulic elements with electronic control units and sensors, which may not add significant costs. It can be seen that the mass and cost implications of active steer systems are relatively high. However, "perfect" path following is an ideal system that would perform considerably better than both current regulatory requirements and existing vehicles. It may be possible to design an active steer system that perhaps controlled just one axle that still improved performance but with reduced mass and cost implications.

In addition to the mass and capital cost effects, all semi-trailer steering axles claim the benefits of reducing rolling resistance, tyre wear and road wear. While fundamental engineering theory strongly supports the existence of such benefits, little objective evidence was found to enable the magnitude of the benefits to be rigorously quantified.

The theory demonstrates that when cornering, steered semi-trailers experience considerably less sideways scrub between the tyres and road. It is, therefore, clear that the benefits will vary depending whether the vehicle is driven typically on long straight roads or in urban environments requiring much low speed manoeuvring.

Evidence from an industry field trial suggests that in long distance driving a self steered axle approximately doubles tridem tyre life on average[7], while the gains could be substantially greater in urban driving. One manufacturer claims that where use is split 80% urban to 20% highway tyre life could be trebled by a command steer system[8] but are undertaking trials to define this more rigorously. Another manufacturer claims that for an urban tridem articulated vehicle, a pivotal bogie system could increase tyre life from between 15,000 and 20,000km up to 110,000km[9].

Coleman and Sweatman (2002) estimated that self steer axles would reduce tyre costs by 40% and command steer systems would reduce them by 50%. This appears broadly consistent with the trial data for self steering axles in long distance transport. Based on an assumption that longer semi-trailers, if permitted in the UK, would mainly be used in longer distance operations, it is, therefore, assumed that tyre life is extended by a factor of 1.65 for self steer axles and for both command steer and active steer systems it is increased by a factor of 2. Compared with some of the claims and the possibility of increased urban use, this estimate could be considered conservative, but this is in the absence of rigorously reported scientific evidence of the effects.

Data regarding the effects on rolling resistance and fuel consumption is even more limited. BPW (2007) claim that the use of a self steered axle saves 10,000 litres of fuel for every million km driven in suburban or delivery traffic. However, this does not necessarily translate to an equivalent average reduction in all traffic and savings would be expected to be much lower in motorway driving than in suburban or delivery traffic.

No quantifiable evidence has been identified concerning the effects on reduced damage to roadways. It has, therefore, been necessary to assume that these effects are negligible, which is likely to represent a conservative approach.

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[7] Derived from data presented at http://www.bpw.co.uk/self-steer.htm
[8] http://www.hollandtrade.com/made-in-holland/pdf/2008_07_Automotive_EN.pdf
[9] http://www.trackaxle.com.au/docs/Logistics_Impact.pdf

3 Vehicle performance

3.1 Research methods

3.1.1 Vehicle dynamics

The vehicles' dynamic behaviour was investigated by computer simulation using simplified mathematical models. The models were adapted from existing models of a 5 axle combination. Two were created:

- Low speed model – 4 degree of freedom (DOF) yaw plane model used to assess;
    - Distribution of load amongst the axles
    - Manoeuvrability (cut-in and outswing)
- High speed model – 11 DOF yaw-roll model used to assess:
    - Transient lane change (rearward amplification (RA), path error (PE), load transfer ratio (LTR))
    - Steady state circular behaviour (Speed at rollover; LTR=1)
    - Cross wind response (PE, LTR)

The models were calibrated against existing test data and were found to perform reliably. However, it must be remembered that these are simplified models and some difference between simulation and reality is to be expected. Although such differences will affect the absolute values of the results they should have a limited effect on relative comparisons between the different variables simulated.

The analysis was quite complex because of the large number of variables to be considered:

- Length from 16.5m to 18.55m
- Wheelbase from approximately 7m to 10.5m
- Type of trailer axle (fixed, self steer, command steer, active steer)
- Gross Vehicle Weight (GVW)
- Height of trailer (4m and 4.9m)
- Load condition (empty/full)

The number of model runs was minimised by eliminating permutations of variables that were unnecessary. For example, no assessments were undertaken of the cross wind response in the fully laden condition because it is well known that the unladen condition is the worst case. The results of the sensitivity analysis are plotted in a simple, coherent and consistent manner against axes of vehicle length and wheelbase. An example of the scales is shown in Figure 5, below.

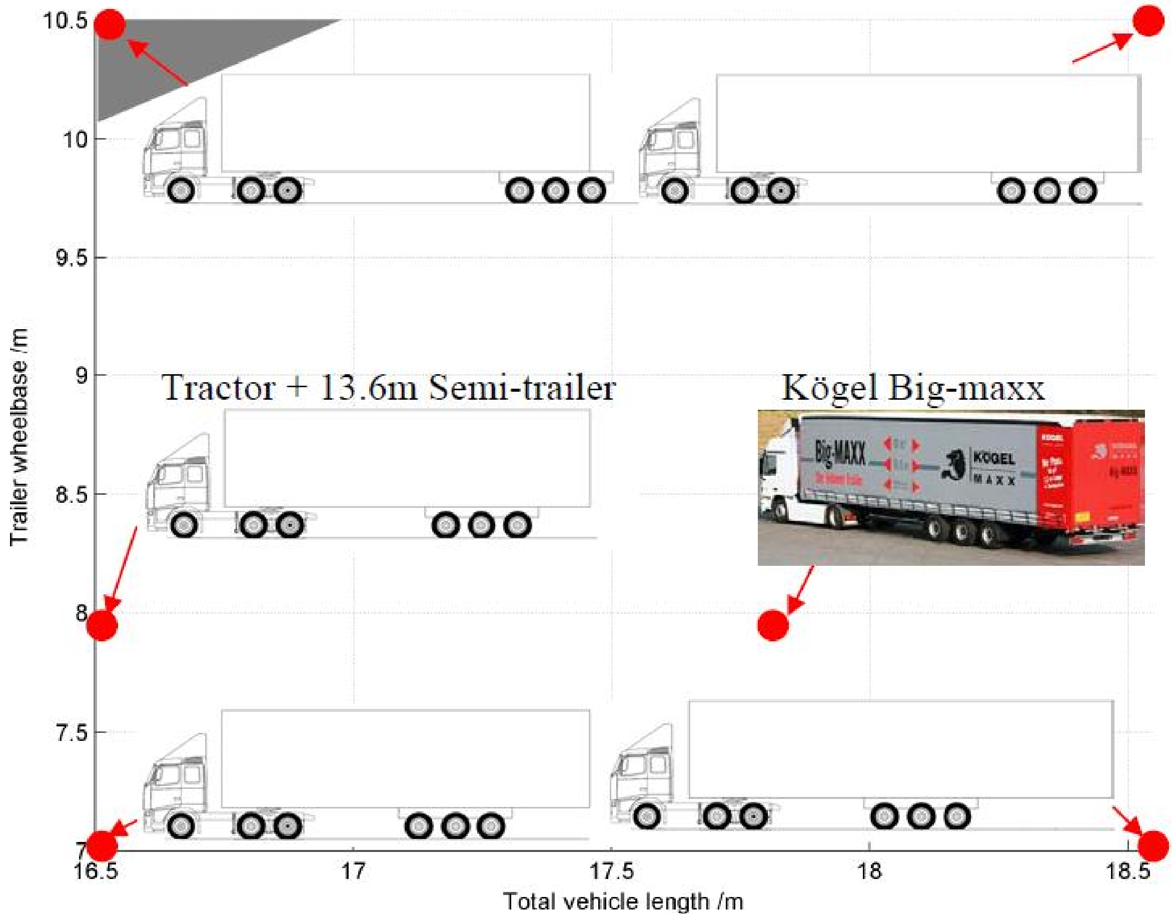


Figure 5. Example of output graph plotted against vehicle length and wheelbase

In this way, simulating specifically proposed vehicle options can be avoided. Any vehicle option can subsequently be assessed by positioning it in the relevant graph, based on its length and wheelbase as shown in Figure 5. For those simulations involving a laden vehicle combination, it has been assumed that the load is evenly distributed throughout the available volume.

3.1.2 Fuel consumption and emissions

Whilst fuel consumption changes may be measured under controlled laboratory conditions, the limited availability of the full range of LST (Longer Semi-Trailers) HGV configurations and the relatively short duration of this project prohibited this approach. Therefore the derivation of the emissions and fuel consumption associated with existing and standard articulated and drawbar HGVs were compared with a series of six potential LST-HGV configurations, as described in Section 3.3. For each of these vehicle configurations, their emissions and fuel consumption were assessed using a state-of-the-art modelling approach.

The EU fifth framework ARTEMIS[10] project and the COST Action 346[11] provided new insight into the emission behaviour of modern vehicles. One of the main outputs of these projects was the development of a model capable of accurately simulating emission factors for all types of vehicles over any driving cycle and for various vehicle loads and road gradients. The resulting tool – PHEM (Passenger car and Heavy-duty Emission Model) - estimates fuel consumption (FC) and the

[10] http://trl.co.uk/artemis
[11] http://www.cordis.lu/cost-transport/src/cost-346.htm

emissions of carbon monoxide (CO), total hydrocarbons (THC), oxides of nitrogen (NO_X) and particulate matter (PM) based on the instantaneous engine power demand and engine speed during a driving cycle specified by the user. Carbon dioxide (CO_2) emissions are derived from the standard carbon balance equation, as specified in the Commission Directive 93/116/EC.

The model combines steady-state engine maps with correction functions for transient operation (Rexeis *et al*., 2005). Within PHEM, for a given driving cycle and road gradient, the required engine power is calculated each second, based on the driving resistance and losses in the transmission system. Engine speed is calculated from the transmission ratios and a gear-shift model. To allow for the effects of transient vehicle operation on emissions, the results from the steady-state maps are altered using transient correction functions.

PHEM takes the form of a computer-executable program with a user-friendly interface. It is optimised for simulating fuel consumption and emissions from HGV fleets, but can also be used for simulations of single vehicles as well as passenger cars. The outputs from the model are engine power, engine speed, fuel consumption and emissions every second, as well as average values for an entire driving cycle.

Figure 6 illustrates the structure of the model.

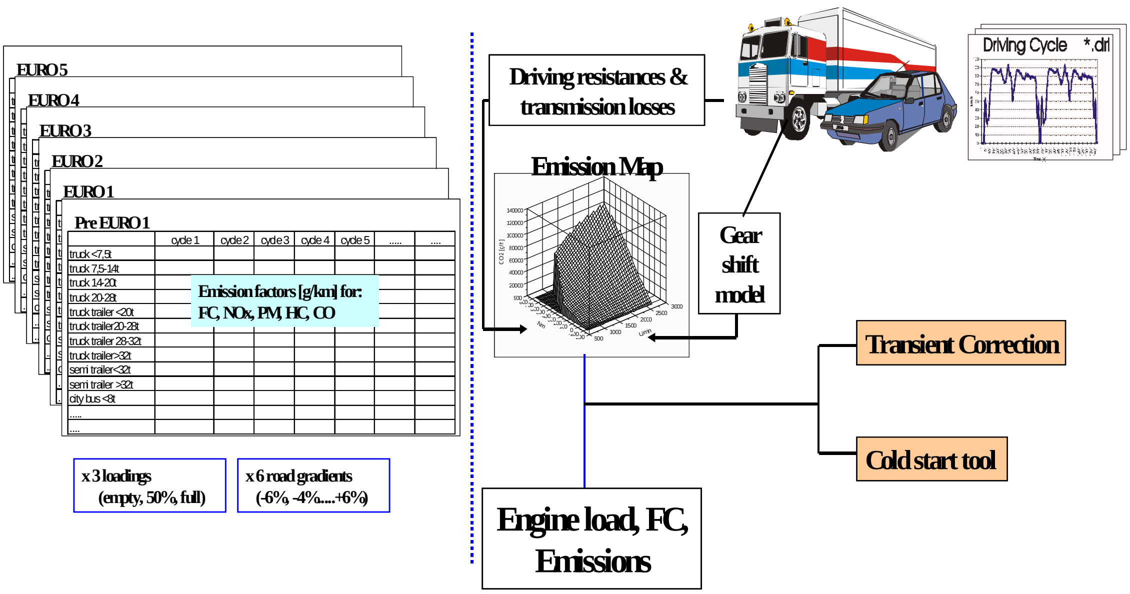


Figure 6: Structure of PHEM (Rexeis *et al*., 2005).

PHEM has some special features which were developed to enable the straightforward simulation of average heavy duty vehicle (HDV) classes. For example, the input data are modular, with different files being used to describe the vehicle characterisation, the driving cycle, the engine emission map and the full-load curve. This enables a rapid simulation of various vehicle and driving cycle combinations. In the input file for the driving cycle, the measured engine speed or the gear position can be given as an optional model input. If neither the engine speed nor the gear position is given in the input file, PHEM uses a gear-shift model to simulate engine speed.

TRL holds a database of in-service driving characteristics, measured over a range of road types and vehicle classes. One hundred and twenty typical HGV driving cycles were selected to represent a range of average speed driving conditions between 5 and 90 km/h. These cycles were previously collected during various studies including the DfT TRAMAQ UG214 project (Green and Barlow, 2002) and the HA project on the assessment of the M42 active traffic management regimes (McCrae and Barlow, 2005). Emission and fuel consumption estimates were derived using PHEM over each of these selected cycles, for each of the vehicle configurations and for Euro 5 emission classes, introduced into the UK fleet in 2008/09. This included simulations of these vehicles operating part laden and fully-laden.

3.2 Vehicle dynamics results

3.2.1 Unsteered 44 tonnes

3.2.1.1 Static distribution of axle load

The way in which static load on the trailer tri-axle bogie varies with total vehicle length and trailer wheelbase is shown in Figure 7.

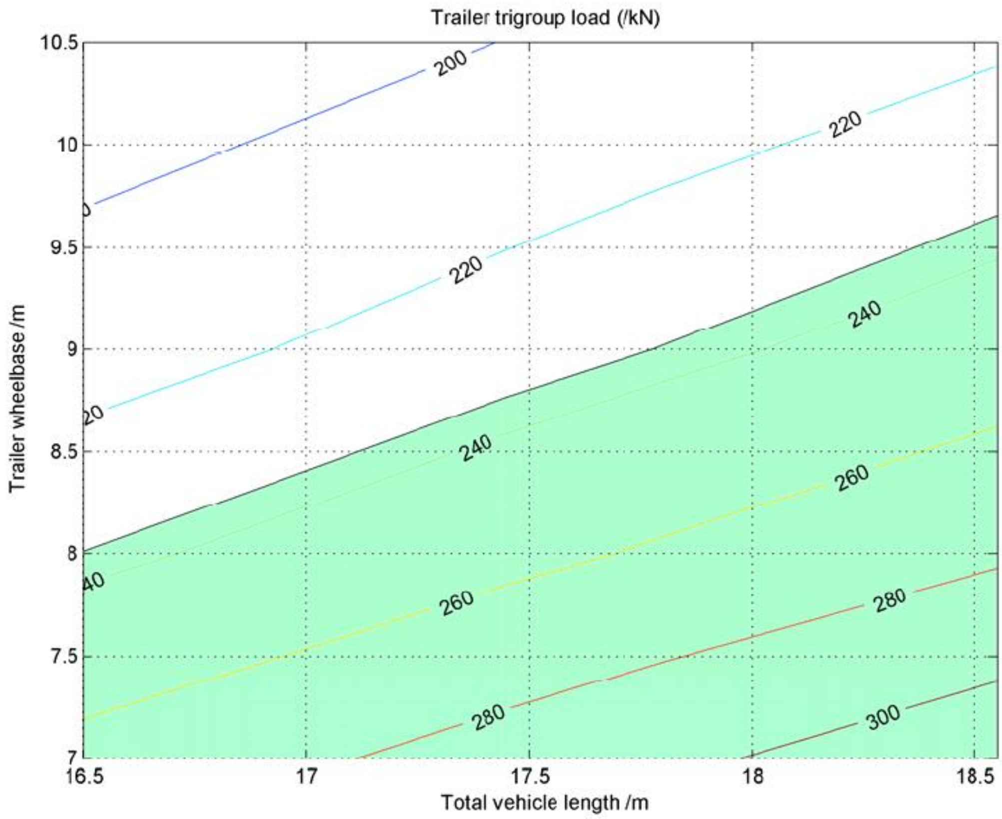


Figure 7. Variation in trailer bogie load (Triaxle overload)

The load on the trailer bogie, in kN, is shown on the plot in a form that is analogous to isobars, that is, each contour line plots points where the load on the bogie is the same. Thus, it can be seen that if the trailer wheelbase remains constant, then increasing the trailer/vehicle length increases the load on the bogie. For an 8m wheelbase, the load increases from a little less than 240kN at 16.5m overall length to a little less than 280 kN at 18.55m length.

UK legislation limits the mass carried on a standard, closely spaced, tri-axle bogie to a maximum of 24 tonnes (235.4kN). Every point on the plot in the area of Figure 7 that is shaded represents a combination of overall length and wheelbase that will result in this maximum trailer axle load being exceeded if the vehicle is filled to maximum capacity (both volume and mass) with goods of uniform density.

Figure 8 applies the same approach to the tractor drive axle loading, although for this there are two constraints, the regulatory limit for maximum axle mass (10.5 tonnes, 103kN, shown in red) and the minimum mass required to be placed on the drive axle to ensure reasonable levels of traction (based on the Australian Performance Based Standards (PBS) requirement of 15% of combination weight, shown in blue).

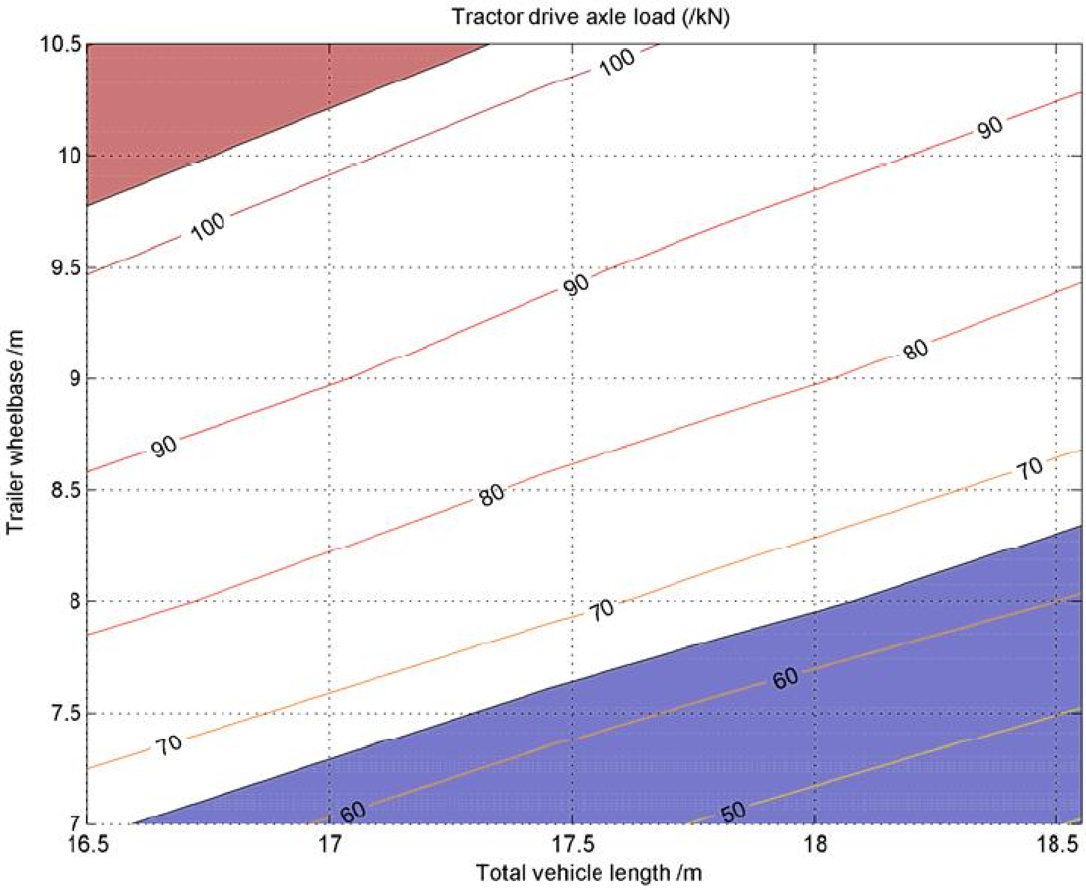


Figure 8. Tractor drive axle load (traction and overload limits)

It can be seen that if the wheelbase remains constant, increasing the vehicle length reduces the mass on the drive axle. It should be noted that these analyses rely on assumptions about the distribution of the unladen mass of the semi-trailer. It is possible that the use of steering axles, amongst other things, will change this distribution such that the exact cut-off points vary slightly, though the shape of the curves would remain the same.

3.2.1.2 Low speed manoeuvrability

The low speed manoeuvrability of the vehicle was assessed by simulating the main regulatory requirement of EC Directive 96/53/EC, which is for a vehicle to turn 360 degrees within two concentric circles of 12.5m and 5.3m radius. The results in relation to the trailer “cut-in” are shown in Figure 9, below. Negative values of the minimum distance to the inner circle indicate that the trailer has gone over the inner circle and has thus failed to meet regulatory requirements. The area where this occurs is shaded.

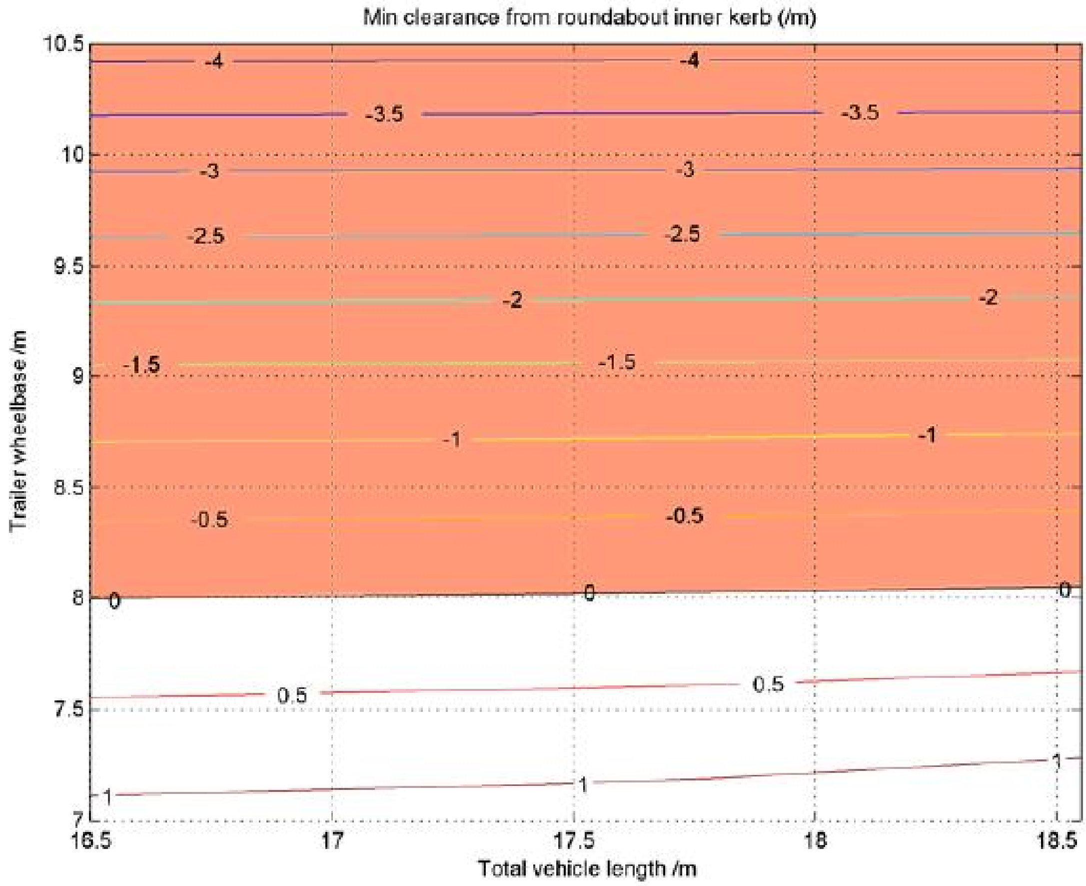


Figure 9. Minimum clearance from inner 5.3m radius circle (6 km/h) (roundabout cut-in)

It should be noted that the limits applied by Council Directive 96/53/EC govern the manoeuvrability standards that must be met by vehicles and vehicle combinations in service if they are to be guaranteed free circulation throughout Europe. However, Directive 97/27/EC governs the manoeuvrability of new vehicles at type approval. This Directive also contains requirements relating to the tail swing of a vehicle (i.e. if a vehicle steers to the right, the amount that the rear of the vehicle initially moves left). The tail swing values recorded in the drive in roundabout test are shown in Figure 10, below. The shaded area indicates performance that is worse than that of a 16.5m vehicle with an 8 metre wheelbase.

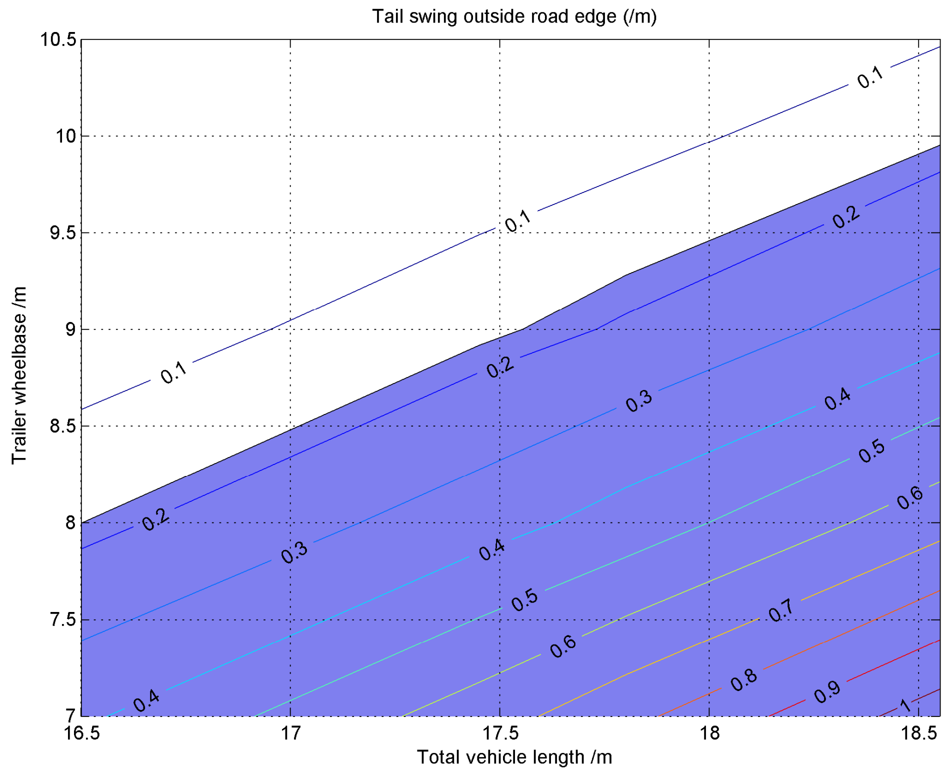


Figure 10. Tail swing (6 km/h)

There are a number of ambiguities and subtle variations in the manoeuvrability requirements that can have an important influence on the results. Firstly, the test procedure and limit value for tail swing is different in Directive 97/27 for goods vehicles and for large passenger vehicles. For goods vehicles of category N the limit is 0.8m and this is determined by measuring the distance that the rear end moves outside of the vertical plane (representing the edge of the vehicle when it is stationary before the manoeuvre) when the vehicle moves away from rest with the front wheels directed such that the front corner of the vehicle follows a path of 12.5m radius (see Figure 11). For buses and coaches, the vehicle must drive in a straight line and then steer such that the front of the vehicle follows a radius of 12.5m. The tail swing is measured as the maximum that the rear moves outside of the original straight path of the vehicle (see Figure 12). The limit is 0.6m.

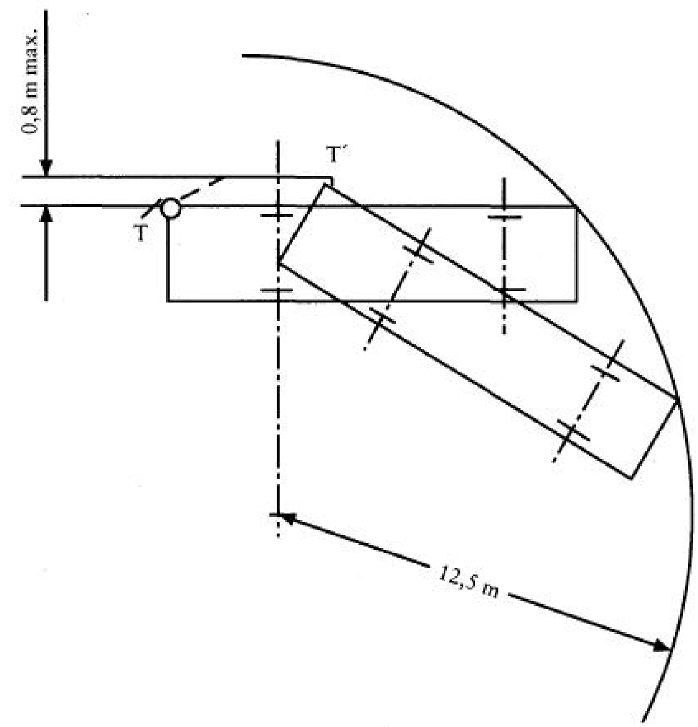
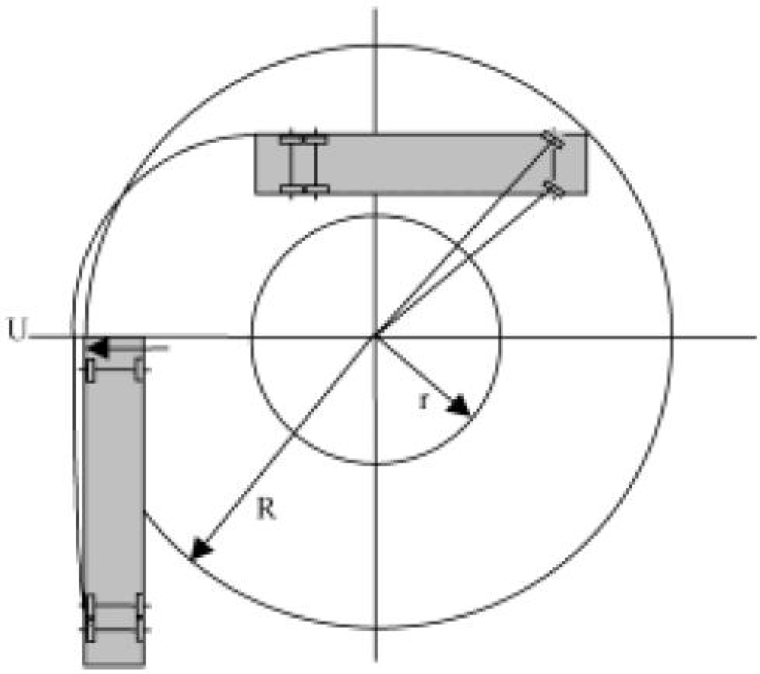


Figure 11. Illustration of the goods vehicle tail swing test in 97/27/EC (steady state manoeuvre)



R = 12,5 m

r = 5,3 m

U = maximum 0,6

Figure 12. Manoeuvrability test for buses and coaches in 97/27/EC (drive in manoeuvre)

It initially appears as if these two tests are very similar and thus that the limit for buses is more stringent than for goods vehicles. However, Smith et al (2003) found that the “drive in” manoeuvre for buses was always a considerably less stringent test of tail swing than the “steady state” manoeuvre for rigid goods vehicles. Although both procedures were found to record the same rank order when applied to different vehicles, the magnitude of the difference between the methods was found to be greater for vehicles exhibiting larger values of tail swing. For example, one 15m long bus tested in both procedures recorded a tail swing of 0.57m in the “drive in” test and 1.54m in the “steady state” test. This implies that in fact the 0.8m limit for goods vehicles is considerably more stringent than the 0.6m limit for buses. Although, this phenomenon has not been investigated in this analysis, data presented by Iveco (Iveco, 2009) supports the view that there is a substantial difference in the tailswing produced by the two test methods. When comparing the tail swing of a 16.5m and 17.8m artic using the steady state method (equivalent to the method for category N vehicles in 97/27) they found an increase from 0.89m to 1.59m. The results shown in Figure 10 were obtained during a “drive-in” manoeuvre and, thus, represent the results of the less stringent test. These results show a considerably smaller increase in tail swing for a 16.5m vehicle increasing to 17.8m with the same wheelbase (approximately 0.17m to 0.33m).

The steady state test is clearly a more stringent test of tailswing. For buses, it can also be reasonably argued that it is representative of a real driving situation associated with a tangible accident risk. This is where a bus is stationary adjacent to the kerb at a bus stop, parked close behind another bus. Often this rearmost bus will attempt to pull away from rest with the steering fully applied to get out from behind the other bus with limited space, potentially causing the rear to swing out across the kerb, exposing any pedestrians stood in that area to risk. However, the chances of an articulated vehicle similarly pulling away from rest in a condition representing fully developed steering is very unlikely because this would require not only that the steering was at full lock but also that there was a large articulation angle between tractor and trailer as the vehicle begins to move. Thus, it could be argued that the “drive in” test is more realistic for articulated vehicles.

The swept path test for goods vehicles in 96/53/EC refers to all goods vehicles and vehicle combinations. However, the tractor and trailer of an articulated vehicle are sold separately and, thus, must be type approved separately. Directive 97/27/EC, which implements the requirements of 96/53/EC in the type approval system, cannot therefore consider the performance of an articulated vehicle combination. The requirements for swept path (360 degree turn within concentric circles of 5.3m and 12.5m radius) applies to all vehicles. Semi-trailers are defined as category O vehicles and the performance of a semi-trailer will depend on the performance of the vehicle towing it. For this reason, a semi-trailer is *“deemed to comply”* if:

$$Wheelbase \leq \sqrt{(12.50 - 2.04)^2 - \left(5.3 + {}^{L}/_{2}\right)^2}$$

Where L is defined as the vehicle width.

Thus, the maximum wheelbase that the regulation deems acceptable for a 13.6m long and 2.55m wide semi-trailer with respect to swept path is 8.135m. It should be noted that this is slightly greater than the wheelbase at which the simulation indicates a standard 16.5m artic would fail the cut-in requirement. There could be a number of reasons for this small apparent discrepancy, including the test speed and the assumed geometry of the tractor unit as well as some of the simplifications inherent in the modelling exercise. However, it does suggest the possibility that the requirements of Directive 97/27 do not guarantee that all combinations of type approved tractors and trailers would pass the requirements of Directive 96/53.

In Directive 97/27 the requirements for tail swing are defined as *"additional requirements for vehicles of category N"*. Semi-trailers are vehicles of category O and as such there is no tail swing requirement for a semi-trailer. By logical extension there can also be no legally required maximum tail swing value for an articulated vehicle combination.

The Directive requires that no part of the vehicle shall travel outside if the 12.5m radius circle. However, the same problem of separate tractor and trailer approval combined with the formula used to approve semi-trailers means that in an approved articulated tractor semi-trailer combination the leading edge of the semi-trailer can track outside of the front of the tractor unit. This can be referred to as nose swing. The nose swing observed in the simulations is shown in Figure 13, below. Again, the shaded area represents performance that is worse than a 16.5m vehicle with an 8m wheelbase.

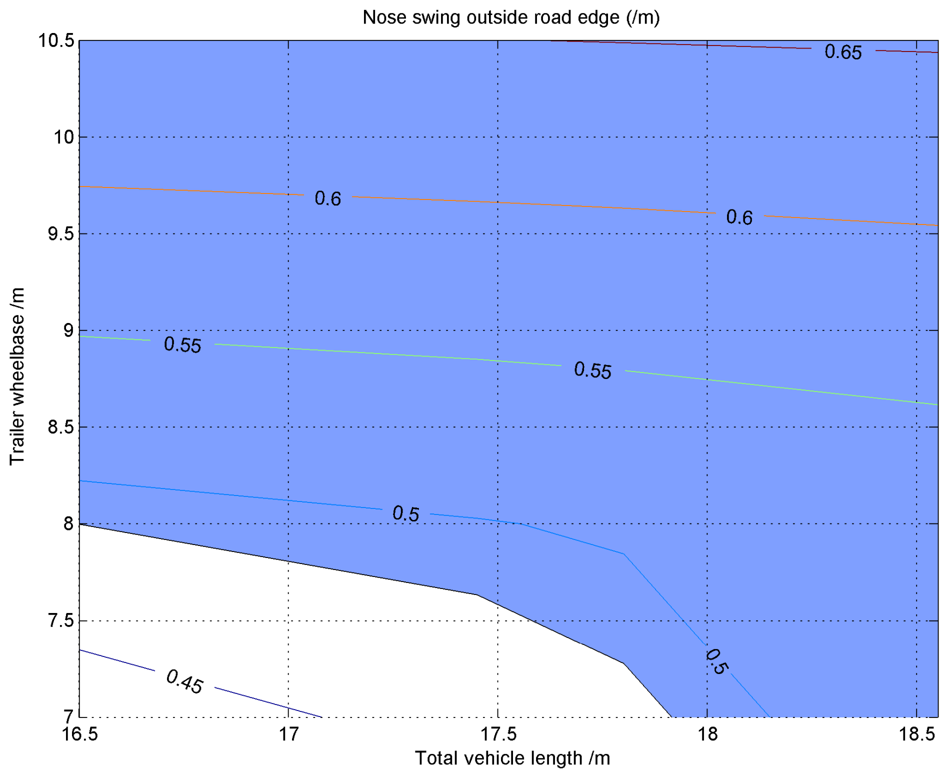


Figure 13. Nose swing (6 km/h), fixed axle trailer

It can be seen that the amount of nose swing is in fact greater than the amount of tailswing. However, in relation to the risk that is presented, there is one important difference; the nose swing is visible in the drivers mirrors whereas tailswing is not. It can also be seen that nose swing gets substantially worse with longer wheelbases. This is a consequence of increased cut-in leading to larger articulation angles between tractor and trailer.

Figure 14 summarises all of the results for load distribution and low speed manoeuvrability for articulated vehicles of 44 tonnes GVW without steered trailer axles. Each of the regulatory or practical constraints are shown as different colour shaded areas. White areas represent the only combinations of wheelbase and overall length that comply with all of the requirements. Tail and nose swing have not been shaded on the graph because they are not constrained by current regulations.

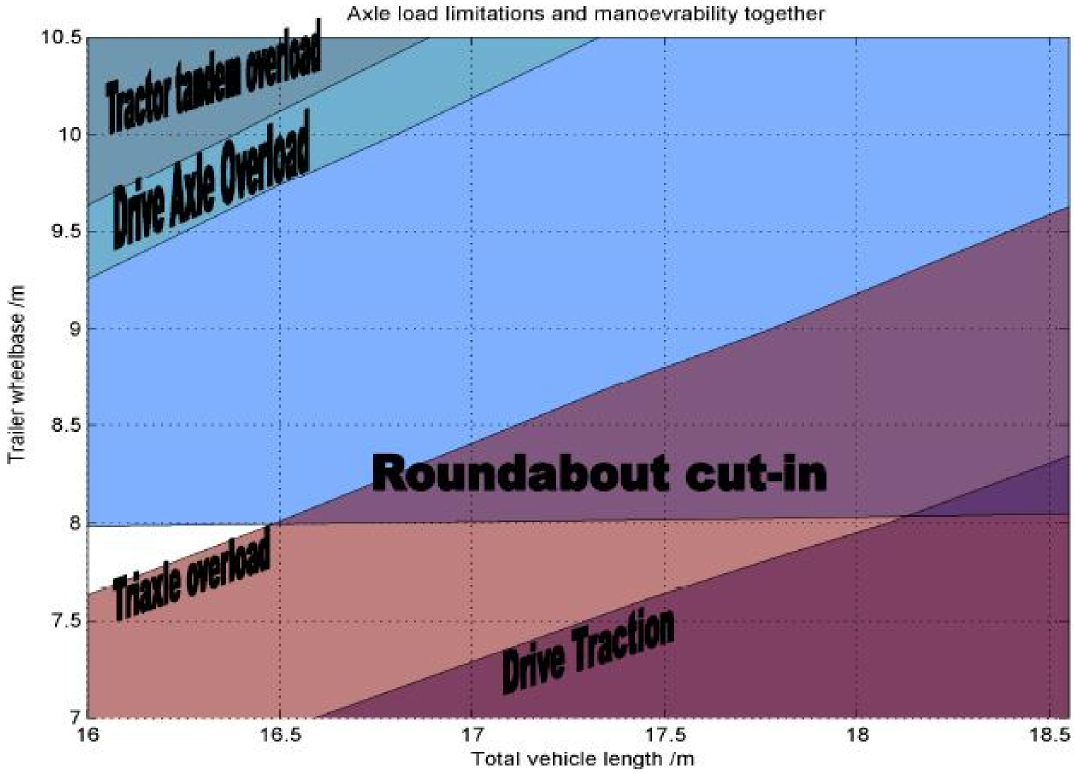


Figure 14. Summary of load distribution and low speed manoeuvrability constraints (6km/h), fixed axles, 44 tonnes

These results show that the overall length of this type of vehicle (44 tonne GVW with closely spaced tri-axle trailer bogie and no steered trailer axles) cannot be significantly increased without overloading the trailer bogie (when uniformly loaded to maximum GVW) or failing the existing manoeuvrability limits for cut-in.

One further ambiguity associated with the legal requirements is that neither Directive 97/27/EC nor Directive 96/53/EC specify a test speed. The results shown in Figure 9 and Figure 10 were obtained at a test speed of 6 km/h. The test speed, and hence the lateral acceleration of the trailer, will influence both the cut-in and the tail swing experienced by the vehicle. The lack of a specified speed will, in theory at least, allow the type approval test to be undertaken at the speed most likely to result in a pass. Figure 15 shows the constraints when the test speed has been increased from 6 km/h to 15 km/h, which is close to the point of rollover for some of the vehicle dimensions assessed.

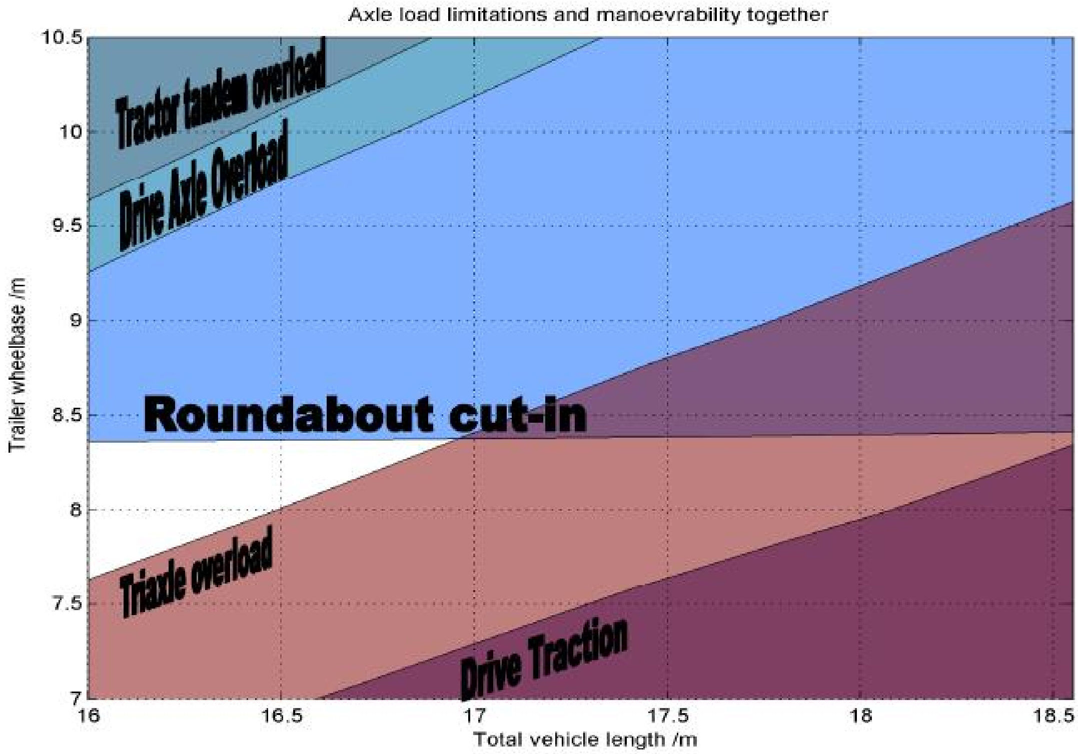


Figure 15. Summary of load distribution and low speed manoeuvrability constraints (15km/h), fixed axles, 44 tonnes

It can be seen that this significantly changes the results such that a vehicle of about 16.9m would become possible without exceeding tri-axle loads or manoeuvrability limits, provided the wheelbase was increased to about 8.4m.

UK regulations do permit a tri-axle trailer to be equipped with a twin axle bogie rated at a maximum of 20 tonnes and a separate single axle rated to 10 tonnes, for a combined axle load of 30 tonnes. The single axle would have to be more than 1.8m away from the nearest axle to qualify. In this case, the trailer axle loads would no longer be a constraint and increased length would be possible. However, in practice having a separate axle widely spaced from the bogie would result in considerable tyre scrub during cornering, resulting in severe tyre wear. Where this configuration is employed in practice, the single axle is typically a self-steering axle to prevent this problem. It is, therefore, considered that although this axle configuration could be used to allow longer 44 tonne fixed steer trailers, if permitted, to comply with axle load limits, it is extremely unlikely to be a practically viable option.

Vehicle height does not affect the static load distribution or manoeuvrability so all of the above results can be considered equally applicable to trailers of any height.

3.2.1.3 High Speed stability

Several manoeuvres at highway speeds (substantially in excess of 15 km/h) were also considered using the more sophisticated model but using the same approach to simulating the different variables and presenting the results. Steady state circular tests according to ISO 4138 were simulated in order to investigate the rollover threshold (lateral acceleration at the point of rollover) in standard cornering situations. A dynamic lane change manoeuvre was simulated to assess the performance in transient avoidance manoeuvres in terms of path error (PE), load transfer ratio (LTR) and rearward amplification (RA). The cross wind speed required to produce rollover was also assessed while travelling in a straight line.

Each of these assessments was undertaken at both 4m and 4.9m heights and the worst case loading condition.

Unlike static load distribution and low speed manoeuvrability, there are no regulatory requirements governing the dynamic cornering performance of vehicles travelling at speed. In order to maintain the same approach to the presentation of results it was initially decided to shade areas of the graph where the performance of a vehicle was inferior to that of the equivalent 16.5m existing vehicle. The combined results for the high speed simulations are shown in Figure 16, below.

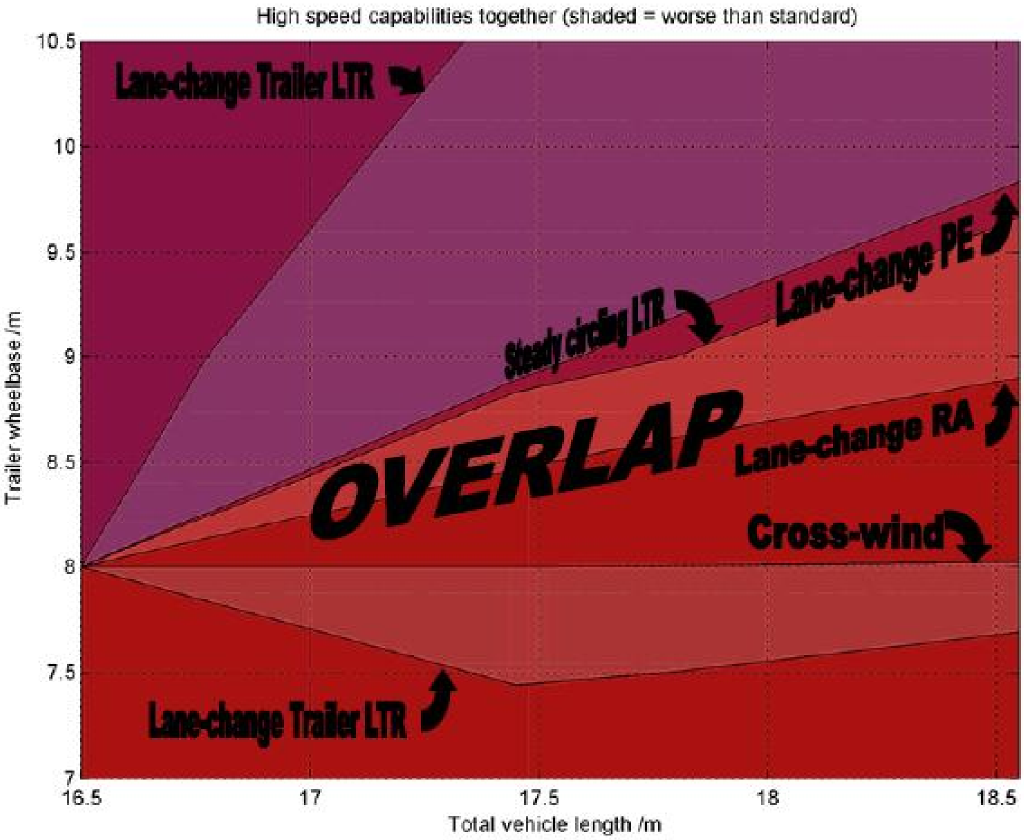


Figure 16. Highway speed (>>15km/h) performance of a 44 tonne unsteered vehicle, 44 tonnes

It can be seen that there are no permutations where a longer (unsteered) vehicle is at least as good as an existing vehicle in all measures. It is, therefore, inevitable that for the same vehicle height, a longer vehicle will suffer some aspects of degraded dynamic performance. However, where some aspects of performance are worse, others will be better than for the standard vehicle.

When the low and high speed results are combined, it can be seen that it is not possible for the length of a 44 tonne, unsteered semi-trailer to be increased within the constraints of other existing regulations so this option was not evaluated any further.

3.2.2 Unsteered 38 tonnes

3.2.2.1 Low speed manoeuvrability

Increasing the length of 44 tonne vehicles without steering axles was found to be infeasible because of the combination of manoeuvrability and maximum axle load requirements. Limiting the GVW that such a combination could carry has the potential to remove the axle loading limits as a constraint. Figure 17 shows the results for a 38 tonne vehicle on 6 axles.

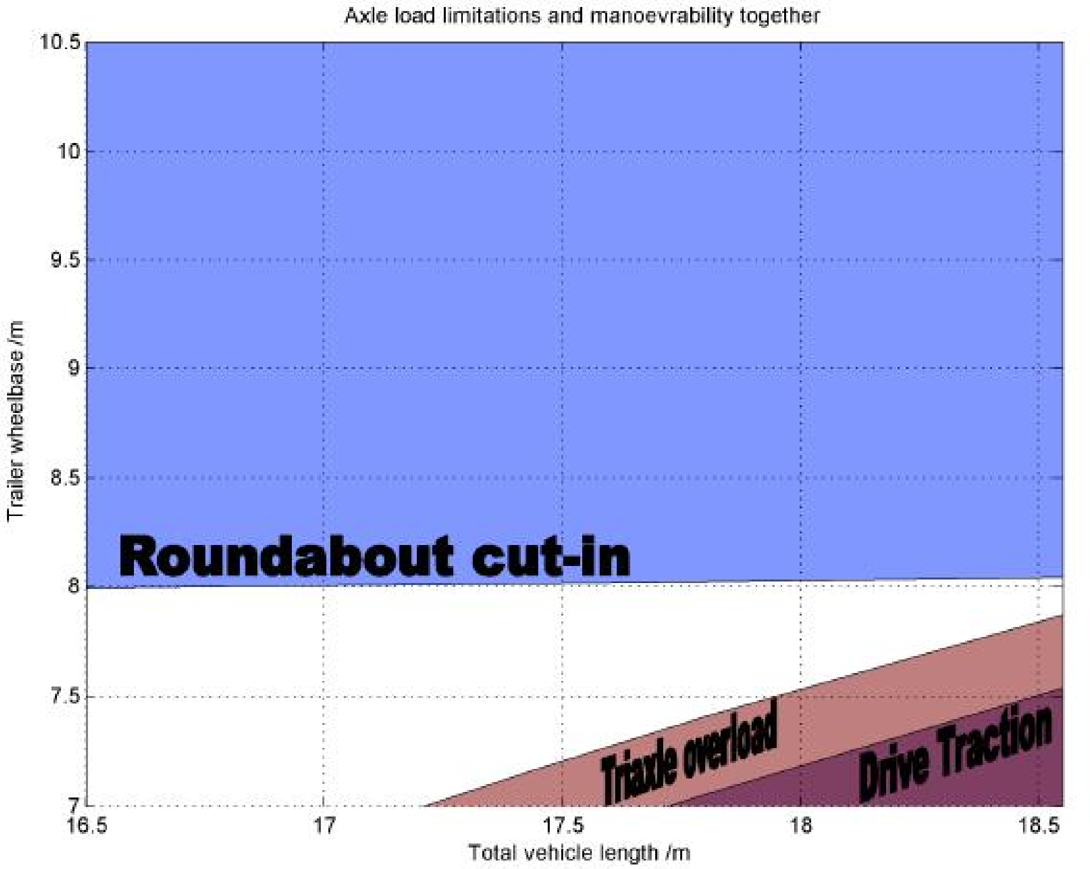


Figure 17. Summary of load distribution and low speed manoeuvrability constraints (6km/h), fixed axles, 38 tonnes.

The results show that reducing the GVW to 38 tonnes would enable vehicle length to be increased to 18.55m while still complying with all existing legal requirements. Although tail swing is not a regulatory constraint, the length would need to be limited to approximately 18.25m to avoid exceeding the maximum permitted for other vehicle types. Both tailswing and nose swing would be the same as that for the 44 tonne fixed axle vehicle as shown in Figure 10 and Figure 13.

It remains true that it is not possible for longer vehicles with unsteered axles to achieve as good or better results in the high speed simulations as existing vehicles. For this reason, Figure 18 shows all results as shaded constraints except lane change path error, which has been omitted to simplify presentation, and rearward amplification which has been shown as contour lines rather than shaded constraints.

3.2.2.2 Combined low and high speed results

Figure 18 shows that a vehicle length of up to approximately 18.55m is feasible, within existing regulatory constraints but at the cost of an increase of approximately 40% in path error, 15% in rearward amplification and Figure 10 shows a 400% increase in tailswing to approximately 0.65m. There would be a slight increase in nose swing (<5cm).

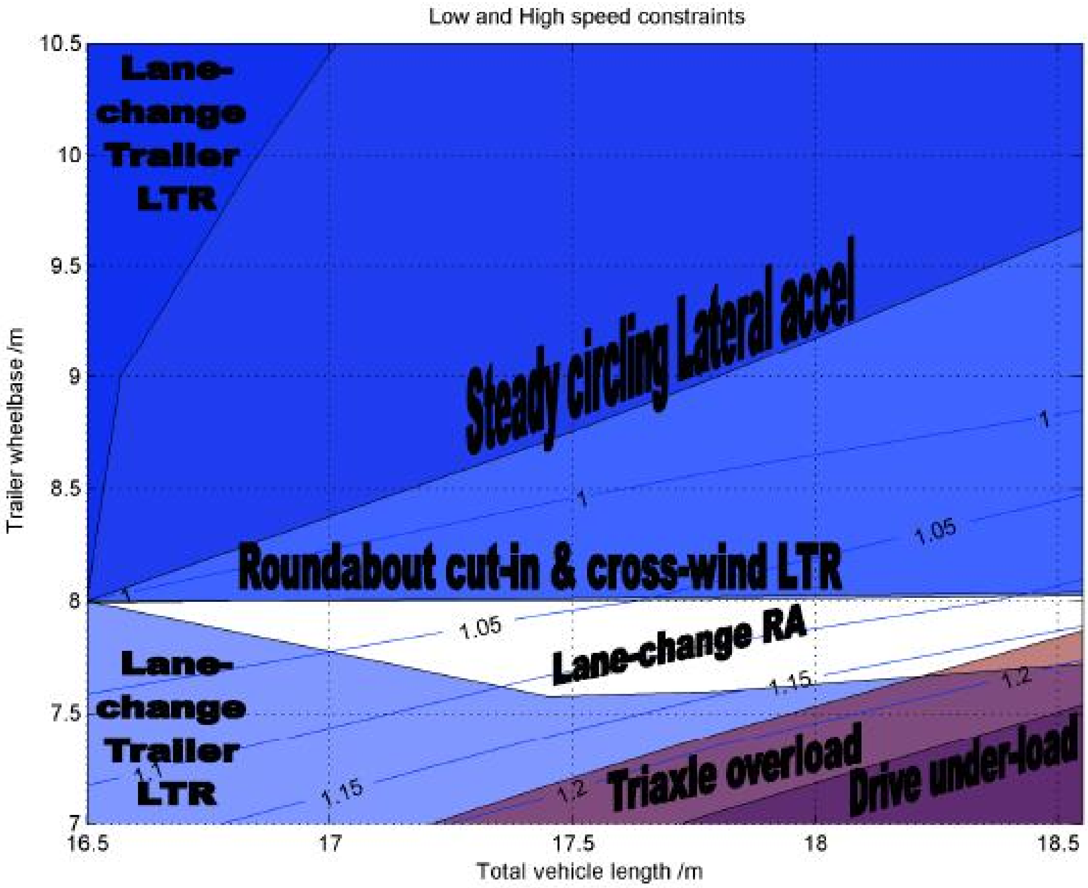


Figure 18. Load distribution and low speed constraints combined with highway speed performance, fixed axles, 38 tonne vehicle.

Only a six axle simulation model was available for this analysis. However, if the practical maximum GVW that a vehicle could carry was less than 41 tonnes then in practice a two axle tractor unit would be used in place of a three axle one. This would have the effect of:

- Slightly increasing the cut-in during the turning circle test (because of increased tractor unit wheelbase/cut-in)
- Slightly changing the shape of the high speed results from the transient test, although these results will remain dominated by the trailer axle load transfer.

Overall, the key conclusions with respect to length and performance would be expected to remain the same for a 5 axle combination as for a 6 axle one.

In continental Europe, longer articulated vehicles with unsteered trailers are operated on 5 axles at 40 tonnes GVW and 17.8m length. A simplified load distribution calculation suggests that this would be possible without exceeding the maximum trailer bogie load.

3.2.3 Self steer axles

A self steer axle has been simulated by assuming that it will not turn until the tyre forces exceed 0.25 times the vertical load imposed on the axle. Once this force is exceeded the axle will steer to whatever angle is required to maintain this level of lateral force. This is illustrated by Figure 19, below.

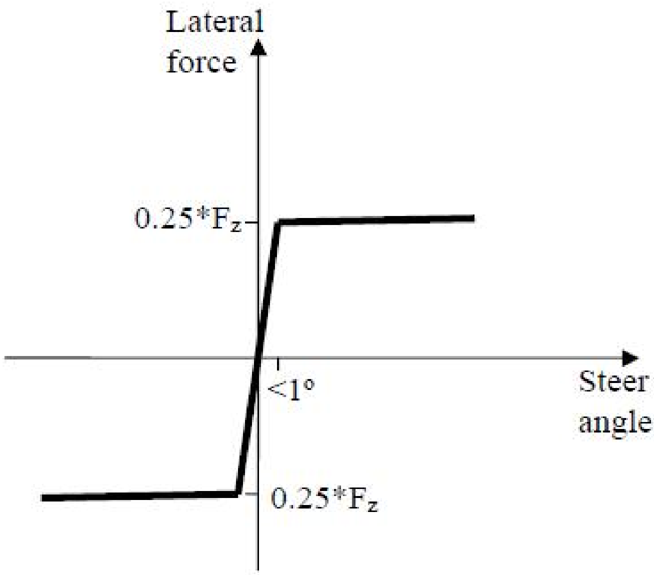


Figure 19. Self steer characteristic in the model

This behaviour has been approximated in the model by limiting the coefficient of friction for self steered axles to a maximum of 0.25.

3.2.3.1 Low speed

The low speed simulation results for a 6 axle articulated vehicle with two self steered axles at the rear of the tri-axle trailer bogie are shown in Figure 20. A GVW of 40 tonnes was selected because this allowed the maximum length.

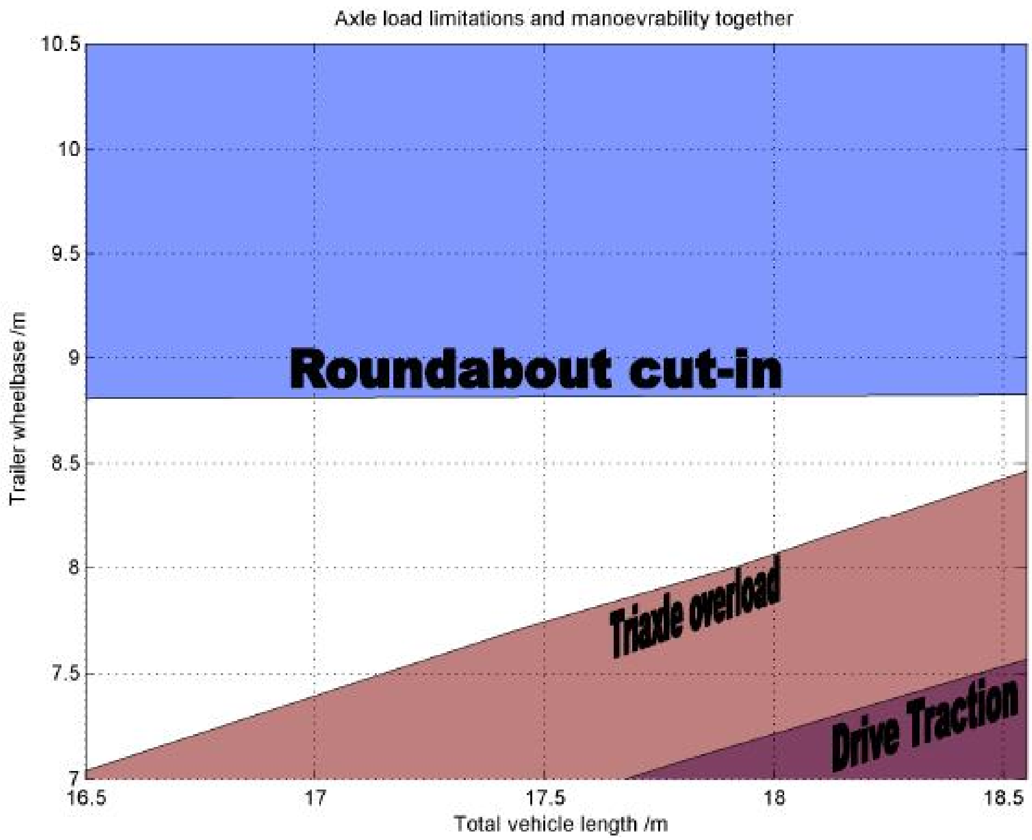


Figure 20. Load distribution and low speed constraints, two self steer axles, 40 tonne GVW

It can be seen that the addition of two self-steered axles enables the wheelbase to be increased to about 8.8m while still complying with the cut-in limit. This combined with the 40 tonne GVW mean that the trailer bogie loading is not a constraint. Length can, therefore, be increased up to 18.55m while complying with existing regulatory constraints.

The additional mass implied by the use of self steer axles is not sufficient to have a substantial affect on the load distribution at full load in comparison to a fixed axle vehicle. This means that the tri-axle load limit constraint from the 44 tonne unsteered vehicle (see Figure 7) can be directly substituted into Figure 20 with a reasonable degree of accuracy. Such an approximation would show that a length of approximately 17.6m would be feasible at a GVW of 44 tonnes with two self steer axles.

Figure 21 shows the effect on tailswing (shaded areas indicate worse performance than a standard 16.5m vehicle with an 8m wheelbase).

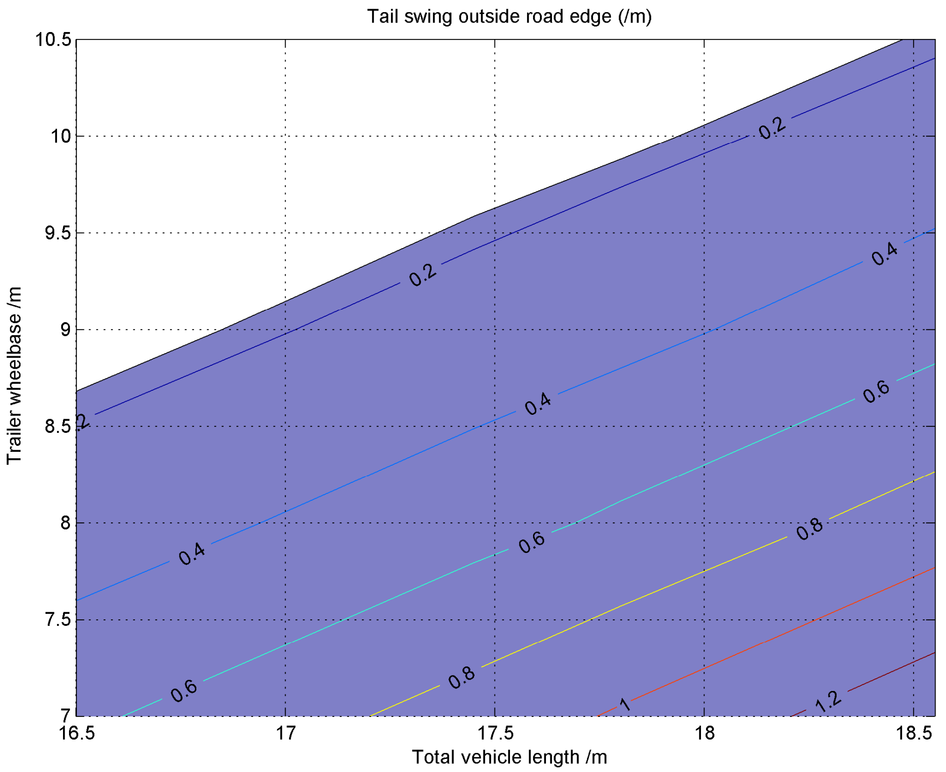


Figure 21: Tailswing results for a vehicle with twin self steer axles (breakaway 0.25g)

It can be seen that an 18.55m vehicle with a wheelbase of approximately 8.8m (to just comply with cut-in limits and give a best case for tailswing) would have a tailswing of approximately 0.6m, more than three times that of a standard vehicle though still less than permitted for buses. Equivalent data for nose swing suggests there would be a slight improvement in nose swing of around 5cm.

Figure 22 shows the low speed constraints for vehicles with a single self steer axle.

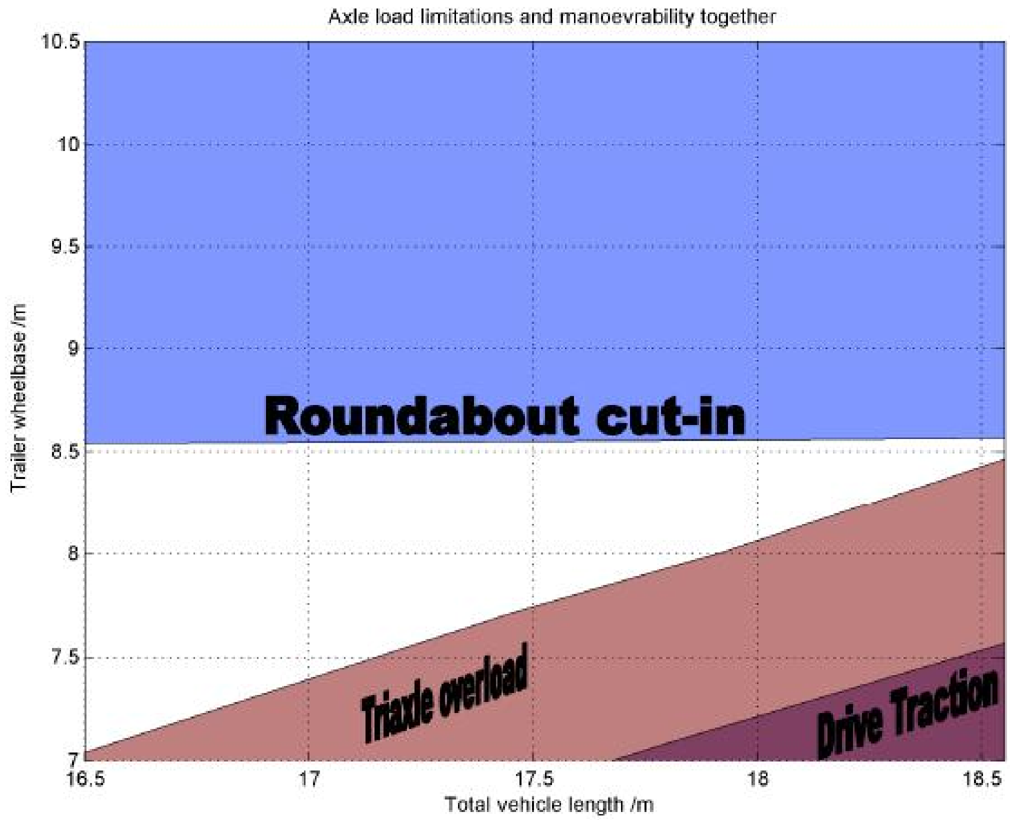


Figure 22. Load distribution and low speed manoeuvrability constraints, single self steered axle, 40 tonne GVW.

A similar comparison with Figure 7 suggests that if the GVW were to be 44 tonnes then the use of a single self steered axle (Figure 22 shows the constraints for a 40 tonne vehicle) would enable the length to be increased to around 17.1m while still complying with all other existing limits. It should be noted that at least one haulier[12] has proposed a 17.45m vehicle at 44 tonnes with a single self steer axle and claims that it meets all existing regulation. The simulations in this report are based on a closely spaced tri-axle group (spacing 1.31m/1.31m) whereas the industry proposal has a closely spaced tandem axle group with the single self steer axle slightly further back (spacing 1.31m/1.81m). It is likely that this accounts for the apparent conflict in results because as far as load distribution is concerned the industry arrangement increases the wheelbase but as far as manoeuvrability the effective wheelbase is not increased and may even decrease. However, the assumed characteristics of the steered axle simulated here may also be an influence.

3.2.3.2 Combined effects

The combined low and high speed effects can be seen in Figure 23 for a twin self steer vehicle at 40 tonnes.

[12] http://www.stobartgroup.co.uk/Environment/Environmental-Responsibility/

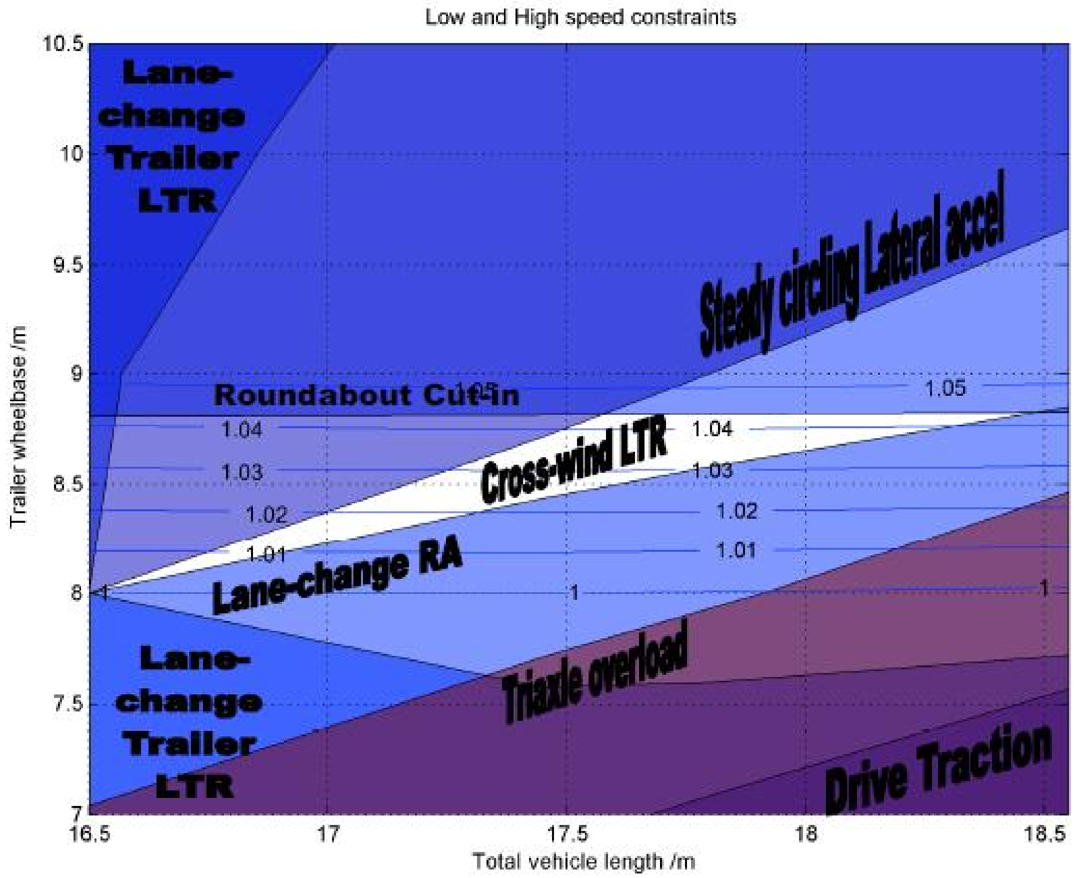


Figure 23. Load distribution and low speed manoeuvrability constraints combined with highway speed stability performance, two self steer axles, 40 tonnes GVW

It can be seen that this combination permits an increase in length of up to 18.55m. However, compared with the standard vehicle there would be an increase of approximately 300% in tailswing, a 14% increase in lane change path error and a 4.2% increase in the load transfer ratio under crosswind loading. A slight increase in rearward amplification would be likely but it is possible that tuning self steer axles with slightly different characteristics may be sufficient to allow the maximum length increase to be achieved with less effect on these variables.

3.2.4 Command steer 44 tonne

3.2.4.1 Tuned to 0.6m tail swing

The relationship between articulation angle and trailer steer angles can be varied with command steer systems. This allows the systems to be tuned either to minimise cut-in or to minimise tail swing. Figure 24 shows the results for a system tuned to keep the tail swing beneath the 0.6m limit applied to buses in a drive in test. This tuning also has the effect of reducing nose swing, by approximately 10 cm for an 18.25m vehicle with a 9.5m wheelbase.

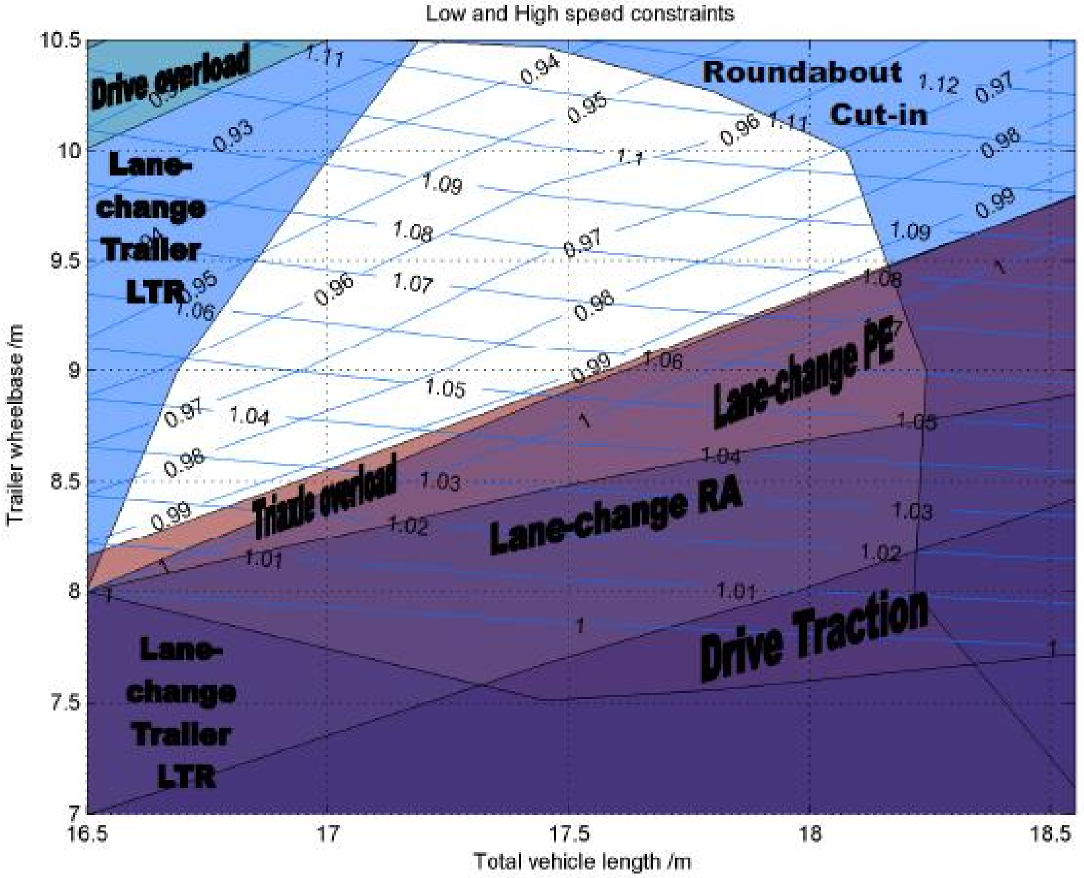


Figure 24. Load distribution and low speed manoeuvrability constraints combined with highway speed performance, command steer system tuned to a 0.6m tail swing limit, 44 tonnes GVW[13]

It can be seen that with the system tuned in this way, the maximum length that can be achieved is approximately 18.2m before tri-axle bogie load and cut-in combine to constrain length. However, if the system were tuned to improve cut-in further increases would be possible at the cost of increasing tail swing beyond what is permitted for other vehicle types.

3.2.4.2 Tuned for 0.8m tail swing

Figure 25, illustrates the results if the steering is tuned to give a maximum tail swing of 0.8m or less (drive-in method).

[13] Contour lines with values less than 1 relate to normalised maximum lateral acceleration in steady state cornering and those with values greater than 1 relate to normalised load transfer ratio during cross winds.

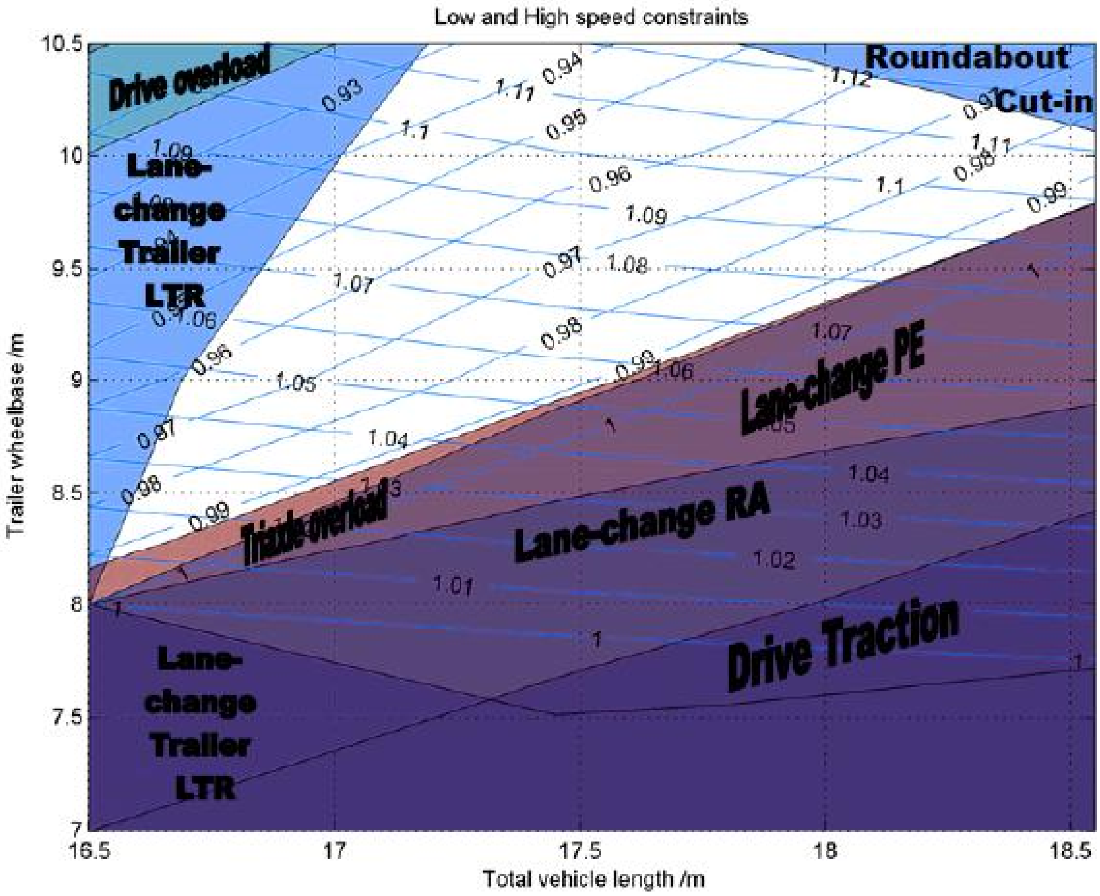


Figure 25. Load distribution and low speed manoeuvrability constraints combined with highway speed performance, command steer system tuned to a 0.8m tail swing limit, 44 tonnes GVW

It can be seen that 18.55m is achievable while meeting legal requirements with a steady state rollover threshold approximately 0.75% poorer and a 10% worse load transfer ratio during cross winds. However, the tail swing with a 10m wheelbase would be approximately 0.74m, more than 4 times the tailswing of a standard 16.5m vehicle with an 8m wheelbase, though the noseswing would be approximately 10cm less than a standard vehicle. If the more stringent tail swing limit were to be applied then a maximum length of around 18.2m would be possible and the consequences for the cross wind susceptibility would be reduced to around 8%. The tail swing would be approximately 0.56m, a little more than three times the standard vehicle.

3.2.5 Active steer 44 tonne

Figure 26 shows the overall results for a vehicle equipped with an active steering system.

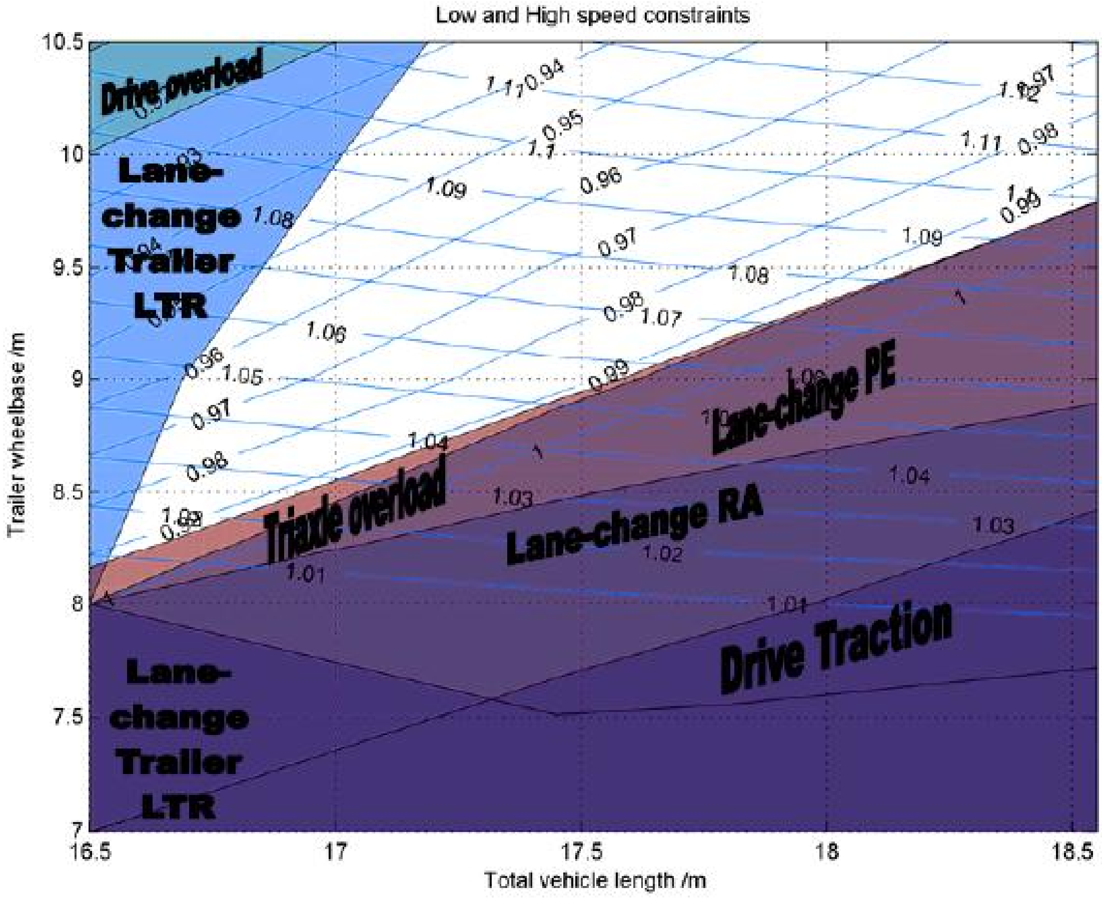


Figure 26. Load distribution and low speed manoeuvrability constraints combined with highway speed performance, active steer system, 44 tonnes GVW

It can be seen that the active steering system is sufficient to enable all requirements to be met right up to the largest 18.55m vehicle length considered in this study. The tuning of the system for these simulations were for minimum tail swing so this was achieved with almost zero tail swing (approximately 0.035m, approximately five times less than existing vehicles. Nose swing would also be reduced by approximately 15 cm compared with an existing vehicle.

The analyses above have simply assumed that the active steer system will be designed to lock at high speeds. Thus, the implications for the steady state rollover threshold and the cross wind susceptibility are, in relative terms, the same as for a command steer system. In reality, the active steer system can be tuned such that the high speed stability can also be improved. However, to simulate this would have required re-designing and re-tuning the system for every combination of wheelbase and length simulated, which would have required considerable effort that was considered to be beyond the scope of this work. Figure 27 provides an example of the potential effects of active steer systems on high speed stability, based on the standard 16.5m vehicle.

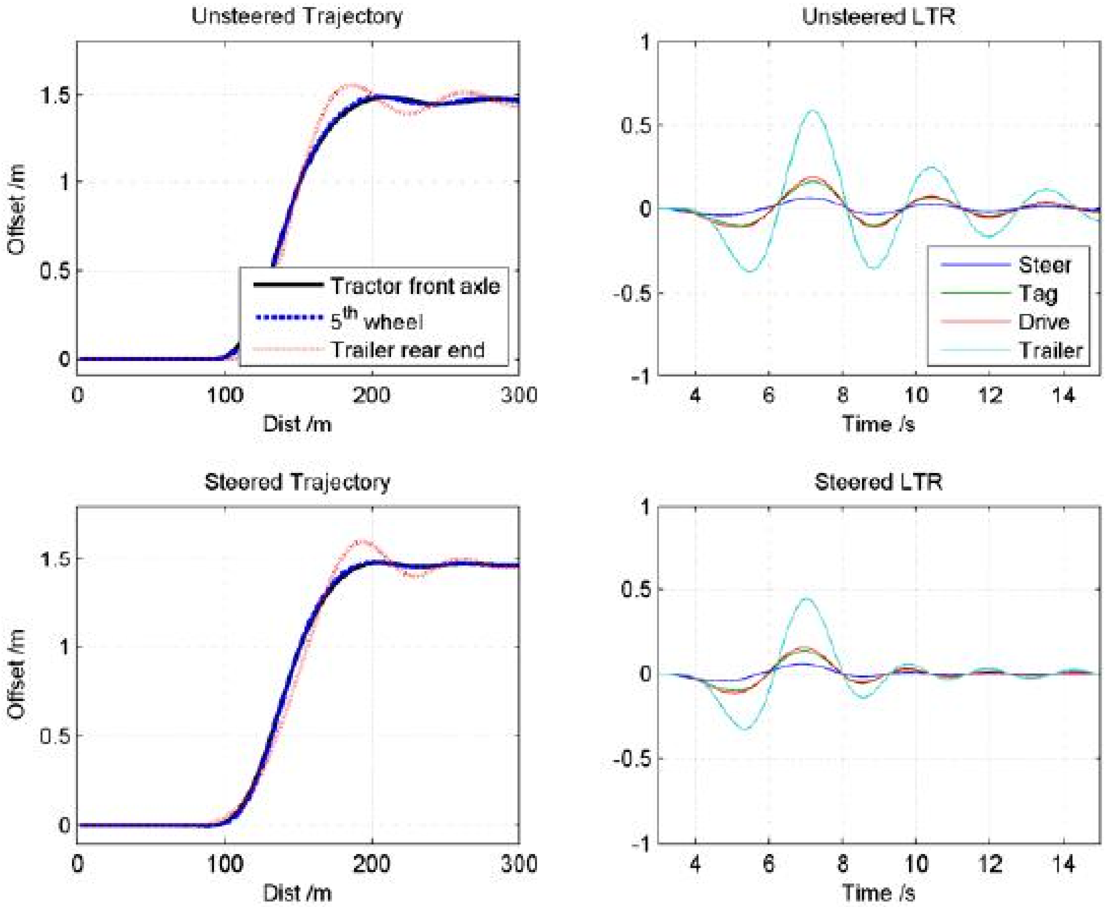


Figure 27. Improvements in Transient Load Transfer Ratio possible with Active Steer with roll stability function (unsteered 16.5m at top, active steered 16.5m bottom).

The reduction in load transfer ratio is around 20% at each axle in the combination. It is likely that this magnitude of effect could be achieved for most vehicle combinations within the scope but that precise effects would vary depending on the exact vehicle configuration.

3.2.6 The influence of overall height

The simulations reported above were based on a vehicle that was 4.9m tall. Overall height has no influence on any of the low speed manoeuvres but can have a strong influence on the high speed dynamics and the susceptibility to cross winds. The high speed simulations were, therefore, repeated with a 4m tall vehicle. It was found that the relative change and the shape of the resulting plots remained the same, showing that trailer length and wheelbase have the same influence at each height. However, the absolute magnitude of the relevant performance measures was substantially improved at reduced height, for example:

- The load transfer ratio during an identical lane change manoeuvre was 36% lower for the 4 m vehicle compared with the 4.9m vehicle.
- In steady state cornering, the rollover threshold was 25% higher for a 4m vehicle compared with a 4.9m vehicle
- The load transfer ratio was 27% less for a 4m tall vehicle exposed to a crosswind gust compared with a 4.9m vehicle exposed to the same gust.

It was shown that the absolute value of the dynamics parameters were broadly comparable for an 18.55m vehicle at 4.6m height and an existing 16.5m vehicle at 4.9m height.

3.2.7 Overall conclusions from the vehicle dynamics simulations

- Increasing vehicle length by more than about 0.4m (to 16.9m) with fixed, closely coupled trailer axles is only possible within current axle load and manoeuvrability regulations if the maximum load carried is reduced (assuming uniformly distributed load). An 18.55m vehicle would be possible if the GVW were limited to 38 tonnes. However, this is only possible because the existing legislation allows semi-trailer manoeuvrability to be approved by numerical methods and no tailswing limit is applied. Longer, fixed axle vehicles at reduced weight will have much greater tail swing than current vehicles (approximately double for a 17.5m vehicle and more than 4 times for an 18.55m vehicle compared with the baseline).
- The appropriate use of existing (non active) steering axle technology can allow vehicles to comply with all existing regulations at a GVW of 44 tonnes and a length of up to 18.55m (semi-trailer length 15.65m) but the tail swing produced in a “drive in” roundabout manoeuvre will be much greater than for current vehicles (around 0.6m, depending on specific design, compared to the existing 0.17m). Prototype active steer systems have demonstrated the potential to allow 18.55m vehicles at 44 tonnes whilst reducing tail swing to near zero.
- Longer vehicles that make use of steering axles to achieve compliance will tend to have longer wheelbases. Those using fixed axles and reduced weight will have shorter wheelbases.
- The stability of vehicles travelling at speed is more sensitive to wheelbase than to length:
    - Vehicles that achieve increased length by increasing their wheelbase will be more susceptible to crosswinds than existing vehicles (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 10% increase in load transfer ratio during crosswinds compared to a 16.5m, 8m wheelbase vehicle). They will also have a slightly worse rollover threshold in steady state cornering than those with shorter wheelbases (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 0.75% poorer steady state rollover threshold compared to a 16.5m, 8m wheelbase vehicle). However, vehicles with a longer wheelbase will tend to have better dynamic performance (e.g. path error, rearward amplification etc.) in transient manoeuvres such as a lane change than existing vehicles.
    - Vehicles that achieve increased length with shorter wheelbases similar to existing vehicles (i.e. extending behind rear axles) will tend to be significantly less stable in transient manoeuvres such as a lane change (e.g. an 18.55m vehicle with 8m wheelbase would display a 40% increase in path error and a 15% increase in rearward amplification compared with the standard vehicle). However, the steady state rollover threshold and susceptibility to cross winds would be comparable to existing vehicles
- The analyses suggest that it would be very difficult for a longer vehicle to provide a better performance than an existing vehicle in every metric considered. However, the analyses also suggest that there are no combinations where the performance is reduced in all metrics at the same

time – there is a trade-off based on wheelbase such that the measures which are adversely affected are often accompanied by measures where there is an improvement. This means that overall there can be net performance improvements relative to existing vehicles. Where individual reductions in performance are predicted these can be mitigated or improved by the imposition of design restrictions or new performance standards that force the use of new technology. For example, a height limit of around 4.6m would allow 18.55m vehicles to have approximately the same high speed stability performance as a 16.5m vehicle at 4.9m height, while electronic stability control would be expected to mitigate the risk associated with reduced rollover stability.

3.3 Fuel consumption and emissions results

The various vehicle masses were derived on the basis of the review contained in section 2 and published data on the average load when laden of existing vehicles. All the longer vehicles simulated were at the maximum length being considered in order to map the extremes. Summary inputs are provided in Table 6. Full details of the PHEM model input parameters for each of the vehicle classes is also given in Appendix A.

Table 6: Vehicle specifications used in the PHEM model.

		Existing Artic Single deck 16.5m (2+3)	Existing Artic Double deck 16.5m (2+3)	Existing Artic Single deck 16.5m (3+3)	Existing Artic Double deck 16.5m (3+3)	Existing Drawbar 18.75m (3+3)	Longer Artic Single deck 18.55m (3+3) Self Steer	Longer Artic Double deck 18.55m (3+3) Self Steer	Longer Artic Single deck 18.55m (3+3) Command Steer	Longer Artic Double deck 18.55m (3+3) Command Steer	Longer Artic Single deck 18.55m (3+3) Active Steer	Longer Artic Double deck 18.55m (3+3) Active Steer
Vehicle reference		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
							Fully-laden					
Unladen weight	kg	13,543	19,035	14,533	20,025	15,000	15,307	20,918	16,072	21,683	16,177	21,788
Maximum payload	kg	26,457	20,965	29,467	23,975	29,000	28,693	23,083	27,928	22,318	27,823	22,213
Gross weight	kg	40,000	40,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000
							Typical load					
Unladen weight	kg	13,543	19,035	14,533	20,025	15,000	15,307	20,918	16,072	21,683	16,177	21,788
Typical payload	kg	10,730	9,297	16,670	13,860	6,614	14,347	11,541	13,964	11,159	13,912	11,106
Gross weight	kg	24,273	28,332	31,203	33,885	21,614	29,654	32,459	30,036	32,841	30,089	32,894

The application of the PHEM model to the 11 vehicle types, the two levels of loading, combined with the 120 vehicle operating cycles and the one Euro emission class resulted in the generation of 2,640 data points for each of the 5 emission parameters, as indicated in Table 7.

Table 7: PHEM model input and output parameters.

Vehicle scenario	Laden condition	Drive cycle	Euro class	Emission parameter (FC, CO, THC, NO_X, PM)
Inputs				Output
11	2	120	1	2,640

For each of the vehicle scenarios, 120 data points were thus derived which related average cycle speed to a pollutant emission, expressed in g/km. For each combination of vehicle scenario, laden condition, Euro-emission standard and pollutant, average speed emission functions were derived. Although carbon dioxide (CO_2) is not calculated directly, it can be derived from the standard carbon balance equation, as specified in the Commission Directive 93/116/EC. Total CO_2 emissions were calculated by summing the fractional contributions of each carbon-containing exhaust pollutant. For CO, THC, and CO_2, the fractional contribution is calculated using relative atomic and molecular weights. For total hydrocarbons, an empirical formula of CH_2 was assumed. Given that the vast majority of carbon is directly emitted in the form of CO_2, the assumptions regarding THC do not significantly affect the result of the calculation.

The full results can be seen in Appendix B, Appendix C, and Appendix D and are summarised below.

For each of the vehicle types, the PHEM model has been used to estimate the emission of CO, HC, NO_X, PM, CO_2 and fuel consumption. The results from these model runs are presented in terms of vehicle specific emission plots and speed related emission functions. These functions were derived using simple power curves, with the following form:

$$E = a.v^b$$

Where:

v is speed in km/h

a & b are the coefficients contained in the tables in Appendix C

E is the emissions in g/km

Table 8, Table 9, and Appendix D provide the estimated emissions for each of the vehicle types, expressed in terms of g/km of pollutant, and in terms of grams per tonne km of payload. These emissions are estimated with an average associated vehicle speed of 86.9 km/h. This average speed is typical of existing 4 axle and 5+ axle articulated HGVs in operation on the existing high speed road network (DfT, 2006), which is expected to be representative of the type of use of longer semi-trailers. However, this may represent a more economical use than that of the average existing articulated vehicle, which will include, for example, vehicles with shorter trailers used for urban delivery.

Table 8: Emission rates for Euro 5 vehicles with typical laden weight

	Emission rates						
	CO (g/km)	HC (g/km)	NOx (g/km)	PM (g/km)	CO_2 (g/km)	FC (g/km)	Payload (kg)
Veh 1	0.094	0.012	2.406	0.021	729.054	230.042	10,730
Veh 2	0.098	0.012	2.773	0.021	856.511	270.258	9,297
Veh 3	0.098	0.012	2.842	0.021	892.060	281.455	16,670
Veh 4	0.102	0.012	3.076	0.022	987.257	311.493	13,860
Veh 5	0.096	0.012	2.483	0.021	734.406	231.741	6,614
Veh 6	0.098	0.012	2.838	0.021	884.623	279.117	14,347
Veh 7	0.103	0.012	3.090	0.022	989.663	312.248	11,541
Veh 8	0.099	0.012	2.859	0.021	890.704	281.040	13,964
Veh 9	0.103	0.012	3.106	0.022	996.861	314.521	11,159
Veh 10	0.099	0.012	2.862	0.021	891.621	281.322	13,912
Veh 11	0.103	0.012	3.109	0.022	997.671	314.779	11,106

	Emission rates per tonne of payload					
	CO (g/km/t)	HC (g/km/t)	NOx (g/km/t)	PM (g/km/t)	CO_2 (g/km/t)	FC (g/km/t)
Veh 1	0.009	0.001	0.224	0.002	67.945	21.439
Veh 2	0.011	0.001	0.298	0.002	92.128	29.069
Veh 3	0.006	0.001	0.170	0.001	53.513	16.884
Veh 4	0.007	0.001	0.222	0.002	71.231	22.474
Veh 5	0.015	0.002	0.375	0.003	111.038	35.038
Veh 6	0.007	0.001	0.198	0.001	61.661	19.455
Veh 7	0.009	0.001	0.268	0.002	85.750	27.055
Veh 8	0.007	0.001	0.205	0.002	63.786	20.126
Veh 9	0.009	0.001	0.278	0.002	89.335	28.186
Veh 10	0.007	0.001	0.206	0.002	64.092	20.222
Veh 11	0.009	0.001	0.280	0.002	89.830	28.343

Table 9: Emission rates for Euro 5 vehicles with maximum laden weight

	Emission rates						
	CO (g/km)	HC (g/km)	NOx (g/km)	PM (g/km)	CO_2 (g/km)	FC (g/km)	Payload (kg)
Veh 1	0.101	0.012	3.122	0.022	1014.192	319.972	26,457
Veh 2	0.104	0.013	3.235	0.022	1058.287	333.894	20,965
Veh 3	0.105	0.013	3.357	0.022	1110.782	350.447	29,467
Veh 4	0.113	0.013	3.549	0.023	1163.690	367.137	23,975
Veh 5	0.109	0.013	3.442	0.023	1136.841	358.669	29,000
Veh 6	0.108	0.013	3.437	0.023	1128.853	356.146	28,693
Veh 7	0.117	0.013	3.635	0.024	1184.341	373.641	23,083
Veh 8	0.108	0.013	3.423	0.023	1128.913	356.161	27,928
Veh 9	0.117	0.013	3.635	0.024	1184.375	373.658	22,318
Veh 10	0.108	0.013	3.423	0.023	1128.913	356.161	27,823
Veh 11	0.117	0.013	3.635	0.024	1184.375	373.658	22,213

	Emission rates per tonne of payload					
	CO (g/km/t)	HC (g/km/t)	NOx (g/km/t)	PM (g/km/t)	CO_2 (g/km/t)	FC (g/km/t)
Veh 1	0.004	0.000	0.118	0.001	38.334	12.094
Veh 2	0.005	0.001	0.154	0.001	50.479	15.926
Veh 3	0.004	0.000	0.114	0.001	37.696	11.893
Veh 4	0.005	0.001	0.148	0.001	48.538	15.313
Veh 5	0.004	0.000	0.119	0.001	39.201	12.368
Veh 6	0.004	0.000	0.120	0.001	39.342	12.412
Veh 7	0.005	0.001	0.157	0.001	51.309	16.187
Veh 8	0.004	0.000	0.123	0.001	40.422	12.753
Veh 9	0.005	0.001	0.163	0.001	53.069	16.743
Veh 10	0.004	0.000	0.123	0.001	40.575	12.801
Veh 11	0.005	0.001	0.164	0.001	53.320	16.822

The tables (and the graphs contained in the Appendices) show the emission rates for the different vehicle combinations – both as the actual tailpipe emission rate (grams per kilometre) and also in terms of the weight of the goods carried (grams per kilometre per tonne of payload). Generally, the heavier the vehicle and the larger the frontal area, the greater the exhaust emissions and fuel consumption.

It is important to note that the fuel consumption per vehicle km is not a good measure of the efficiency of the freight task. A better measure of fuel efficiency is the fuel consumption per unit of payload volume and distance travelled, i.e. per tonne km for mass constrained loads or per cubic-metre kilometre for volume constrained loads. Of course the most appropriate fuel efficiency measure would be the fuel consumed per unit of goods moved by the entire freight transport system, including all modes. Although not shown in the results tables here, efficiency is considered in all of these terms in the economic analyses.

The longer vehicle options produce very similar emissions to their corresponding current vehicle. There is a small increment in the emissions, due to a small increase in the aerodynamic drag from the vehicle's longer length and also due to a small increase in the unladen weight of the vehicle. These results are illustrated by Figure 28, showing strong correlation between total mass and fuel consumption when double deck and single deck variants are separated.

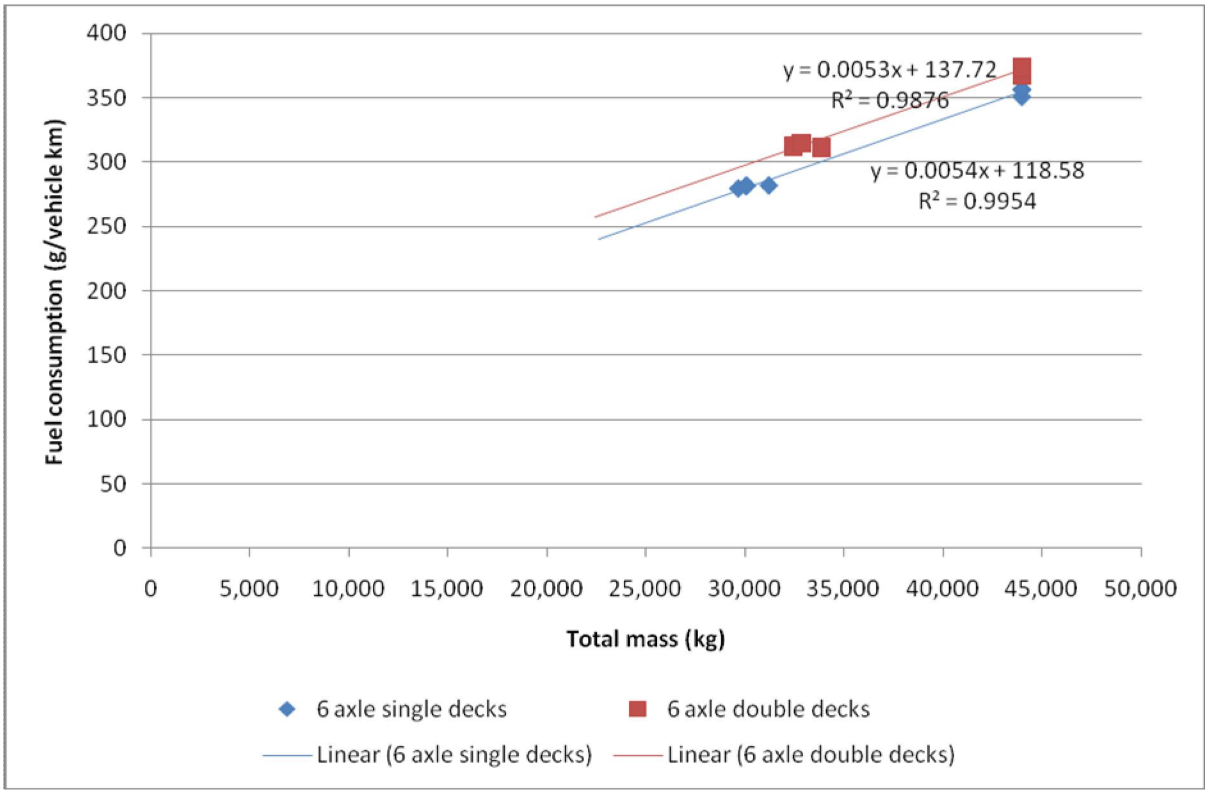


Figure 28. Relationship between mass and fuel consumption

These linear relationships can be used to estimate the fuel consumption and emissions for any load carried with a reasonable degree of accuracy.

4 Regulatory implications

The intention of this research was that the evidence gathering exercise to be undertaken with the freight industry would determine the increase in load units carried that would be of most benefit to them and that the vehicle analysis would then define three possible approaches to enable the vehicle to carry those load units. The anticipated levels were, first, to simply require the new vehicles to comply with all existing regulatory requirements. The second was to introduce new regulatory requirements intended to ensure that vehicles performed to the same standard that existing vehicles actually achieved (in some cases in excess of the minimum requirements). The third was to introduce new regulatory requirements that were intended to ensure that longer vehicles exceeded the performance of typical existing vehicles.

The findings of the simulation work have shown that it is not feasible to have requirements that, for every performance measure, consistently achieve equal or better performance compared with the existing vehicles. For this reason, three slightly different regulatory possibilities have been defined:

1. Retain existing length limits (do nothing)
2. Increase length, require compliance with all other existing regulations
3. Increase length, require longer vehicles to match or exceed actual performance of existing vehicles

Within the regulatory constraints of possibility number 2 it would be possible for industry to react in a number of different ways.

- Low tech – A maximum length of up to approximately 18.25m would be possible with a wheelbase of approximately 8m. However, if a uniformly distributed load that filled the vehicle was to be carried then existing axle mass limits for the tri-axle trailer bogie would prevent loading to more than 38 tonnes gross mass. Such a vehicle would be likely to produce a 40% increase in lane change path error and a 15% increase in rearward amplification compared with a standard vehicle. Other vehicle dynamics parameters such as cross wind performance would match or exceed those of the standard vehicle. Limiting the length increase would increase the maximum mass of uniformly distributed load that could be carried without exceeding axle weight limits and it is highly likely that a 17.8m vehicle would be feasible at 40 tonnes.
- Medium tech – This approach would, if implemented, involve the use of existing production steering systems for trailers. Vehicles could be up to 44 tonnes GVW and up to 18.55m overall length. It is expected that a single self steer axle would be required for a vehicle length of up to 17.5m (provided the axle geometry was correct) and that vehicles in excess of 17.5m (14.6m semi-trailer length) would require at least a single command steer axle, although it is possible that manufacturers may also find solutions involving either two self steer or two command steer axles. The consequences of such a move would be an increase in the susceptibility to cross winds of approximately 5% at 17.5m and approximately 10% at 18.55m (15.65m semi-trailer length), with a reduction of just under 2% in steady state rollover threshold, compared with a 13.6m vehicle. Other vehicle dynamics parameters such as rearward amplification or path error would match or exceed those of the standard vehicle. The dynamic performance assumes that like all existing systems the steer axles are locked at speed. New regulation may be required to enforce this condition.

In theory regulatory possibility number 2 should require no additional means of enforcement because it merely requires compliance with existing regulations. However, existing regulations do contain some deficiencies. In particular, the manoeuvrability requirements are intended to provide tail swing limits for all vehicle types. However, the fact that the two parts of an articulated vehicle are approved separately and used in different combinations in practice gives rise to some difficulties. These are overcome by allowing trailers to be approved by formula. This results in a tail swing of existing combinations that is well within the limits applied for rigid trucks and buses. However, the formula used is not dependant on vehicle length and thus if length were to be increased using the same formula it would allow only semi-trailers with the same wheelbase as existing semi-trailers, meaning only the low tech vehicle combinations discussed above would be permissible. In addition the formula applies no tail swing limit and as such the combinations that could arise from longer semi-trailers approved to the same formula would exhibit much greater tailswing than existing vehicles and, in some cases, greater than the limits applied to other vehicle types.

In order to prevent this outcome it would either be necessary to produce a new, more sophisticated formula or to effectively require the semi-trailer to be designed in such a way that the combination would meet the manoeuvrability limits applied to a rigid truck (or alternatively bus) regardless of what (approved) tractor unit was towing it. This would allow increased wheelbase and limit tailswing to either 0.8m (steady state method) or 0.6m (drive in method). This would have the effect of limiting the maximum length that could be achieved with a fixed axle trailer to approximately 18.3m.

The medium technology combinations that could potentially arise from regulatory possibility ii) use existing steer axle technology. All such axles are effectively locked at high speed, which is necessary to avoid dangerous instability. This is in accordance with the general provisions in the steering Directive 70/311/EC that:

"*The steering equipment shall ensure easy and safe handling of the vehicle up to its maximum design speed or, in the case of a trailer, up to its technically permitted maximum speed".*

However, there is no specific requirement governing this. If it was considered necessary to avoid doubt then specific provisions could be added. This could be based on technical requirements to lock the axles but this would be design prescriptive and would limit the benefits of more advanced active steer system to the low speed manoeuvrability area. Alternatively, a dynamic test such as the lane change simulated in Section 3.2. could be required which would achieve the desired level of performance without restricting how this was achieved in terms of vehicle design, which would allow industry more opportunity to innovate.

Under regulatory possibility number 3, only one approach would be possible:

- High tech - Vehicles would need to be fitted with a new generation of active trailer steering systems, such as those described by Jujnovich et al (2008). Vehicles of up to 44 tonnes and 18.55m overall length (15.65m semi-trailer length) could be considered. Maximum length vehicles would have a 10% increase in load transfer during crosswinds and just under 2% reduction in steady state rollover threshold compared with a 16.5m vehicle. Other vehicle dynamics parameters such as cross wind performance would match or exceed those of the standard vehicle. It is also worth noting that active steering systems mean significant improvements would be possible in some of the high speed parameters if the system was tuned to the specific vehicle configuration, e.g. a 20% reduction in lane change load transfer.

Each of these approaches could potentially involve continuing with no height limit or implementing a new height limit, assumed to be 4m in line with the European standard for the purposes of this analysis. The height of the vehicle has no influence on the static distribution of load amongst the axles and the manoeuvrability. The relative effects described above on the vehicle dynamics measures (e.g. steady state rollover, lane change RA, cross wind susceptibility etc) are also much the same for vehicles at both heights (i.e. the influence of length and wheelbase are the same irrespective of height). However, comparing the two heights (4m compared with 4.9m) at any particular length shows that a 4m high vehicle will have a stability performance considerably better than 4.9m tall vehicle.

If a 16.5m long, 4.9m tall vehicle is considered the benchmark that any new vehicle must perform better than, then the results show that it is not possible for longer 4.9m vehicles to perform as well or better in all high speed stability parameters. Where performance is worse it will be at least partially offset by improved performance in other dynamic parameters because there are important trade-offs depending on wheelbase. However, it could be considered that such a benchmark should be rigorously applied such that no deterioration in any performance measure, even those that are currently unregulated, would be acceptable. In this case it would be possible to achieve this by limiting the maximum height of a longer trailer to approximately 4.6m. However, such a height limit would be design prescriptive, which is generally avoided if possible. It may be possible to achieve the desired performance at 4.9m height by alternative means, perhaps by aerodynamic styling of the roof edges, active suspension and/or tuning of an active steering system. Enforcing the requirements without preventing innovative solutions would require a performance based evaluation, which could for example include a lane change test and a cross wind sensitivity test. Potentially either could be permitted a “virtual” equivalent by computer simulation techniques.

Although the economics of the operation were to be considered separately from the vehicle design and regulatory environment, the two cannot be considered in isolation. Each of the three approaches described above has quite different implications for capital cost, unladen weight, ability to access difficult sites and fuel consumption and this in turn could have a substantial influence on whether it is economically attractive to have the increased carrying capacity. All of these factors were, therefore, accounted for in the MDS Transmodal analysis of running costs (MDS Transmodal, 2010).

5 Assessing the effects on accidents and casualties

Knight *et al* (2008) identified potential safety effects of LHVs of different types, which were categorised as follows:

- Manoeuvrability, including swept path of the vehicle;
- Field of view;
- Braking;
- Stability;
- Collision severity; and
- Junctions, railway crossings and overtaking.

Since the 2008 report, the susceptibility of longer vehicles to cross winds has also been identified as another potential hazard. This section of the report aims to investigate which of these identified risk areas will be applicable to the form of longer articulated vehicle considered by this report based on the analysis of accident data involving current vehicles and the results from the dynamics simulations reported in section 3.2.

5.1 Methodology

Each of the potential safety risks listed above was reviewed in relation to risks posed by increasing the length of semi-trailers to 15.65m. Where the risk was considered relevant to longer semi-trailers, criteria were developed to enable the number of accidents that currently occur in situations likely to be affected (defined as “target populations”) to be identified. Where the risk was not considered to be applicable to longer semi-trailers, the reasoning behind excluding the risk from further analysis is reported.

Each target population was then quantified using accident data. The number of casualties was combined with exposure data from the Continuing Survey of Road Goods Transport (CSRGT) and the traffic census to derive casualty rates per vehicle kilometre and per tonne kilometre. Where possible, the target populations were defined using the Stats19 database to ensure that the data is nationally representative. However, the ideal target population cannot always be defined using the variables available in Stats19. In such circumstances a more generalised target population has been defined in Stats19 and refined based on more detailed sample data from the HVCIS fatal accident database.

The effect that the predicted changes in physical performance, identified from the simulations of the baseline and candidate vehicles, is likely to have on the accident rates for the target populations was then estimated. The total accident rate for all accident types (both for those accident types affected by the changes and those that are not) were then calculated for use as inputs to the economic model.

5.2 Definition of the target populations

The target population is a group of accidents/vehicles/casualties that could potentially be affected by the proposed change. There can be a single target population, or as in this case, multiple target populations. Each target population has been defined for articulated HGVs only. It should be noted that this analysis is attempting only to identify where the risks presented by longer articulated vehicles is different to that presented by existing articulated vehicles. It is not attempting to catalogue all safety risks associated with existing articulated vehicles and excluding any risk from further analysis does not mean that the risk does not exist, only that it is not likely to be significantly greater if vehicle length were to be increased.

5.2.1 Low speed manoeuvrability

Increased vehicle length can reduce the manoeuvrability of the vehicle, potentially presenting an increased risk of accidents and injuries. There are two main factors to consider; low speed off-tracking (or cut-in) and rear out-swing (or tail swing).

Low speed off-tracking occurs when a vehicle combination turns at a low speed, where the path of the trailer can be several meters inside the path taken by the tractive unit. The types of accident likely to be affected are those where:

- The HGV is turning left and has an impact to its nearside. The road users injured can either be pedestrians, pedal cyclists or occupants of other vehicles.
- The HGV is turning right and has an impact on its offside. The road users injured are likely to be other vehicle occupants.
- The HGV is performing a U-turn and is impacted on either side.
- The HGV is negotiating a roundabout and has an impact on its offside.

Out-swing or tail swing is the lateral distance that a point on a vehicle moves outwards, perpendicular to its initial orientation, when the vehicle commences a small radius turn at low speed. The types of accident likely to be affected are those where:

- The HGV is turning left and has an impact to its offside. The road users injured can either be pedestrians, pedal cyclists or occupants of other types of vehicle.
- The HGV is turning right and has an impact to its nearside. The road users injured can either be pedestrians, pedal cyclists or occupants of other types of vehicle.
- The HGV is performing a U-turn.
- The HGV is negotiating a roundabout and has an impact on its nearside.

5.2.2 Field of view

The field of view from a vehicle is defined as the areas that can be seen by the driver, either directly through the glazed areas or indirectly through the use of mirrors or other types of field of view aid. Despite increases to the minimum field of view requirements for HGVs, some blind spots still remain, which can contribute to accidents, particularly when manoeuvring at low speed or changing lanes. Many of the blind spots are associated with the field of view from the cab of the HGV, which is not expected to be affected by changes to the length of semi-trailers.

The longer semi-trailers would not introduce any additional points of articulation relative to current vehicles and therefore no additional blind spots associated with the gap between the tow vehicle and the trailer would be expected.

The only potential effect on field of view for longer semi-trailers would be related to the drivers' ability to see the extreme rear of the trailer in the mirrors when making tight turns. This potential effect would mean that the rear end would not be visible in the mirror at a smaller articulation angle for longer semi-trailers than for standard ones. However, for right turns, at least, the trailer is likely to be visible directly and where manoeuvrability is maintained or improved using steering axles, the articulation angle may in fact be less than for standard vehicles, thus meaning the view of the rear would be the same as, or better than, that of standard vehicles.

The potential effects of field of view have therefore not been considered any further because of the similarities between the proposed vehicle type and existing vehicles.

5.2.3 Braking

While braking, a vehicle should achieve as high a level of deceleration as possible without losing stability or directional control. Knight et al (2008) identified that providing vehicles were all equipped with ABS, the main risks were associated with longer heavier vehicles of the type considered was the additional delay between activating the brake pedal and developing full brake forces at the rearmost axle. This was a function of the increased distance between brake pedal and furthest axle and the finite amount of time it takes the air pressure wave to travel along the pipe.

However, the change in wheelbase for the semi-trailers under consideration is likely to range between zero (low tech approach) and around 1.5m (for medium and high tech approaches at 18.55m overall length). The difference between the proposed vehicle and existing vehicle is, therefore, relatively small. Even with a purely pneumatic braking system this is not likely to have a significant effect on braking distance and the use of electronically controlled brakes would certainly eliminate any disadvantage. For this reason, braking has not been considered further.

5.2.4 Lateral Stability

Vehicle lateral stability can involve either:

- Yaw (or directional) instability where at least one part of the combination starts to follow a path different to that demanded by the driver; or
- Roll instability where at least one part of the combination begins to roll over

The simulations reported in section 3.2 have shown a variety of lateral stability effects, in particular with a small reduction in steady state rollover threshold being likely for medium and high tech approaches (longer wheelbase) and a more significant increase in rearward amplification and path error in transient manoeuvres for the low tech approach (shorter wheelbase).

Accident types that could potentially be influenced by lateral stability issues are:

- Leaving the road on a bend (loss of control not fatigue related);
- Loss of control whilst changing lane
- Rollover on a bend; and
- Rollover while changing lane.

5.2.5 Side-wind induced rollover

Increasing the length of a vehicle has the potential to increase the risk of the vehicle rolling over because the increased surface area at the side will increase the aerodynamic forces applied by side-winds. However, the simulations reported in section 3.2 showed that this was largely offset by the increased unladen weight such that cross wind susceptibility was largely insensitive to overall length. It was, however, found to be sensitive to wheelbase such that medium and high tech options would be likely to be slightly more vulnerable to cross winds than standard vehicles.

The first step for this factor was to identify accidents where the HGV overturned and there were high winds recorded. The presence of high winds is recorded in Stats19 if the winds were considered to have adversely affected the driving conditions for one or more of the vehicles involved but it does not directly record if the high winds were a contributory cause of the accident. Further evaluation has, therefore, been undertaken using more detailed accident databases, described later in this report.

5.2.6 Collision severity

Knight *et al* (2008) considered collision severity because the proposed vehicle types included increases to the GVW. However the current study is only considering an increase to vehicle length and not GVW. If there is no change to the overall mass there will be no effect on collision energy and thus no influence on casualty severity (assuming the same speed distribution, vehicle geometric compatibility and structural stiffness for new and existing vehicles). Collision severity has therefore not been considered any further. It should be noted, however, that all the target populations have been identified using the STATS19 database, which only covers injury accidents; it is possible that a disproportionately high number of articulated HGVs are involved in single vehicle crashes where no injuries are involved (compared to other vehicle types). Such incidents (e.g. low speed roll-overs on roundabouts or due to cross winds) may well not be recorded in STATS19 because there are no reportable injuries, but may still represent significant costs in terms of property damage and congestion. There is thus the possibility that the benefits estimates relating to heavy vehicle stability (based on STATS19) may slightly under-estimate the costs relating to these crash types and the benefits of any reductions.

This represents a limitation of the analyses of these accident types because no systematic data on non injury accidents is available to quantify this potential effect. Although this may call into some question the absolute values of the target populations and costs estimated for these accident types, the final estimates of the effects of longer semi-trailers are based on estimates of relative risk and are therefore unlikely to be affected by this limitation.

5.2.7 Junctions, railway crossings and overtaking

Increasing the length of a vehicle has the potential to affect the time taken for such vehicles to clear junctions or railway crossings, or to be overtaken by other vehicles. Increasing the time taken for a vehicle to be overtaken can result in the overtaking vehicle being exposed to oncoming traffic for a slightly longer period of time. This is particularly relevant to single carriageway roads. It is also possible to speculate that traffic following a longer vehicle would be slightly less likely to risk an overtake, which may mitigate some or all of the increased risk if an overtake is attempted. This factor is not considered further in the analyses, but it does mean that the additional risk factors calculated have the potential at least to over-estimate any increased accident risk.

The accident types potentially affected are:

- Accidents at a junction (including mini-roundabouts, roundabouts and slip roads);
- Accidents where an HGV is being overtaken on a single carriageway road.

The identification of accidents where an HGV has been overtaken is difficult because there are generally at least three vehicles involved in the accident and there is no accident description to ensure that the vehicle that was being overtaken has been correctly identified. Therefore a simplified approach has been taken. This involved the selection of accidents where:

- There was an articulated HGV involved on a single carriageway road, not at a junction;
- More than two vehicles were involved in the accident; and
- One vehicle was overtaking (a moving or stationary vehicle) and had a front-front collision with another vehicle that was “going ahead”.

Cross referencing accident descriptions in the HVCIS fatal accident database suggested that this definition correctly identified the accidents, although it will provide an over-estimate of the target population because other types of vehicle were also included. For example, accidents where a car overtakes another car and has a head-on collision with an HGV were also identified by this definition.

Accidents on railway level crossings could only be partially identified because they are only included in Stats19 if there was no train involved (Stats20, 2005). Whilst it may be possible to obtain further information regarding accidents on level crossings that did involve a train from the Rail Accident Investigation Branch of the DfT, this was considered to be outside of the scope of the project and likely to involve such a small number of cases that there would be no significant effect on the overall target population estimates.

5.3 Quantifying the target populations using Stats19 data

Table 10 shows some contextual data, the number of accidents involving HGVs and the number of casualties resulting from these accidents. The numbers reported are the annual average for the period 2006 to 2008 inclusive. The proportion of accidents involving articulated HGVs and the resulting casualties are also shown.

Table 10. Annual average (2006-2008) number of accidents and casualties involving HGVs and proportion of which involved articulated HGVs.

Severity	All types of HGV		% involving articulated HGVs	
	Accidents	Casualties	Accidents	Casualties
Fatal	371	407	44.9%	46.2%
Serious	1,308	1,539	37.2%	38.7%
Slight	7,891	11,393	36.4%	37.0%

The proportion of truck accidents (and casualties) that involved articulated HGVs increases with accident severity, from approximately 36% for slight accidents to 45% for fatal accidents. This is highly likely to reflect the fact that articulated HGVs are on average considerably heavier than rigid HGVs.

5.3.1 Low speed manoeuvrability

Table 11 identifies the number and severity of truck accidents that could potentially be considered relevant to the low speed manoeuvrability performance of vehicles, based on an annual average for the years 2006-2008.

Table 11. Low speed manoeuvrability target population.

Accidents involving…		Fatal	Serious	Slight
All HGVs		371.00	1,308.00	7,891.00
Articulated HGVs		166.67	486.67	2875.67
Low speed off-tracking	Turning left with impact to nearside	2.33	6.33	24.33
	Turning right with impact to offside	0.33	10.00	42.33
	U-turn with impact to off-side	0.33	2.67	5.00
	Negotiating roundabout with impact to offside	0	2.33	35.00
Out-swing or tail-swing	Turning left with impact to offside	0.33	4.00	15.67
	Turning right with impact to nearside	0.67	7.67	39.00
	U-turn with impact to nearside	0.33	0.67	1.00
	Negotiating roundabout with impact to nearside	2.33	8.33	49.33
Manoeuvrability Target population		6.7	42.0	211.3*

* This is not equal to the sum of the number of accidents in rows above because one accident (0.33 when averaged over 3 years) appears twice in the categories above. The accident involved two articulated HGVs both recorded as going ahead on a roundabout, one with an impact to the nearside and one with an impact to the offside.

5.3.2 Lateral stability and side-wind induced rollover

When identifying the target population of accidents that could potentially be influenced by vehicle stability performance, it became apparent that the stability target population was not mutually exclusive of the side-wind induced rollover target population. Thus, further consideration of the overlap in these target populations was required. There was also potential overlap between accidents where a vehicle lost control while changing lane and those where the HGV left the carriageway on bend. To identify the stability related accidents, the following fields from Stats19 were used:

- Weather conditions – where high winds were present;
- Skidding and overturning – where overturning was recorded;
- Vehicle manoeuvre – going ahead on a left or right hand bend, changing lane to left or right, or overtaking a moving vehicle, going ahead.
- Vehicle leaving carriageway – where the vehicle left the carriageway including rebounding but excluding where the vehicle left carriageway by going straight on at a junction.
- Road type – to determine if the accident occurred on a roundabout or slip road.
- Contributory factor – loss of control.

These criteria can be classified into those which contributed to the accident and those which were a consequence of the drivers' actions. These can then be organised in a hierarchy as shown in Figure 29.

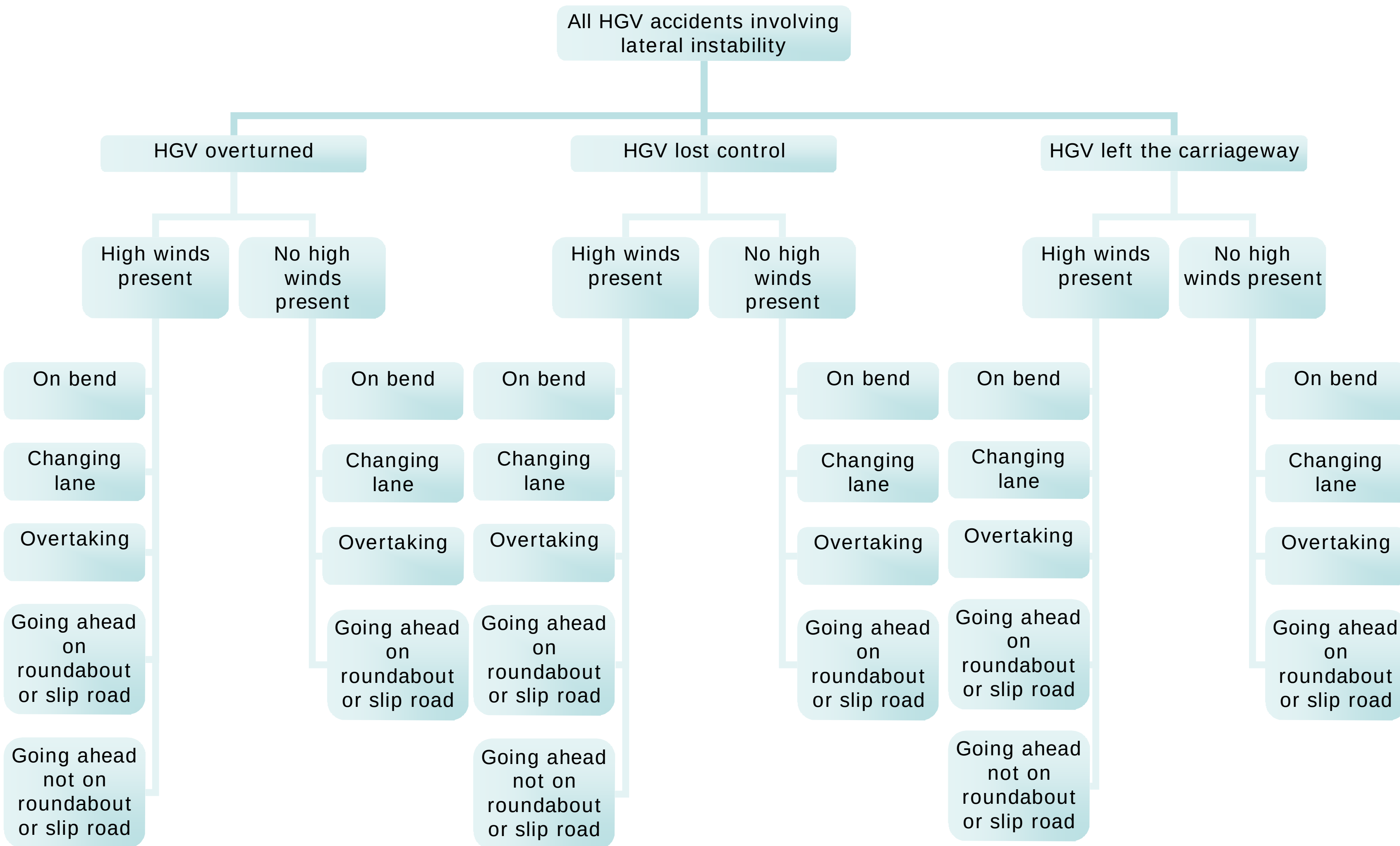


Figure 29. Hierarchical organisation of criteria for selection of accidents involving lateral instability.

Table 12 to Table 15 show the number of accidents associated with each of the accident groups defined in Figure 29.

Table 12. Accidents involving HGVs where lateral instability occurred.

Accidents involving...		Fatal	Serious	Slight
All HGVs		371.00	1,308.00	7,891.00
Articulated HGVs		166.67	486.67	2875.67
Which...	Overturned*	16.33	64.00	208.00
	Left the carriageway*	36.67	76.00	263.33
	Lost control*	11.67	49.33	179.00

*Not mutually exclusive

However, not all accidents within these groups will be affected by the increased semi-trailer length. For example, not all vehicles that overturn did so because of poor vehicle stability, for example, some overturned after colliding head on with other vehicles.

Table 13. Accidents where an articulated HGV overturned where vehicle instability was a possible contributory cause of the accident.

High winds present	Manoeuvre	Fatal	Serious	Slight
Yes	On bend	0.33	1.67	3.33
	Changing lane	0	0	0.33
	Overtaking	0	0	0.33
	Going ahead on roundabout or slip road	0	0.33	3.67
	Going ahead not on roundabout or slip road	1.00	4.67	15.00
	Other	0	0.33	0.33
No	On bend	4.67	21.00	66.00
	Changing lane	0.33	1.00	3.33
	Overtaking	0.67	0	1.33
	Going ahead on roundabout or slip road	1.00	6.67	23.67
Total Overturned		8.0	35.7	117.3

Table 14. Accidents where an articulated HGV left the carriageway where vehicle instability was a possible contributory cause of the accident.

High winds present	Manoeuvre	Fatal	Serious	Slight
Yes	On bend	0.33	1.33	4.33
	Changing lane	0	0	0.67
	Overtaking	0	0.33	0.33
	Going ahead on roundabout or slip road	0	0	2.00
	Going ahead not on roundabout or slip road	1.33	4.67	13.33
	Other	0	0	0.67
No	On bend	8.33	22.00	66.67
	Changing lane	2.00	2.00	9.67
	Overtaking	1.00	0.33	4.33
	Going ahead on roundabout or slip road	0.67	2.67	17.67
Leaving carriageway total		13.7	33.3	119.7

Table 15. Accidents where an articulated HGV lost control where vehicle instability was a possible contributory cause of the accident

High winds present	Manoeuvre	Fatal	Serious	Slight
Yes	On bend	0	1.33	3.00
	Changing lane	0	0	0.67
	Overtaking	0	0	0.33
	Going ahead on roundabout or slip road	0	0.33	2.00
	Going ahead not on roundabout or slip road	0.33	2.33	6.67
	Other	0	0	0.33
No	On bend	4.67	15.33	59.00
	Changing lane	1.00	1.33	4.67
	Overtaking	0	0.67	1.33
	Going ahead on roundabout or slip road	0.33	4.33	15.33
Loss of control total		6.3	25.7	93.3

This approach results in a total of 27 groups of accidents which make up the stability target population. However these groups are not mutually exclusive at the highest level, as shown in Figure 30.

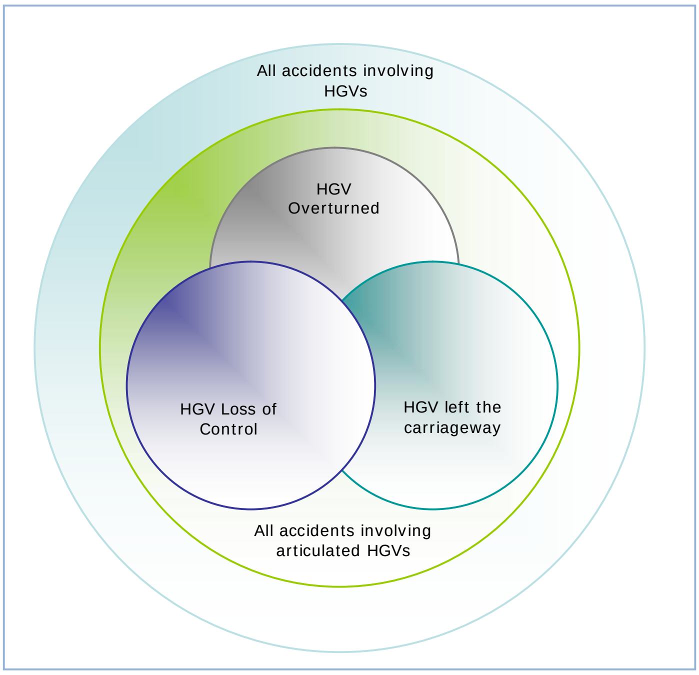


Figure 30. Relationship between the upper level accident selection criteria.

Figure 31 shows the overlap between the three high level target populations. This shows that there were 18.3 fatal accidents in the target population where vehicle instability may have been a contributory cause.

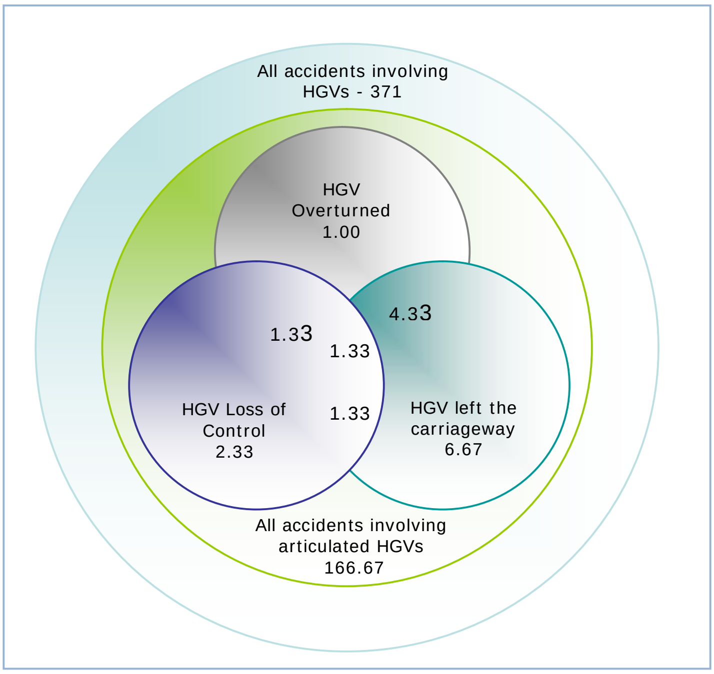


Figure 31. Number of fatal accidents and overlap between vehicle stability TPs.

Figure 32 shows the relationships between the high level target populations for serious accidents, with 54.3 serious accidents relating to vehicle stability.

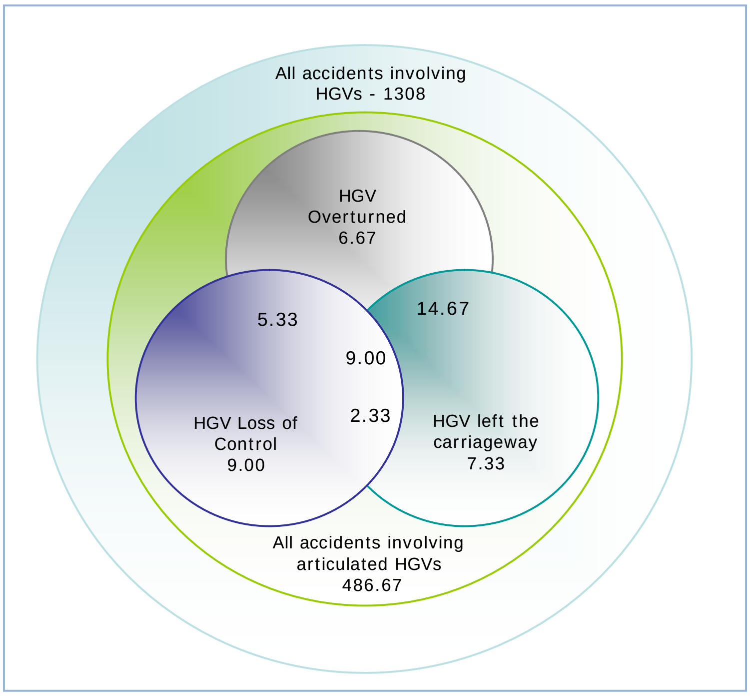


Figure 32. Number of serious accidents and overlap between target populations relating to vehicle stability.

Figure 33 shows that the stability target population consists of 199.3 slight accidents.

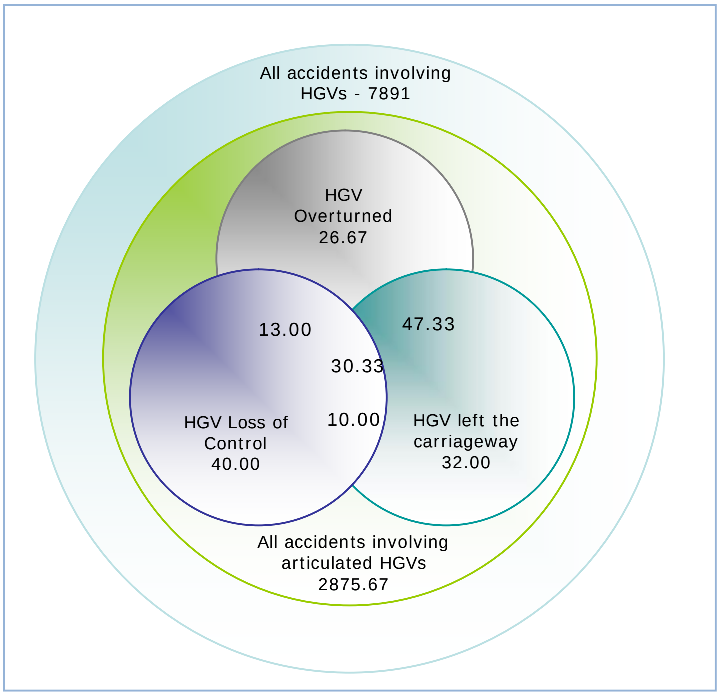


Figure 33. Number of slight accidents and overlap between target populations relating to vehicle stability.

The stability target population (summed for all three years analysed) is summarised in Table 16. Figures in brackets are the three year averages.

Table 16. Stability and wind loading target population.

Accidents involving...		Fatal	Serious	Slight
All HGVs		1,113 (371.00)	3,924 (1,308.00)	25,673 (8,557.67)
Articulated HGVs		500 (166.67)	1,460 (486.67)	8,627 (2,875.67)
Which...	Overturned*	24 (8.00)	107 (35.67)	352 (117.33)
	Left the carriageway*	41 (13.67)	100 (33.33)	359 (119.67)
	Lost control*	19 (6.33)	77 (25.67)	280 (93.33)
Stability target population		55 (18.3)	163 (54.3)	598 (199.3)

*Not mutually exclusive, hence they sum to more than the total

The stability target population accounts for 4.9% of fatal accidents, 4.2% of serious accidents and 2.3% of slight accidents involving HGVs of all types.

5.3.3 Junctions, railway crossings and overtaking

Table 17 shows the target populations for accidents occurring at junctions and accidents where an articulated HGV was being overtaken. These two groups were designed to be mutually exclusive, with accidents where the HGV is being overtaken specifically excluding any that occurred at any sort of junction.

Accidents on railway level crossings are not included in Stats19 if a train was involved. There is no specific guidance in terms of the road classification or layout on how to deal with accidents occurring on level crossings that do not involve a train.

Table 17. Target populations for accidents at junctions and those involving articulated HGVs being overtaken (06-08 average).

Accidents involving...	Road Type	Fatal	Serious	Slight
All HGVs	All	371.00	1,308.00	7,891.00
Articulated HGVs	All	166.67	486.67	2875.67
At a junction	All	43.00	168.33	1,079.67
	Motorway/A(M)	*2.00*	*13.67*	*118.67*
	A Road	*34.67*	*121.00*	*768.33*
	Other	*6.33*	*33.67*	*192.67*
Where HGV was being overtaken	All	4.00	13.33	20.00
	Motorway/A(M)	*0*	*0*	*0*
	A Road	*4.00*	*12.00*	*14.33*
	Other	*0*	*1.33*	*5.67*
Junction and overtaking target population		47.0	181.7	1,099.7

5.3.4 *The combined target population*

The combined target population combines the three target populations defined earlier; low speed manoeuvrability, stability and junction/overtaking. Some accidents will fit into more than one of these three categories and therefore it is necessary to identify the overlap between the groups of accidents.

Figure 34 shows the overlap between the casualty groups for fatal accidents. The annual average number of fatal accidents within the overall target population is 61.3.

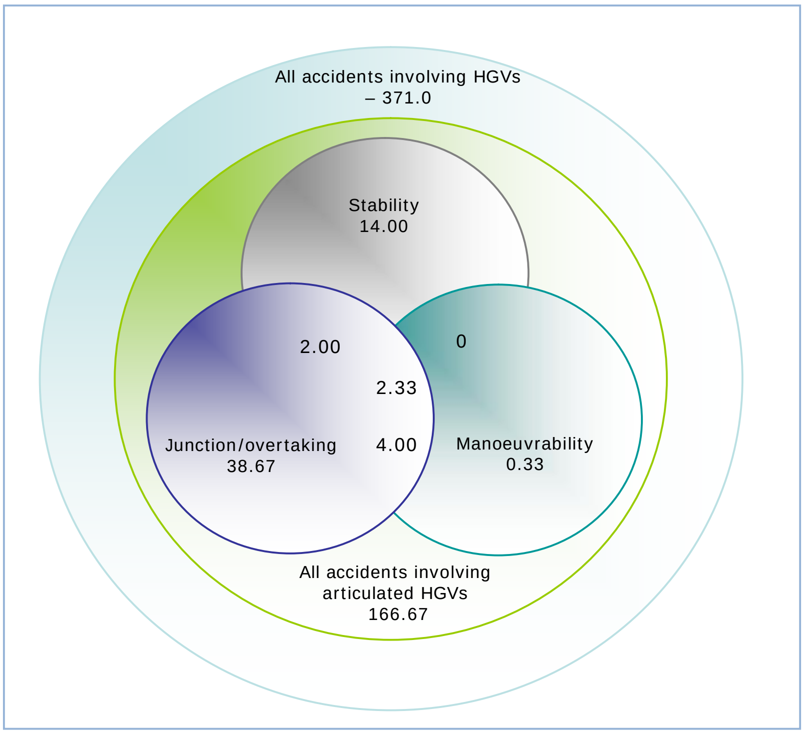


Figure 34. Overall target population – fatal accidents.

Figure 35 shows the overall target population for serious accidents is 219.3 per year.

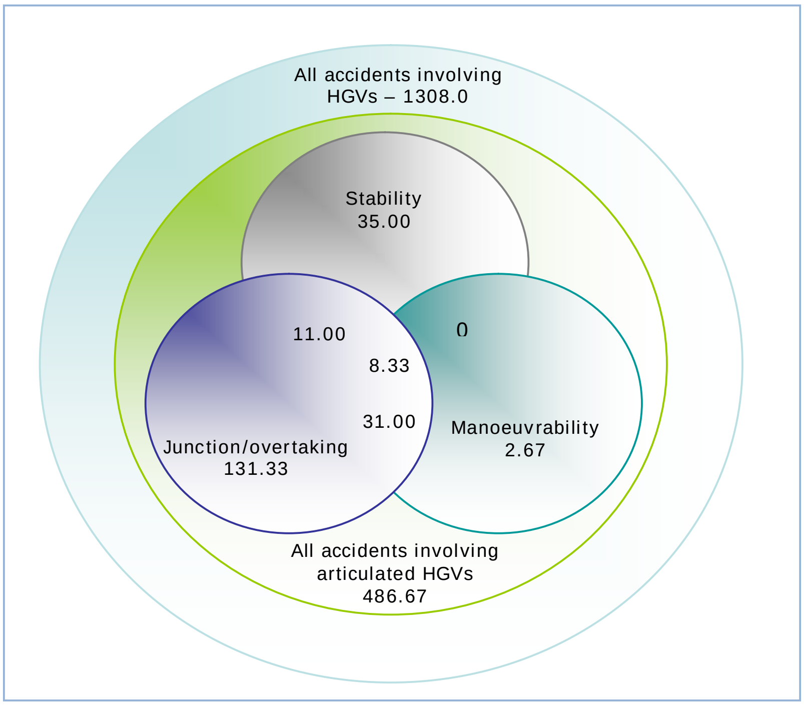


Figure 35. Overall target population – serious accidents.

The overall target population for slight casualties is 1223.7 per year, shown in Figure 36.

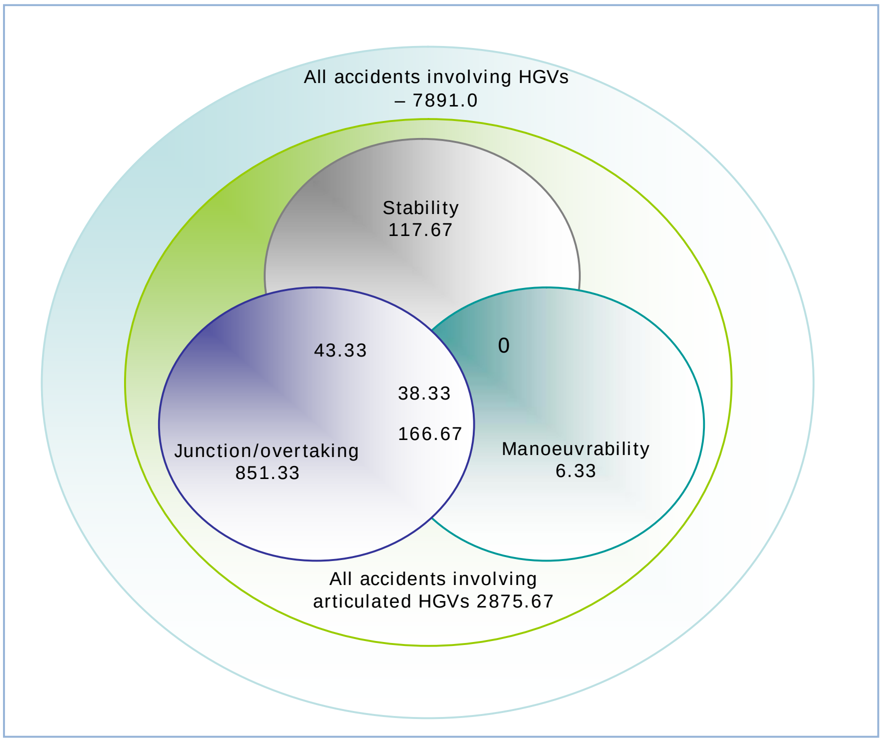


Figure 36. Overall target population – slight accidents.

Table 18 summarises the target populations and the overall target population.

Table 18. Overall target population.

Accidents involving...		Fatal	Serious	Slight
All HGVs		371.00	1308.00	8557.67
Articulated HGVs		166.67	486.67	2875.67
	Manoeuvrability*	6.67	42.00	211.33
	Stability*	18.33	54.33	199.33
	Junction/Overtake*	47.00	181.67	1099.67
Overall target population		61.3	219.3	1223.7

*Not mutually exclusive hence sum of parts is greater than the stated total.

5.4 Refining the target populations using HVCIS data

The target populations have been defined using Stats19. There are limitations with this approach because it is not possible to define the target population at the perfect level of detail. This section describes analyses intended to refine those target populations where the available Stats19 variables were considered to offer only weak identification of relevant accidents, mainly wind induced rollover and accidents involving junction blocking and overtaking. This has been undertaken using the Heavy Vehicle Crash Injury Study (HVCIS) fatal accident database which contains more detailed data on accidents involving HGVs from 1997 to 2006 inclusive.

5.4.1 *Wind induced rollover*

In Stats19 it is only possible to identify accidents where an HGV overturned and where high winds were present. It is not possible to identify specifically if the high winds caused the vehicle to overturn. The query designed to select accidents where the HGV overturned and high winds were present was applied to a Stats19 data set including data from accidents between 1997 and 2006 inclusive. This data set was used to match the years of data available in the HVCIS fatal accident database.

Cross-referencing the Stats19 accidents with the HVCIS database identified three accidents common to both where there was an articulated HGV involved and there were high winds present. Reviewing the accident descriptions:

- The rollover of the HGV was induced by the wind for one accident;
- The rollover of the HGV was not induced by the wind for one accident; and
- The rollover of the third HGV may have been contributed to by the wind, but the HGV was also travelling around a roundabout at an inappropriate speed.

This analysis suggests that approximately half of the rollovers where high winds were present were caused by the wind. However, the sample is too limited to have confidence in this result, and thus the original wind-related target populations identified by Stats19 have been retained. This will represent a conservative assumption because it is highly likely that at least some rollovers that occur when high winds are present would have occurred even if high winds were not present.

5.4.2 *Accidents at junctions*

Using Stats19 it was possible to identify accidents involving articulated HGVs that occurred within 20m of a junction. However the main concern with longer semi-trailers is that the extra length could block junctions. To help identify the proportion of accidents that occur within 20m of a junction where the length of the semi-trailer could be a problem, the accidents from Stats19 (1997-2006) identified by the query were cross referenced to the HVCIS fatal accident database. The HVCIS database contained 276 accident descriptions that were matched to accidents identified in Stats19, three of which were related to the vehicle overhanging/blocking a junction. Two accidents involved the HGV waiting to turn right in the gap in the central reservation and the third involved the HGV waiting to turn right while blocking the carriageway. This analysis suggests that approximately 1% of the accidents at junctions related to the length of the vehicle involved blocking the carriageway.

5.4.3 *Accidents where HGV is being overtaken*

The same approach was taken for accidents where an articulated HGV was being overtaken on a single carriageway road. Cross referencing accident descriptions in the HVCIS fatal accident database suggested that this definition correctly identified the accidents but also captured other types of accident, for example, those where a car overtook another car and had a head-on collision with an HGV. There were 38 accident descriptions identified in the HVCIS database that were selected by the Stats19 query, 27 of which were accidents where an HGV was being overtaken, suggesting that the target population relating to HGVs being overtaken is approximately 71% of that identified by Stats19.

5.4.4 *Refined target populations*

There is insufficient data to repeat this analysis for non-fatal accidents. Assuming that the same proportions of relevant accidents identified by the HVCIS data can be equally applied to the Stats 19 sample for non-fatal accidents, Table 19 shows how this information can be used to refine the target populations.

Table 19. Modified junction and overtaking target population.

Accidents	Fatal	Serious	Slight
At a junction (S19)	43.00	168.33	1,079.67
Modified by HVCIS (1%)	0.43	1.68	10.80
Where HGV was being overtaken (S19)	4.00	13.33	20.00
Modified by HVCIS (71%)	2.84	9.47	14.20
Junction and overtaking target population (S19)	*47.00*	*181.67*	*1,099.67*
Modified by HVCIS	*3.3*	*11.2*	*25.0*

To account for this modification to the junction and overtaking target population:

- The overall number of accidents in the junction and overtaking category were reduced to the values shown in Table 19.
- The total numbers of accidents in the manoeuvrability and stability target populations were kept constant, as were the proportions of the junction and overtaking accidents falling into each overlap category.
- The remaining accidents originally classified as involving junction/overtaking and also classified as involving manoeuvrability and/or stability were reclassified as manoeuvrability only, stability only or involving both stability and manoeuvrability, as appropriate to their original classifications.

Table 20 shows the data used and the estimated modified overall target populations.

Table 20. Modified overall target populations (averaged accidents per year).

Overlap groupings			Original populations			Modified populations		
Junction/ overtaking	Stability	Manoeuvrability	Fatal	Serious	Slight	Fatal	Serious	Slight
✓	X	X	38.7	131.3	851.3	2.7	8.1	19.4
✓	✓	X	2.0	11.0	43.3	0.1	0.7	1.0
✓	✓	✓	2.3	8.3	38.3	0.2	0.5	0.9
✓	X	✓	4.0	31.0	166.7	0.3	1.9	3.8
X	✓	X	14.0	35.0	117.7	15.9	45.3	160.0
X	✓	✓	0	0	0	2.2	7.8	37.5
X	X	✓	0.3	2.7	6.3	4.1	31.8	169.2
All junction/overtaking			47.0	181.7	1099.7	3.3	11.2	25.0
All stability			18.3	54.3	199.3	18.3	54.3	199.3
All manoeuvrability			6.7	42.0	211.3	6.7	42.0	211.3
Overall Target Population			61.3	219.3	1223.7	25.4	96.1	391.7
% of all articulated HGV accidents						15%	20%	14%
% of all HGV accidents						7%	7%	5%

Note: numbers may not sum to totals shown due to rounding

5.5 Potential effects of longer semi-trailers on accident rates

This section describes how the different performance characteristics of longer articulated vehicles have been applied to the target populations defined above to estimate the potential for changes to accident and casualty rates, if longer articulated vehicles were to be permitted.

5.5.1 Vehicle configurations

The baseline vehicles used in this analysis were a 44 tonne, 16.5m long articulated vehicle with an 8.0m wheelbase at a height of 4.9m, chosen as being representative of the longest and tallest articulated vehicles already commonly used on UK roads. Five longer configurations were assessed, including a length of 17.5m representing an increase equivalent to the length of one ISO pallet and a length of 18.55m, representing the biggest increase that the UK could independently permit without being forced to permit even longer combination vehicles under EU rules. These vehicles used various different types of steer-axle technology, each at two different heights, giving a total of eight modelled configurations, as shown in more detail in Table 21. The configurations were chosen to be compatible with the three main regulatory possibilities identified in section 4 – the baseline vehicle for the do nothing option (Regulatory possibility 1), various configurations employing established steer axle technologies to ensure the new vehicles comply with all existing regulations except maximum length (Regulatory possibility 2), and two “high-tech” configuration employing active steering technology capable of exceeding existing regulatory requirements even at 18.55m overall length (Regulatory possibility 3).

Table 21. Modelled vehicle configurations

Vehicle configuration	Length (m)	Wheelbase* (m)	Height (m)
Baseline, 44t un-steered (Reg. Poss.1)	16.50	8.0	4.9
40t un-steered (Reg. Poss. 2)	17.50	8.0	4.9
44t 1 self-steer axle (Reg. Poss. 2)	17.50	9.0	4.9
44t command steered (Reg. Poss. 2)	18.55	9.8	4.9
44t active steered (Reg. Poss. 3)	17.50	9.0	4.9
44t active steered (Reg. Poss. 3)	18.55	9.8	4.9
Baseline, 44t un-steered (Reg. Poss.1)	16.50	8.0	4.0
40t un-steered (Reg. Poss. 2)	17.50	8.0	4.0
44t 1 self-steer axle (Reg. Poss. 2)	17.50	9.0	4.0
44t command steered (Reg. Poss. 2)	18.55	9.8	4.0
44t active steered (Reg. Poss. 3)	17.50	9.0	4.0
44t active steered (Reg. Poss. 3)	18.55	9.8	4.0

* Figures shown are geometric wheelbases – effective wheelbase for low speed manoeuvres varies according to number, type and spacing of steered axles. The 1 self steer configuration in the Table would need to have a widely spaced steer axle to comply with the maximum axle load requirements and hence a lower effective wheelbase than the 9.0m geometric wheelbase shown.

5.5.2 Traffic and goods moved data

To convert the accident numbers in each target population to an appropriate accident rate, it is necessary to divide the number of accidents by the appropriate measure of articulated HGV traffic volumes. Overall articulated HGV traffic volumes on all GB roads are estimated each year as part of the traffic survey. The data for the last five years (up to 2008) is shown in Table 22. While the general trend is gradually increasing, the economic downturn of 2008 meant traffic volumes that year fell quite sharply. To compensate for such annual variations, the modelling work has used an average of the last three years (2006-2008).

None of the available data on articulated HGV traffic volumes is perfect so the analyses will be limited by the accuracy and extent of the base data. The CSRGT is based on a survey of truck operators and is, therefore, considered to provide accurate classification of vehicles but it only includes GB-registered vehicles. The national traffic census is based on roadside counts of vehicles in sample locations and thus includes the use of foreign registered vehicles on GB roads. However, it is known that this data can include an element of misclassification of vehicle types. When choosing the correct data source, it is therefore important to consider the needs of the analysis. In this case it is a relative change in accident rate that needs to be measured rather than an absolute value and it is necessary to be able to separate articulated truck traffic from rigid truck traffic. A comparison of the percentage of overall HGV traffic performed by articulated HGVs measured by CSRGT and the traffic census shows very similar results (50% and 49% respectively for the period 2006-2008), suggesting that either data source should offer comparable accuracy in classifying articulated vehicles. To optimise compatibility with the target population data, which includes accidents involving both GB-registered and foreign articulated HGVs, the traffic census survey data has been used.

An indication of the safety effects of longer semi-trailers when freight productivity is also considered can be gained from the accident rates per tonne-km, although this does not include the potential traffic generation or mode shift effects that will be separately assessed in the overall economic analysis. The goods moved data shown in Table 22 are based on the tonne-km figures published by CSRGT (because they are not gathered by the traffic census) and then factored up by the same proportion as between the traffic survey and CSRGT vehicle-km figures. This method relies on the assumption that the articulated HGV traffic not captured by CSRGT (mostly foreign registered vehicles) carries the same average load as GB-registered vehicles that are captured by CSRGT.

Data for 2009 is not yet available, but it is thought likely to show a small rise in both traffic levels and goods moved compared to 2008 and thus be very much in line with the three year averages (2006-2008) used.

For accidents relevant to specific road classes, the rates need to be based on traffic volumes on those roads only.

Table 22. Articulated vehicle traffic and goods moved data

	2004	2005	2006	2007	2008	2006-2008 Average
All Artic Traffic (Billion vehicle km)						
All Roads	14.1	13.9	14.3	14.5	14.1	14.26
Motorways		7.9	8.0	8.1	7.9	8.00
A Roads		5.6	5.8	5.9	5.8	5.83
Other Roads		0.4	0.5	0.4	0.4	0.43
CSRGT Data						
Goods moved (Billion Tonne km)	116.4	116.0	119.0	123.7	117.6	120.1
Traffic (Billion vehicle km)	10.8	10.9	11.1	11.3	10.8	11.07
Estimated total goods moved (Billion Tonne km)	152.0	147.9	153.3	158.7	153.5	154.7

5.5.3 *Risk factors*

Dividing the target populations by the appropriate traffic figure gives the baseline accident rates, expressed as fatal, serious and slight injury accidents per billion vehicle km. To estimate the effects of altering the vehicle configurations, these rates have then been multiplied by a set of risk factors. Different risk factors have been chosen as being relevant to different accident scenarios, and the values of those risk factors vary according to the specific vehicle configuration being analysed.

There are 8 risk factors in total, derived either from the simulation results described in section 3.2 or by other means explained below. To simplify the analysis, the risk factors have been coded A to H.

In accident scenarios where more than one risk factor is relevant, the factors have been multiplied together. A sensitivity analysis has also been undertaken to quantify the effects of using very different risk factor values.

5.5.3.1 *Risk Factors A, B & C – lane change manoeuvres*

The simulation study assessed three variables relevant to the dynamic performance of an articulated vehicle during a lane change manoeuvre. For each of these variables, and for each vehicle configuration, the value of the variable was compared with the value of the same variable for the baseline vehicle, and the result was expressed in terms of the percentage difference between the two, relative to the baseline case. The three variables, and thus the three lane change risk factors, are:

Risk Factor A – Rearward Amplification

Risk Factor B – Path Error

Risk Factor C - Load Transfer Ratio

These variables are commonly used to indicate a vehicle's performance during a lane change manoeuvre, but no previous research has been found that directly relates them to accident risk. Doing so would be likely to require an extensive programme of on-road vehicle and/or driving simulator trials and is, therefore, well beyond the scope of this project. As identified in the tender for this work, a series of assumptions will, therefore, be required. As a first conservative estimate the percentage increases or decreases in the risk factors have been simply converted into the same percentage increases or decreases in accident risk. This means, for example, that if a particular variable, with a particular vehicle configuration, was found to have a value 21% worse than the baseline vehicle, then a risk factor of 1.21 would be used; 15% better performance and the risk factor would be 0.85, etc.

For all the target populations relevant to lane change manoeuvres, risk factors A, B and C for the particular vehicle configuration being investigated have been multiplied together and then applied to the baseline accident rates for those populations.

5.5.3.2 Risk factor D – steady state overturning

The simulations identified the percentage changes in the lateral acceleration at the point of rollover during a steady state cornering manoeuvre (often referred to as the static rollover threshold, SRT), which is a good indicator of a vehicle's propensity to overturn when cornering at speed, e.g. on a bend or roundabout. Again, no information has been found that directly relates this variable to accident risk on UK roads, so the same approach as for factors A, B and C is used. In this case, though, the simulation results have been presented such that a positive increase in the variable value (lateral acceleration) relates to a reduction in the overturning risk, so the inverse of the stated value is used. For example, if a particular vehicle configuration has a static rollover threshold (SRT) 30% higher than the baseline vehicle, this means the risk factor is 0.77 (i.e. 1/1.30).

5.5.3.3 Risk factor E – Crosswind sensitivity

The simulation study used the crosswind load transfer ratio (LTR) for the unladen vehicle as an indicator of the vehicle's propensity to overturn in high winds. As with the other factors, it is not possible to directly correlate the changes in crosswind LTR with accident risk, so the percentage changes are applied as the risk factor. For example, a vehicle configuration found by simulation to have a crosswind LTR 10% higher than the baseline vehicle is given a risk factor of 1.10 in those target populations where high winds were present.

5.5.3.4 Risk factors F and G – low speed manoeuvring

The simulation analysis describes two variables relevant to changes in the width of the swept path of an articulated vehicle during low speed manoeuvres;

- Risk factor F – Cut-in
- Risk factor G – Tail/nose swing

The cut-in distance was defined as the amount by which the side of the vehicle passes over an inner circle of radius 5.3m when the outside of the vehicle is kept within a circular path of 12.5m radius (equivalent to Directive 97/27/EC, although the Directive does not apply this test directly to semi-trailers). The baseline vehicle was found to just avoid crossing the inner radius and thus had a predicted total swept path width of 7.2m (12.5 minus 5.3). A vehicle with a cut-in distance, for example of 1m would thus have a total swept path of 8.2m. Once again, no direct correlation between cut-in or swept path width and accident risk has been identified, so the analysis uses the overall swept path ratio as the risk factor; in the example given the factor would be 1.14 (i.e. 8.2/7.2).

Tail and nose swing is the distance by which the outside edge of the vehicle moves outside of its initial straight ahead position when turning in the other direction, e.g. how far the near-side rear edge of the semi-trailer moves to the left when the vehicle turns right. The simulations were based on a right turn of 12.5m outside radius, as per 97/27/EC.

In the straight ahead position, the vehicles (all 2.5m wide) occupy a road width of 2.5m. For this analysis, the tail/nose swing distances estimated by the simulation exercise are added to this width to give an equivalent swept path width. For the baseline vehicle, the tail/nose swing was found to be 0.49m (at an assumed turning speed of 6 km/h), giving a baseline swept path width of 2.99m. The risk factor used for relevant accidents is the ratio of the vehicle's swept path width (i.e. 2.5m + the nose/tail swing distance) to this baseline width. For example, a vehicle with a tail/nose swing of 0.6m would have a risk factor of 1.04 (i.e. 3.10/2.99).

5.5.3.5 Risk Factor H – junctions and overtaking

The final risk factor relates to accidents at junctions or involving an articulated vehicle being overtaken. In these cases the accident risk is assumed to be proportional to the vehicle's overall length, with 16.5m as the baseline. For example, an 18.55m long vehicle would thus be assumed to be 1.12 times more likely (i.e. 18.55/16.5) to be involved in such accidents, by virtue of it occupying that proportion more road space.

5.5.4 Risk factors applied to target populations

Each of the accident scenarios (target populations) defined earlier has been assigned a set of one or more risk factors A to H. Table 23 lists each population, defines the risk factors that have been applied and explains the logical reasoning involved.

Table 23. Risk factors applied to target populations

Accident Group	Accident Description	Risk Factors	Explanation
Manoeuvrability – low speed off-tracking.	Turning left, n/s impact.	F	Low speed manoeuvres where impact partners encroach into cut-in side of swept path of HGV; risk assumed proportional to width of that swept path.
	Turning right, o/s impact.	F	
	U-turn, o/s impact.	F	
	Roundabout, o/s impact.	F	
Manoeuvrability – out-swing or tail-swing.	Turning left, o/s impact.	G	Low speed manoeuvres where impact partners encroach into tail/nose swing side of swept path of HGV; risk assumed proportional to width of that swept path.
	Turning right, n/s impact.	G	
	U-turn, n/s impact.	G	
	Roundabout, n/s impact.	G	
Stability – overturning, steady state cornering.	On bend, no high winds.	D	Steady state cornering conditions; risk assumed proportional to load transfer ratio at rollover. Crosswind load transfer ratio also used if high winds present.
	On bend, high winds.	DE	
Stability – overturning, steady state.	Going ahead, not on roundabout or slip road and other, high winds	E	Straight ahead driving with rollover risk affected by crosswinds.
Stability – overturning, dynamic lane change manoeuvre.	Changing lane, overtaking or going ahead on roundabout or slip-road, no high winds.	ABC	High speed, dynamic lane change manoeuvres; risk assumed to be proportional to rearward amplification, path error and load transfer ratio. Crosswind load transfer ratio also used if high winds present.
	Changing lane, overtaking or going ahead on roundabout or slip-road, high winds.	ABCE	
Stability – left carriageway, steady state cornering.	On bend, no high winds.	D	Steady state cornering conditions; risk assumed proportional to load transfer ratio at rollover. Crosswind load transfer ratio also used if high winds present.
	On bend, high winds.	DE	

Accident Group	Accident Description	Risk Factors	Explanation
Stability – left carriageway, steady state.	Going ahead, not on roundabout or slip road and other, high winds	E	Straight ahead driving with leaving carriageway risk affected by crosswinds.
Stability – left carriageway, dynamic lane change manoeuvre.	Changing lane, overtaking or going ahead on roundabout or slip-road, no high winds. Changing lane, overtaking or going ahead on roundabout or slip-road, high winds.	ABC ABCE	High speed, dynamic lane change manoeuvres; risk assumed to be proportional to rearward amplification, path error and load transfer ratio. Crosswind load transfer ratio also used if high winds present.
Stability – loss of control, steady state.	On bend, no high winds. On bend, high winds.	D DE	Steady state cornering conditions; risk assumed proportional to load transfer ratio at rollover. Crosswind load transfer ratio also used if high winds present.
Stability – loss of control, steady state.	Going ahead, not on roundabout or slip road and other, high winds	E	Steady state straight ahead driving conditions in high winds; risk of loss of control assumed proportional to crosswind load transfer ratio.
Stability – loss of control, dynamic lane change manoeuvre.	Changing lane, overtaking or going ahead on roundabout or slip-road, no high winds. Changing lane, overtaking or going ahead on roundabout or slip-road, high winds.	ABC ABCE	High speed, dynamic lane change manoeuvres; risk assumed to be proportional to rearward amplification, path error and load transfer ratio. Crosswind load transfer ratio also used if high winds present.
Junction and overtaking accidents	HGV blocking junction or being overtaken.	H	Risk of impacts assumed proportional to road space occupied by HGV, so risk factor based on vehicle length ratios.

5.5.5 Results

5.5.5.1 Results based on 4.9m high baseline vehicle

Table 24 sets out the values of each risk factor for each vehicle configuration, based either on simulation results (factor A-G) or the overall length ratio (factor H).

Table 24. Risk factors for each vehicle configuration (4.9m height baseline)

Vehicle	Length, Wheel-base	Height	Lane change			Over-turn	Cross-wind	Low speed turning		Junct'n or O'take
			A	B	C	D	E	F	G	H
44t, Baseline	16.5,8	4.9m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		4.0m	0.93	0.87	0.64	0.80	0.75	1.00	1.00	1.00
40t, unsteered	17.5,8	4.9m	1.05	1.17	0.97	0.93	1.00	1.00	1.00	1.06
		4.0m	0.99	1.04	0.64	0.75	0.75	1.00	1.00	1.06
44t, 1 self steer axle	17.5,9	4.9m	0.96	0.99	0.96	1.01	1.05	1.00	1.01	1.06
		4.0m	0.90	0.87	0.61	0.82	0.78	1.00	1.01	1.06
44t, command steered	18.55,9.8	4.9m	0.93	0.97	0.93	1.01	1.10	1.00	1.09	1.12
		4.0m	0.88	0.85	0.57	0.82	0.83	1.00	1.09	1.12
44t, active steered	17.5,9	4.9m	0.96	0.99	0.77	1.01	1.06	0.79	0.91	1.06
		4.0m	0.90	0.87	0.49	0.82	0.79	0.79	0.91	1.06
	18.55,9.8	4.9m	0.93	0.97	0.74	1.01	1.10	0.90	0.94	1.12
		4.0m	0.88	0.85	0.46	0.82	0.83	0.90	0.94	1.12

The combined target populations, for fatal, serious and slight accidents (Table 20) when divided by the 14.3 billion vehicle kilometres of articulated HGV traffic each year (Table 22), imply baseline accident rates of 1.8 fatal, 6.7 serious and 27.5 slight injury accidents per billion vehicle kilometres where the length of the semi-trailer may have been relevant to the cause. For each vehicle configuration, risk factors have been applied to the specific target populations to predict new involvement rates. Those rates have then been combined to produce overall total involvement rates for each configuration. The calculation of this total allowed for overlaps between the different specific target populations by assuming that the proportion of accidents in the overlap categories remains constant, even if the numbers of accidents in each group (each circle of the Venn diagrams) goes up or down according to the risk factors applied.

Conversely, the figures also imply that articulated HGVs are involved in accidents not relevant to length at rates of 9.9 fatal, 27.4 serious and 174 slight accidents per billion vehicle kilometres (i.e. total rates of 11.7 fatal, 34.1 serious and 201.5 slight accidents per billion vehicle kms).

A summary of the results is presented in Table 25.

Table 25. Projected overall length-relevant accident involvement rates by vehicle configuration (accidents per billion vehicle kilometres, 4.9m height baseline)

Vehicle	Length, Wheelbase	Height	Involvement rates			Differences between modified and baseline rates *		
			Fatal	Serious	Slight	Fatal	Serious	Slight
44t, Baseline	16.5,8	4.9m	1.78	6.73	27.48	0.00	0.00	0.00
		4.0m	1.45	5.79	23.78	-0.32	-0.94	-3.70
40t, unsteered	17.5,8	4.9m	1.79	6.76	27.73	0.02	0.03	0.25
		4.0m	1.47	5.83	24.00	-0.31	-0.90	-3.48
44t, 1 self steer axle	17.5,9	4.9m	1.79	6.79	27.57	0.01	0.06	0.10
		4.0m	1.47	5.86	23.95	-0.31	-0.87	-3.53
44t, command steered	18.55,9.8	4.9m	1.80	6.90	27.97	0.02	0.17	0.49
		4.0m	1.50	6.02	24.53	-0.28	-0.72	-2.94
44t, active steered	17.5,9	4.9m	1.67	6.25	24.86	-0.11	-0.48	-2.62
		4.0m	1.39	5.41	21.63	-0.39	-1.33	-5.85
	18.55,9.8	4.9m	1.70	6.45	25.73	-0.08	-0.28	-1.75
		4.0m	1.42	5.64	22.62	-0.35	-1.10	-4.86

* -ve indicates involvement rate being reduced

5.5.5.2 Results based on 4m high baseline vehicle

To assess the possible effects in the wider context, the above analyses have been repeated, but with a 44t, 4m high, 16.5m long vehicle as the reference baseline. This is very similar to the longest, tallest and heaviest articulated vehicles currently guaranteed unrestricted movement anywhere in the EU (as baseline but with 40t max GVW). Risk factors are thus based on a 4m high baseline, rather than the 4.9m case used for the main analysis. The analysis is fully valid in the UK context of 44t vehicles, and can be extrapolated to apply to the EU scenario, by assuming that the gross vehicle weight and axle number difference (44t on 6 in GB and 40t on 5 in EU) would not affect the risk factors. The simulation results suggest that overall length, wheelbase and trailer steering systems are the dominant influences on the factors being considered and, where relevant, the assumption of a uniformly distributed load means that (for a given vehicle height) the centre of gravity height of the load remains the same regardless of the load mass. However, in reality the 4t difference in GVW will have some influence on the high speed performance.

The risk factors for each target population are shown relative to a 4m baseline in Table 26, below and a summary of the involvement rate results with a 4m high baseline is shown in Table 27. Each individual vehicle has the same predicted involvement rate as shown in Figure 25 but the difference is now measured with respect to the 4m baseline vehicle in every case.

Table 26: Risk factors by target population (4m baseline)

Vehicle	Length, Wheel-base	Height	Lane change			Over-turn	Cross-wind	Manoeuv-rability		Junct'n or O'take
			A	B	C	D	E	F	G	H
44t, Baseline	16.5,8	4.9m	1.08	1.15	1.56	1.25	1.33	1.00	1.00	1.00
		4.0m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40t, unsteered	17.5,8	4.9m	1.13	1.34	1.52	1.16	1.33	1.00	1.00	1.06
		4.0m	1.06	1.20	1.00	0.94	1.00	1.00	1.00	1.06
44t, 1 self steer axle	17.5,9	4.9m	1.03	1.14	1.50	1.26	1.40	1.00	1.01	1.06
		4.0m	0.97	1.00	0.95	1.03	1.04	1.00	1.01	1.06
44t, command steered	18.55,9.8	4.9m	1.00	1.11	1.45	1.26	1.47	1.00	1.09	1.12
		4.0m	0.95	0.98	0.89	1.03	1.11	1.00	1.09	1.12
44t, active steered	17.5,9	4.9m	1.03	1.14	1.20	1.26	1.41	0.79	0.91	1.06
		4.0m	0.97	1.00	0.77	1.03	1.05	0.79	0.91	1.06
	18.55,9.8	4.9m	1.00	1.11	1.16	1.26	1.47	0.90	0.94	1.12
		4.0m	0.95	0.98	0.72	1.03	1.11	0.90	0.94	1.12

Table 27. Projected overall length-relevant accident involvement rates by vehicle configuration (accidents per billion vehicle kilometres, 4m height baseline)

Vehicle	Length, Wheelbase	Height	Involvement rates			Differences between modified and baseline rates *		
			Fatal	Serious	Slight	Fatal	Serious	Slight
44t, Baseline	16.5,8	4.9m	1.78	6.73	27.48	0.33	0.94	3.7
		4.0m	1.45	5.79	23.78	0	0	0
40t, unsteered	17.5,8	4.9m	1.79	6.76	27.73	0.34	0.97	3.95
		4.0m	1.47	5.83	24	0.02	0.04	0.22
44t, 1 self steer axle	17.5,9	4.9m	1.79	6.79	27.57	0.34	1.00	3.79
		4.0m	1.47	5.86	23.95	0.02	0.07	0.17
44t, command steered	18.55,9.8	4.9m	1.8	6.9	27.97	0.35	1.11	4.19
		4.0m	1.5	6.02	24.53	0.05	0.23	0.75
44t, active steered	17.5,9	4.9m	1.67	6.25	24.86	0.22	0.46	1.08
		4.0m	1.39	5.41	21.63	-0.06	-0.38	-2.15
	18.55,9.8	4.9m	1.7	6.45	25.73	0.25	0.66	1.95
		4.0m	1.42	5.64	22.62	-0.03	-0.15	-1.16

* -ve indicates involvement rate being reduced

These results clearly show that increasing the volume capacity of vehicles by increasing maximum height would be likely to present substantially greater risks per vehicle km than increasing length. However, this does not consider the rate per m^3 of goods carried and the fact that a 0.9m height increase on a 16.5m articulated vehicle (approx. $31m^{3)}$ offers a much bigger increase in volumetric capacity than a 2.05m increase in length at 4m height (approx. $13m^3$). It can be seen that only the active steer system produces a casualty rate reduction relative to a 4m baseline vehicle.

5.5.6 Discussion and sensitivity analysis

5.5.6.1 Limitations of the analysis

The analysis is fundamentally limited by the fact that the vehicles for which casualty figures are required do not exist in the UK fleet. The analysis, therefore attempts to predict these casualty figures based on the accident types and numbers experienced by existing vehicles and computer simulation of the likely changes in vehicle characteristics. The vehicle characteristics simulated do not have proven correlations with casualty frequency or severity so the analysis has necessarily been based on a series of assumptions. The central assumption is very coarse and simply states that if a physical performance measure, for example the lateral acceleration at which rollover will occur in steady state cornering, changes by a certain percentage then there will be an equivalent percentage change in the number of accidents that existing vehicles suffer in those sorts of circumstances, for example the number of rollover accidents on a bend.

There are a number of factors which, in combination, make it very likely that this method will produce a significant over estimate of the effects, for example:

- The data available with which to quantify the target populations is not as detailed as required for a fully accurate evaluation. Where uncertainty exists, the analysis has tended to take the conservative assumption, for example;
    - It is assumed all rollover accidents where high winds were present were caused solely by the high winds
    - Stability target populations will include vehicles that rolled over because they collided with another vehicle, not because of their geometric characteristics or dynamic performance
- It is assumed that no drivers (HGV or other vehicle) compensate for the additional risks by taking a more cautious approach
- The numbers involved in the analyses were too small for further disaggregation so an analysis by road type was not possible. The economics analysis (MDS Transmodal, 2010) suggests that longer semi-trailers are more likely to be used on primary trunking rather than secondary distribution tasks and will, therefore, travel a proportionately higher distance on motorways and trunk roads than the average existing artic. Accident rates are lower on these roads which would give the longer vehicles a relatively lower exposure to risk than standard vehicles. This has not been accounted for in the analysis.

This means that the analysis presented is likely to significantly err on the side of caution. However, given the uncertainty inherent in the analysis this is considered to be appropriate.

5.5.6.2 Sensitivity analysis

There is a substantial amount of uncertainty inherent in this analysis, so in order to assess the potential scale of variation the sensitivity of the analysis was tested by increasing:

- Any risk factor originally modelled as being >1 (i.e. accidents are more likely in this configuration than with the baseline vehicle) to 2.0 (i.e. the risk of accidents is not necessarily linearly related to the change in vehicle characteristic but is instead doubled in all cases).
- any risk factor modelled to be less than 1.0 to 1 (i.e. ignoring any potential reduction in accident likelihood).

As an example of the extreme nature of these assumptions, this would mean that a 12% increase in the length of an articulated vehicle would double the risk of an overtaking accident, despite the fact that the overall length would still be less than for a drawbar combination where there have been no documented concerns with overtaking (over and above those applied to large trucks generally).

In the worst case scenario (a 40t un-steered, 4.9m high configuration), these new risk factors produce overall involvement rates (length sensitive accidents) of 3.1 fatal, 10.9 serious and 46.1 slight injury (compared with the baseline 4.9m vehicle which was 1.78, 6.73 and 27.48 respectively) accidents per billion vehicle kilometres. Despite the extremely conservative input estimates used in arriving at the component risk factors, the overall effect is still relatively small – rounding to the nearest integer, the overall articulated HGV involvement rates, for example (which also include all the accidents not relevant to length) would be 13 fatal, 38 serious and 220 slight injury accidents per billion vehicle kilometres, compared with a baseline of 12 fatal, 34 serious and 202 slight injury accidents. Considering all severities then the worst longer vehicle would experience 23 more accidents per billion kms travelled than a standard artic. If all existing artics were replaced by the longer vehicle *and* there was no change in the total number of kms travelled then this would be equivalent to an increase in the number of accidents of approximately 8%[14]. This suggests that the results are not particularly sensitive to variations in the risk factors studied.

5.5.6.3 Contextual data in relation to previous changes in weights and dimensions

There is insufficient information available to undertake a reliable post-hoc analysis on the effects of previous changes to maximum length from 15.5m to 16.5m and, in any case, the details of the change are such that even this would not provide a direct assessment of the effects of the change now under consideration because the effects on manoeuvrability etc will be different (i.e. no steering axles etc).

The simulation study and the analysis of the risk factors presented in Table 25, make it very clear that the influence of vehicle height on the risk is an order of magnitude greater than the influence of the length increases under consideration. Up until 1995, UK Construction and Use Regulations imposed a maximum height of 4.2m on trucks but in 1995 this was removed and height became unlimited. The analysis in this report would suggest that this decision carried considerably greater safety risk than the length changes currently being considered. Again, insufficient data is available to enable a reliable post-hoc study of the effects of this so only contextual information is available.

The main effect of increased height would be on the likelihood of roll stability in steady state manoeuvres and transient manoeuvres, both with and without cross winds. Figure 37 shows the trends in the number of HGVs that rolled over in accidents over time. All data is indexed to a 1990=100 baseline and the three plots show:

a) Overall HGV involvement rate (numbers of HGVs involved in all severity accidents per unit of distance travelled by HGVs);

b) HGV rollover involvement rate (number of HGVs that overturned in all severity accidents per unit of distance travelled by HGVs);

[14] It should be noted that MDS Transmodal (2010) predicts a reduction in vehicle km sufficient to produce a reduction in accidents even in this "worst case".

c) Rollover proportion (the number of HGVs involved in all severity accidents that overturned as proportion of all HGVs involved in all severity accidents).

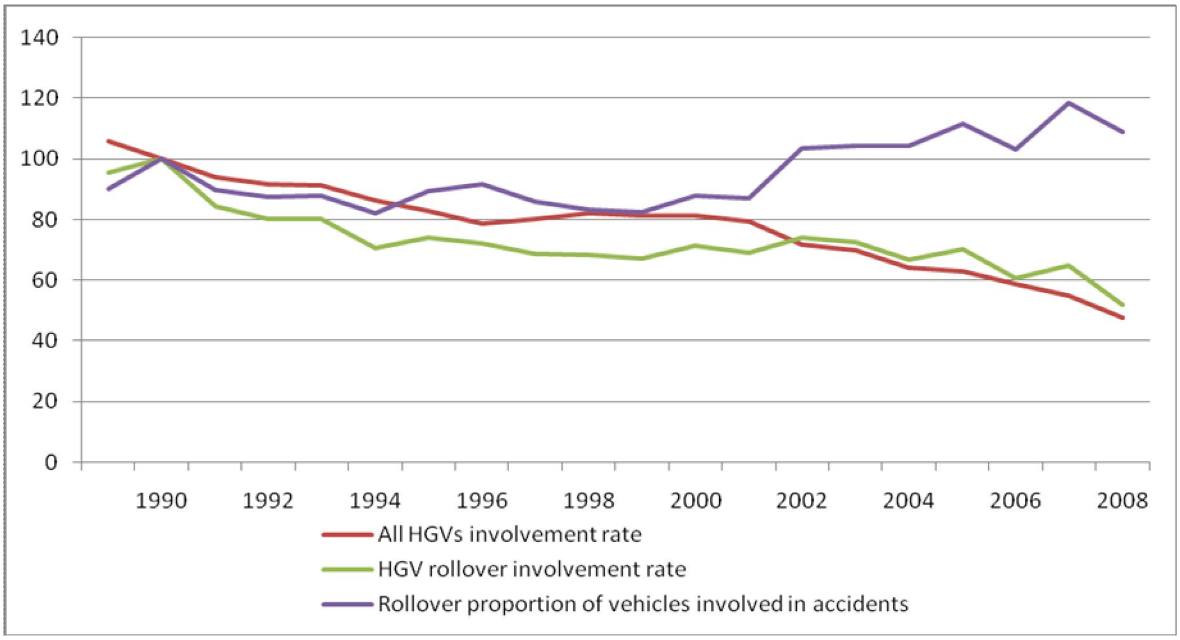


Figure 37. The number of HGV vehicle rollovers (1990 = 100)

It can be seen that all the indices remained relatively constant or fell slightly between 1991 and 2000, with no indication of any major changes around 1995, although there is evidence of an increasing rollover proportion from 2001. However, at this time the maximum mass on articulated vehicles was also increased by 6 tonnes and with no increase to width or length this would mean that the centre of gravity height on many vehicles would have increased. This may have been a more significant factor than an increase to overall travelling height because tall vehicles would have tended to be used for lightweight goods. Even then, the overall involvement rates, both for all HGVs and for overturning continued to decline at similar rates.

Although this analysis in no way proves that there will be no additional risks with longer vehicles it does show that a feature having an order of magnitude greater physical effect is very hard to detect in accident data. It does, therefore, suggest that any change in the accident rate per billion vehicle kms as a result of the increased length will be so small as to be extremely difficult, if not impossible, to reliably detect in accident data after implementation.

5.5.6.4 Comparison with drawbar combinations

Increasing the maximum length of articulated vehicles to 18.55m would allow them the same maximum loading length (15.65m) as existing drawbar combinations. Knight *et al* (2008) found that the casualty rate per billion vehicle kms appeared to be considerably higher for drawbar combinations than it was for articulated vehicles, although substantial uncertainty was noted because of inconsistencies in the way vehicles were coded in different data sets and small sample sizes for both accident and travel data for drawbars. Although this result was highly uncertain, there was also considerable physical test data to show that their performance in terms of high speed dynamics (similar to those used in the assessments in this report) was considerably poorer than for articulated vehicles. If such findings could be validated and introducing longer semi-trailers encouraged a shift from drawbar combinations to the new articulated vehicles, then this would be expected to produce an improvement in the safety of road freight movement.

In order to further assess the validity of the previous finding, the coding inconsistencies between the STATS 19 and DVLA data sets were examined in more detail by comparison with the HVCIS fatal database. More details can be found in Appendix E. This analysis found that there were major errors inherent in the recording of drawbar vehicles within Stats 19, such that even with the link to the DVLA database the only conclusion possible is that there is no reliable means of determining the number of GB accidents or casualties that involve a drawbar HGV.

A crude analysis based on very small numbers of fatal accidents suggests that the method used by Knight et al (2008) would have over-estimated the casualty rate by a factor of two, which would mean that the rate for drawbars was only double that of articulated vehicles not four times. An alternative means, shown in Appendix E to be equally unreliable, predicts a fatality rate of 10.1 per billion vehicle kms, slightly less than (86% of) the equivalent figure for articulated vehicles. This implies a range for drawbars of between about 86% and 200% of the fatal accident rate for articulated vehicles but little, if any scientific confidence can be placed in this result. For this reason, the economic analysis (MDS Transmodal, 2010) was forced to assume the same casualty rates for drawbars and articulated vehicles.

Despite this statistical uncertainty, the results of computer simulations undertaken as part of an OECD working group (OECD, 2010) would suggest that the low speed manoeuvrability of drawbar combinations would be slightly better than existing articulated vehicles but the high speed stability performance would be substantially inferior to both the standard and longer vehicles assessed in this report.

It should be noted that similar Stats 19 coding errors were also common for articulated vehicles but the proportions were much lower than for drawbars which, combined with the much higher absolute number of articulated vehicles, allows greater confidence in the results for these vehicles.

5.5.7 Overall conclusions from the accident analysis

It can be seen that the casualty analysis undertaken predicts a small increase in the casualty rates per vehicle km if regulatory possibility 2 (requiring compliance with all existing regulations) was to be implemented with no additional controls. However, this would change to a small reduction in risk per km if regulatory option 3 were to be implemented. In either case, it can be seen that the effect of vehicle height is an order of magnitude greater than the length increases being considered and the simulation results suggest that limiting the maximum height of vehicles permitted under regulatory possibility 2, to around 4.6m, would be one possible means of avoiding adverse effects on a per km basis.

The analysis undertaken has been deliberately conservative and is likely to produce an over-estimate. Sensitivity analyses shows that even extreme input assumptions do not produce a dramatic increase in risk and comparison with the effect of the previous decision to remove the UK height limit for trucks supports the view that the effects are likely to be very small. Overall it is considered likely that the effects of the measures under consideration will be sufficiently small to make it extremely difficult, if not impossible, to identify them in a reliable post-hoc analysis after implementation or to have any measurable effect on the overall long-term downward trend in HGV accident involvement rates.

6 Conclusions

1) The cost and mass implications of longer semi-trailers have been well defined in cooperation with the vehicle industry and increasing the length of semi-trailers to 15.65m would be likely to increase unladen mass by between approximately 575kg and 1,750kg. Capital costs could increase by between about £3,300 and £7,200. Both would depend on the level of steering technology applied and cheaper, lighter solutions would be available for length increases of less than 2.05m.

2) Bridge loading and pavement wear effects have not been studied in detail because the previous study (Knight *et al*, 2008) confirmed that increased length without increased GVW or axle weight would cause no adverse bridge loading effects and would have only marginal effects on structural pavement wear from vertical loading. However, the review has identified theoretical evidence to suggest that steered trailer axles reduce pavement wear caused by turning HGVS, although there was insufficient data to allow this to be quantified.

3) Simulation results predicted that increasing the length of semi-trailers would produce a small increase in the fuel consumed (up to 1.8%) and consequent tail pipe emissions per vehicle km at full load. This is considered against an increase in pallet capacity of approximately 15% and a decrease in payload mass capacity of up to approximately 5%. There is also evidence to suggest that steered axles on trailers can substantially reduce tyre wear, which would reduce the emissions associated both with their manufacture (e.g. CO_2) and wear (e.g. particulates).

4) Increasing vehicle length by more than about 0.4m (to 16.9m) with fixed, closely coupled trailer axles is only possible within current axle load and manoeuvrability regulations if the maximum load carried is reduced (assuming uniformly distributed load). An 18.55m vehicle would be possible if the GVW were limited to 38 tonnes. However, this is only possible because the existing legislation allows semi-trailer manoeuvrability to be approved by numerical methods and no tailswing limit is applied. Longer, fixed axle vehicles at reduced weight will have much greater tail swing than current vehicles (more than double, from 0.17m to 0.37m, for a 17.5m vehicle and approximately 4 times, from 0.17m to 0.67m for an 18.55m vehicle compared with the baseline).

5) The appropriate use of existing (non active) steering axle technology can allow vehicles to comply with all existing regulations at a GVW of 44 tonnes and a length of up to 18.55m (semi-trailer length 15.65m) but the tail swing produced in a “drive in” roundabout manoeuvre will be much greater than for current vehicles (around 0.6m, depending on specific design, compared to the existing 0.17m). Prototype active steer systems have demonstrated the potential to allow 18.55m vehicles at 44 tonnes whilst reducing tail swing to near zero.

6) Longer vehicles that make use of steering axles to achieve compliance will tend to have longer wheelbases. Those using fixed axles and reduced weight will have shorter wheelbases.

7) The dynamic stability of vehicles travelling at speed is more sensitive to wheelbase than to length:

    a) Vehicles that achieve increased length by increasing their wheelbase will be more susceptible to crosswinds than existing vehicles (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 10% increase in load transfer ratio during crosswinds compared to a 16.5m, 8m wheelbase vehicle). They will also have a slightly worse rollover threshold in steady state cornering than those with shorter wheelbases (e.g. an 18.55m long, 9.75m wheelbase vehicle will have a 0.75% poorer steady state rollover threshold compared to a 16.5m, 8m wheelbase vehicle). However, vehicles with a longer wheelbase will tend to have better dynamic performance (e.g. path error, rearward amplification etc.) in transient manoeuvres such as a lane change than existing vehicles.

b) Vehicles that achieve increased length with shorter wheelbases similar to existing vehicles (i.e. extending behind rear axles) will tend to be significantly less stable in transient manoeuvres such as a lane change (e.g. an 18.55m vehicle with 8m wheelbase would display a 40% increase in path error and a 15% increase in rearward amplification compared with the standard vehicle). However, the steady state rollover threshold and susceptibility to cross winds would be comparable to existing vehicles

8) The analyses suggest that it would be very difficult for a longer vehicle to provide a better performance than an existing vehicle in every metric considered. However, the analyses also suggest that there are no combinations where the performance is reduced in all metrics at the same time – there is a trade-off based on wheelbase such that the measures which are adversely affected are often accompanied by measures where there is an improvement. This means that overall there can be net performance improvements relative to existing vehicles. Where individual reductions in performance are predicted these can be mitigated or improved by the imposition of design restrictions or new performance standards that force the use of new technology. For example, a height limit of around 4.6m would allow 18.55m vehicles to have approximately the same high speed stability performance as a 16.5m vehicle at 4.9m height, while electronic stability control would be expected to mitigate the risk associated with reduced rollover stability.

9) The findings of the simulation work helped identify three regulatory possibilities:

   i) Retain existing length limits (do nothing)

   ii) Increase length, require compliance with all other existing regulations

   iii) Increase length, require longer vehicles to match or exceed actual performance of existing vehicles

10) Within the regulatory constraints of possibility number ii) it would be possible for industry to react in a number of different ways:

   a) Low tech – A maximum length of up to approximately 18.25m would be possible with a wheelbase of approximately 8m without steering axles. However, the maximum load carried would need to be limited to 38 tonnes to avoid trailer axle overload. Forty tonnes would be possible at a length of up to around 17.8m. Both configurations would exhibit reduced stability in dynamic manoeuvres such as lane changes, for example, the path error exhibited by the 18.25m configuration would be around 33% more than for an existing 16.5m vehicle.

   b) Medium tech – Vehicles could be up to 44 tonnes GVW and up to 18.55m overall length if existing steer axle technology was to be used. Such vehicles would increase tailswing by approximately 60% (in a “drive in” manoeuvre), suffer a small increase in the susceptibility to cross winds of approximately 5% at 17.5m and approximately 10% at 18.55m, with a reduction of just under 2% in steady state rollover threshold, compared with a 16.5m vehicle. However, the other vehicle dynamics parameters would match or better those of the standard 16.5m vehicle, for example a reduction of 7% in the rearward amplification and a slight reduction in cut-in during low speed manoeuvring. The high speed performance assumes that like all existing systems the steer axles are locked at speed. New regulation may be required to enforce this condition.

11) There are possible deficiencies in current regulation, for example, manoeuvrability regulations are intended to limit tailswing for all vehicle types but trailers are approved by calculation. This produces existing vehicle combinations that exhibit tailswing well within the limits applied for rigid trucks and buses. However, if the formula were applied to longer semi-trailers it would prevent an increase in wheelbase limiting industry to the low tech approach described above. These low tech vehicles could exceed the tailswing limits applied to other vehicle types. If it was

considered desirable to allow the medium tech approach and to enforce the spirit of the existing legislation then it would be necessary to introduce a specific test for an articulated combination with an appropriate tailswing limit (either 0.6 for a drive in test, comparable to buses, or 0.8 in a steady state test comparable to rigid trucks) and to prescribe the test speed for evaluation (e.g. 6km/h). Similarly, all existing steered trailer axles are locked at high speed but this is not a regulatory requirement. If it was considered necessary to ensure that this could not change it would be necessary to introduce either a technology limiting requirement that steered axles were locked at high speed or a performance based requirement that the vehicle remained stable in a lane change (or similar dynamic) manoeuvre.

12) Under regulatory possibility number iii), only one approach would be possible:

a) High tech - Vehicles would need to be fitted with a new generation of active trailer steering systems, such as those described by Jujnovich et al (2008). Vehicles of up to 44 tonnes and 18.55m overall length (15.65m semi-trailer length) could be considered. Maximum length vehicles would have a 10% increase in load transfer during crosswinds and slightly less than 2% reduction in steady state rollover threshold compared with a 16.5m vehicle. However, tailswing could be almost eliminated and cut-in could be reduced, thus substantially improving low speed manoeuvrability in comparison with existing 16.5m vehicles, and it is possible that tuning the system could improve performance in high speed transient manoeuvres such as lane changes by around 20%.

13) If it was decided that regulatory possibility number iii) were to be implemented, this could be achieved by implementing a more stringent tail swing limit for an articulated combination (around 0.2m in a drive-in test at 6 km/h). Regulatory possibility iii) allows vehicles that match or exceed existing performance in all regulatory tests and in terms of overall net performance, including unregulated high speed stability metrics. However, within this some individual metrics, for example cross wind stability, can still be of a reduced standard compared with existing vehicles. Enforcing a condition where all individual metrics matched or exceeded existing performance would require either a height limit of around 4.6m (design prescriptive) or a dynamic stability and cross wind sensitivity test (performance based).

14) It should be noted that the active steer system likely to be required for regulatory possibility iii) (high tech) may take in the region of 18 months to two years to develop for production and currently it appears that the system is outside the scope of the technical requirements of UNECE Regulation 79. Although Type Approval could possibly still be granted via an exemption for new technology, provided equivalent levels of safety can be demonstrated, an amendment to Regulation 79 may ultimately be required.

15) A conservative analysis has been undertaken to assess the potential casualty effects of these changes. This analysis has suggested that:

a) Regulatory possibility ii) would be likely to result in a very small increase in the casualty risk per vehicle km but so small as to be immeasurable in casualty data after implementation. Introducing a limit that reduced slightly the height of the tallest vehicles would be enough to eliminate this increase in risk.

b) Regulatory possibility iii) would be likely to result in a small reduction in the casualty risk per vehicle km but again this is likely to be so small as to be immeasurable.

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http://www.koegel.com/fahrzeugweb/PDF/GB/DEU/Datenblatt905071.pdf

http://www.koegel.com/fahrzeugweb/PDF/GB/DEU/Datenblatt905083.pdf

http://www.koegel.com/fahrzeugweb/PDF/GB/DEU/Datenblatt905072.pdf

http://www.koegel.com/fahrzeugweb/PDF/GB/DEU/Datenblatt925071.pdf

www.ntc.gov.au

bosstruck.co.uk/images/curtainsider_semi_trailer%20.doc

http://www.cargobull.com/files/uk/filemanager_files//Neufahrzeuge/Curtainsider/Data_Sheet/S_CS-UNIVERSAL-GB.pdf

http://www.donbur.co.uk/gb/demo/50348/50348_Demo_Instr.pdf

Appendix A Vehicle specifications used with the PHEM model

Vehicles specifications used for the PHEM model – typical laden weights

Vehicle specifications	**Veh 1** Existing Artic Single (2+3)	**Veh 2** Existing Artic Double (2+3)	**Veh 3** Existing Artic Single (3+3)	**Veh 4** Existing Artic Double (3+3)	**Veh 5** Existing Trawbar (3+3)	**Veh 6** Longer Vehicle Artic Single (3+3) Self Steer	**Veh 7** Longer Vehicle Artic Double (3+3) Self Steer	**Veh 8** Longer Vehicle Artic Single (3+3) Command Steer	**Veh 9** Longer Vehicle Artic Double (3+3) Command Steer	**Veh 10** Longer Vehicle Artic Single (3+3) Active Steer	**Veh 11** Longer Vehicle Artic Double (3+3) Active Steer
Driving resistances:											
vehicle mass [kg]:	13543	19035	14533	20025	15000	15307	20918	16072	21683	16177	21788
Loading [kg]	10730	9297	16670	13860	6614	14347	11541	13964	11159	13912	11106
Total weight	24273	28332	31203	33885	21614	29654	32459	30036	32841	30089	32894
C_d	0.5	0.5	0.55	0.55	0.55	0.6	0.6	0.6	0.6	0.6	0.6
Cross sectional area [m^2]	10.2	12.495	10.2	12.495	11.348	10.2	12.495	10.2	12.495	10.2	12.495
Delta [-]:	0	0	0	0	0	0	0	0	0	0	0
Inertia - Engine	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771
No axles	5	5	6	6	6	6	6	6	6	6	6
No wheels	14	14	16	16	16	16	16	16	16	16	16
Inertia - Wheels	815.08	815.08	931.52	931.52	931.52	931.52	931.52	931.52	931.52	931.52	931.52
Inertia - Gearbox	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Power takeoff [% from rated power]:	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Rated power [kW]	315	315	315	315	315	315	315	315	315	315	315
Rated engine speed [rpm]:	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Engine speed at idling [rpm]:	600	600	600	600	600	600	600	600	600	600	600
Gear box type (0=man; 1=auto):	0	0	0	0	0	0	0	0	0	0	0
Rolling Resistance Coefficients											
Fr0:	0.0073	0.0073	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
Fr1:	0	0	0	0	0	0	0	0	0	0	0
Fr2	0	0	0	0	0	0	0	0	0	0	0
Fr3:	0	0	0	0	0	0	0	0	0	0	0
Fr 4	0	0	0	0	0	0	0	0	0	0	0
Free parameter 1	0	0	0	0	0	0	0	0	0	0	0
Factor transmission losses (1.0 = standard)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Vehicle specifications (Continued)	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7	Veh 8	Veh 9	Veh 10	Veh 11
Transmission:											
Final drive ratio [-]:	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65
Wheel diameter [m]	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
Transmission 1. gear [-]:	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
Transmission 2. gear [-]:	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55
Transmission 3. gear [-]:	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59
Transmission 4. gear [-]:	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02
Transmission 5. gear [-]:	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81
Transmission 6. gear [-]:	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Transmission 7. gear [-]:	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58
Transmission 8. gear [-]:	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84
Transmission 9. gear [-]:	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01
Transmission 10. gear [-]:	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
Transmission 11. gear [-]:	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09
Transmission 12. gear [-]:	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Transmission 13. gear [-]:	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Transmission 14. gear [-]:	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Transmission 15. gear [-]:	1	1	1	1	1	1	1	1	1	1	1
Transmission 16. gear [-]:	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Gear shift behaviour:											
Gearshift model (Version fast driver) Shift up at rpm_norm in actual gear greater than:	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Shift down when rpm_norm in lower gear is lower than:	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Gearshift model (Version economy driver) Shift up at ratio rpm_norm in higher gear greater than:	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Shift down when rpm_norm in actual gear is lower than:	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Share of version economy driver (0 to 1):	0	0	0	0	0	0	0	0	0	0	0
Share of version mixed model (0 to 1): Share of version fast driver =1-economic-mixed model	1	1	1	1	1	1	1	1	1	1	1

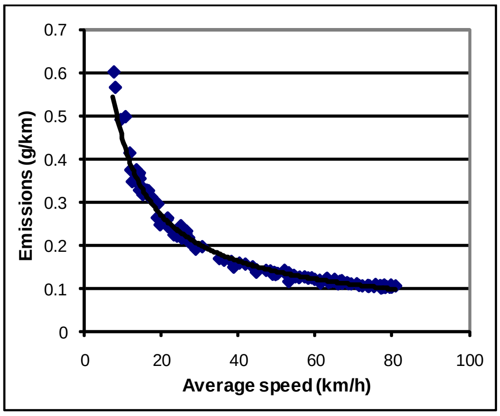
Vehicles specifications used for the PHEM model – maximum laden weights

Vehicle specifications	Veh 1 Existing Artic Single (2+3)	Veh 2 Existing Artic Double (2+3)	Veh 3 Existing Artic Single (3+3)	Veh 4 Existing Artic Double (3+3)	Veh 5 Existing Trawbar (3+3)	Veh 6 Longer Vehicle Artic Single (3+3) Self Steer	Veh 7 Longer Vehicle Artic Double (3+3) Self Steer	Veh 8 Longer Vehicle Artic Single (3+3) Command Steer	Veh 9 Longer Vehicle Artic Double (3+3) Command Steer	Veh 10 Longer Vehicle Artic Single (3+3) Active Steer	Veh 11 Longer Vehicle Artic Double (3+3) Active Steer
Driving resistances:											
vehicle mass [kg]:	13543	19035	14533	20025	15000	15307	20918	16072	21683	16177	21788
Loading [kg]	26457	20965	29467	23975	29000	28693	23083	27928	22318	27823	22213
Total weight	40000	40000	44000	44000	44000	44000	44000	44000	44000	44000	44000
C_d	0.5	0.5	0.55	0.55	0.55	0.6	0.6	0.6	0.6	0.6	0.6
Cross sectional area [m^2]	10.2	12.495	10.2	12.495	11.348	10.2	12.495	10.2	12.495	10.2	12.495
Delta [-]:	0	0	0	0	0	0	0	0	0	0	0
Inertia - Engine	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771	3.771
No axles	5	5	6	6	6	6	6	6	6	6	6
No wheels	14	14	16	16	16	16	16	16	16	16	16
Inertia - Wheels	815.08	815.08	931.52	931.52	931.52	931.52	931.52	931.52	931.52	931.52	931.52
Inertia - Gearbox	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Power takeoff [% from rated power]:	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Rated power [kW]	315	315	315	315	315	315	315	315	315	315	315
Rated engine speed [rpm]:	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Engine speed at idling [rpm]:	600	600	600	600	600	600	600	600	600	600	600
Gear box type (0=man; 1=auto):	0	0	0	0	0	0	0	0	0	0	0
Rolling Resistance Coefficients											
Fr0:	0.0073	0.0073	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
Fr1:	0	0	0	0	0	0	0	0	0	0	0
Fr2	0	0	0	0	0	0	0	0	0	0	0
Fr3:	0	0	0	0	0	0	0	0	0	0	0
Fr 4	0	0	0	0	0	0	0	0	0	0	0
Free parameter 1	0	0	0	0	0	0	0	0	0	0	0
Factor transmission losses (1.0 = standard)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

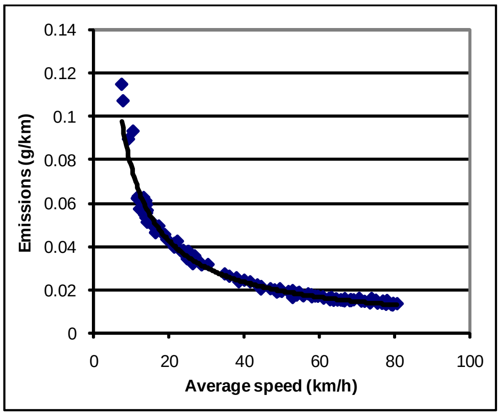
Vehicle specifications (Continued)	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7	Veh 8	Veh 9	Veh 10	Veh 11
Transmission:											
Final drive ratio [-]:	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65
Wheel diameter [m]	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
Transmission 1. gear [-]:	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
Transmission 2. gear [-]:	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55	11.55
Transmission 3. gear [-]:	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59	9.59
Transmission 4. gear [-]:	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02
Transmission 5. gear [-]:	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81	6.81
Transmission 6. gear [-]:	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Transmission 7. gear [-]:	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58
Transmission 8. gear [-]:	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84
Transmission 9. gear [-]:	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01	3.01
Transmission 10. gear [-]:	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
Transmission 11. gear [-]:	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09
Transmission 12. gear [-]:	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Transmission 13. gear [-]:	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49
Transmission 14. gear [-]:	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Transmission 15. gear [-]:	1	1	1	1	1	1	1	1	1	1	1
Transmission 16. gear [-]:	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Gear shift behaviour:											
Gearshift model (Version fast driver)											
Shift up at rpm_norm in actual gear greater than:	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Shift down when rpm_norm in lower gear is lower than:	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Gearshift model (Version economy driver)											
Shift up at ratio rpm_norm in higher gear greater than:	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Shift down when rpm_norm in actual gear is lower than:	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Share of version economy driver (0 to 1):	0	0	0	0	0	0	0	0	0	0	0
Share of version mixed model (0 to 1): Share of version fast driver =1-economic-mixed model	1	1	1	1	1	1	1	1	1	1	1

Appendix B LHV PHEM data and emission curves

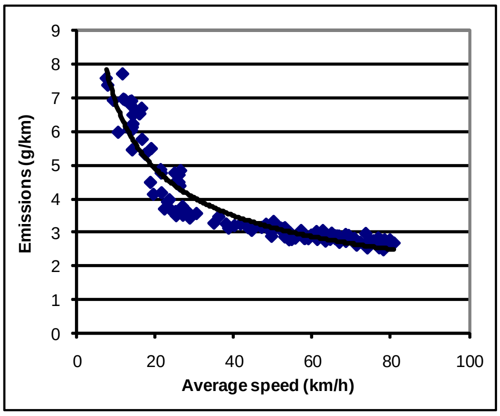
PHEM emissions: Vehicle 1
Existing Artic Single (2+3)
Euro class: 5
typical load



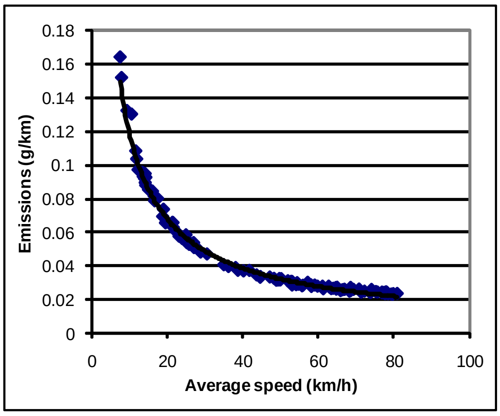
Carbon monoxide (CO)



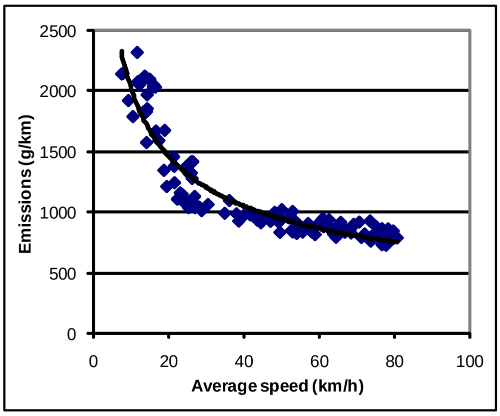
Hydrocarbons (HC)



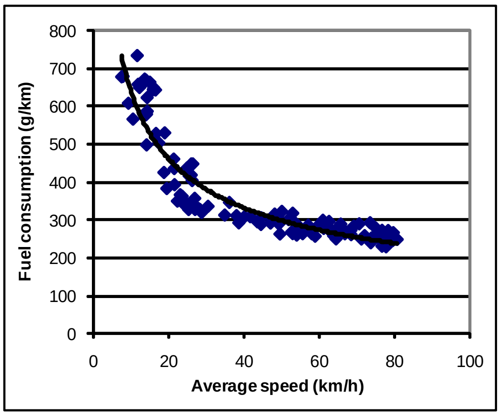
Oxides of nitrogen (NO_x)



Particulate matter (PM)

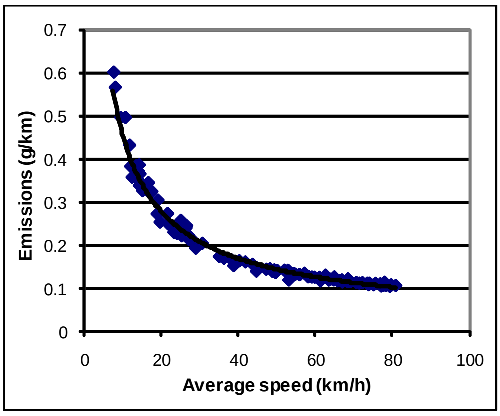


Carbon dioxide (CO_2)

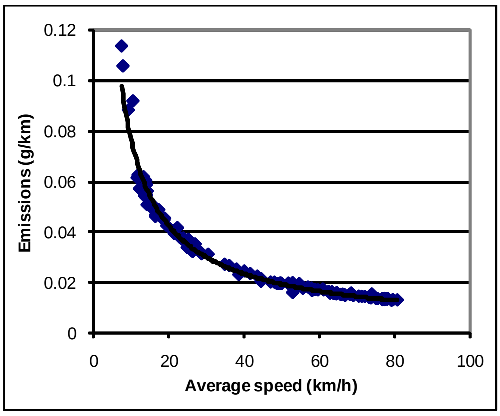


Fuel consumption (FC)

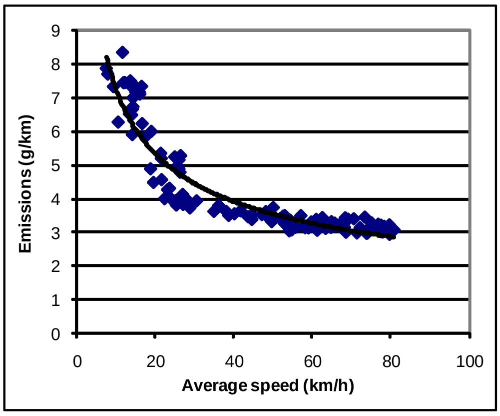
PHEM emissions: Vehicle 2
Existing Artic Double (2+3)
Euro class: 5
typical load



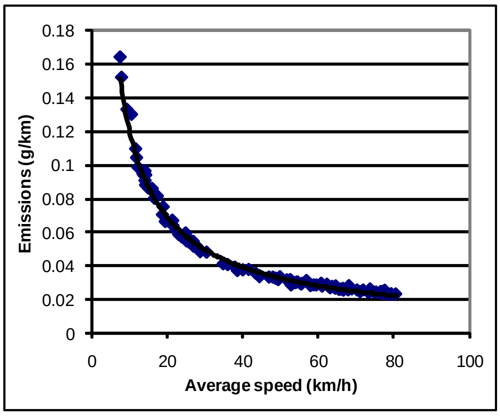
Carbon monoxide (CO)



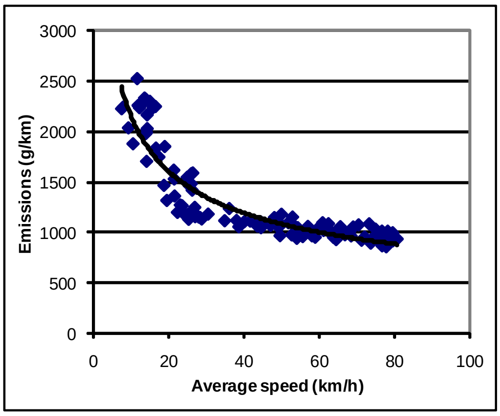
Hydrocarbons (HC)



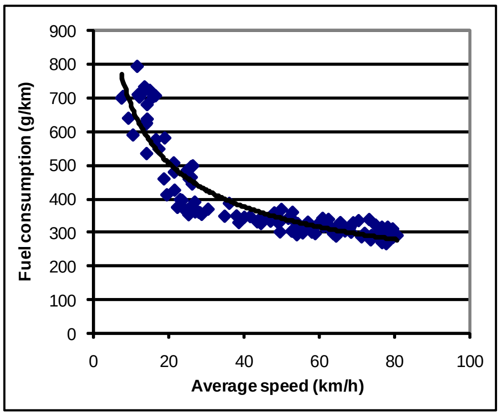
Oxides of nitrogen (NO_x)



Particulate matter (PM)

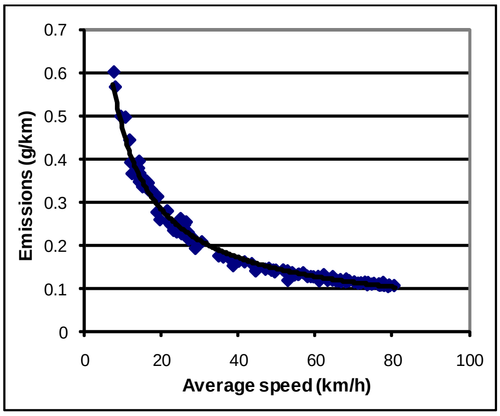


Carbon dioxide (CO_2)

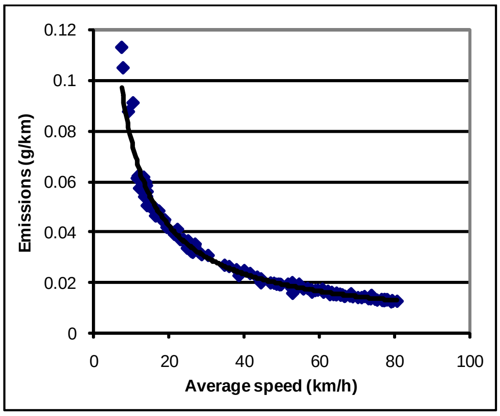


Fuel consumption (FC)

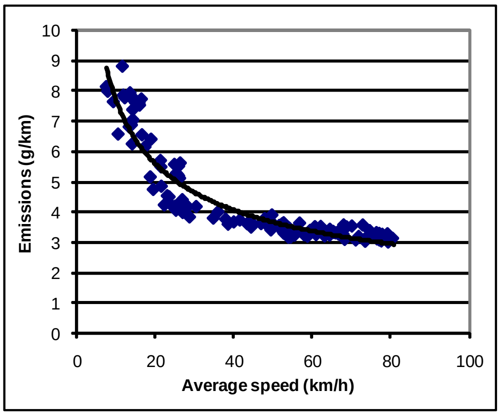
PHEM emissions: Vehicle 3
Existing Artic Single (3+3)
Euro class: 5
typical load



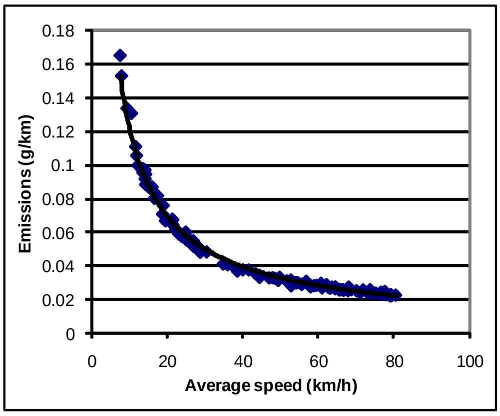
Carbon monoxide (CO)



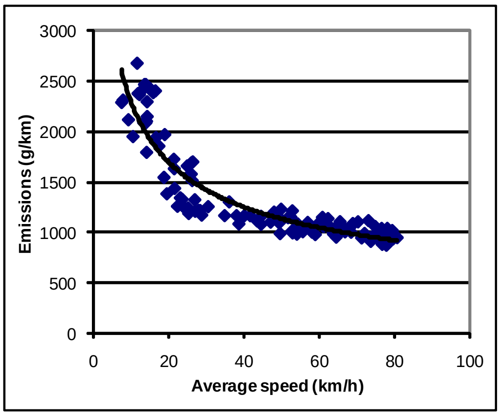
Hydrocarbons (HC)



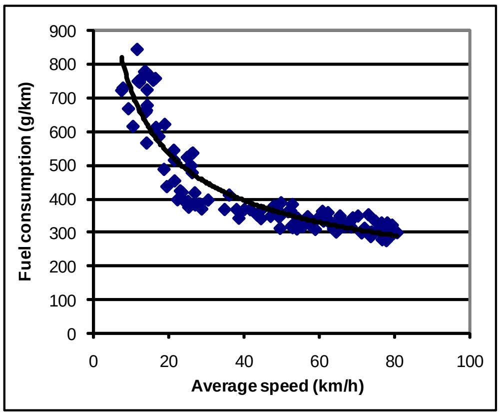
Oxides of nitrogen (NO_x)



Particulate matter (PM)

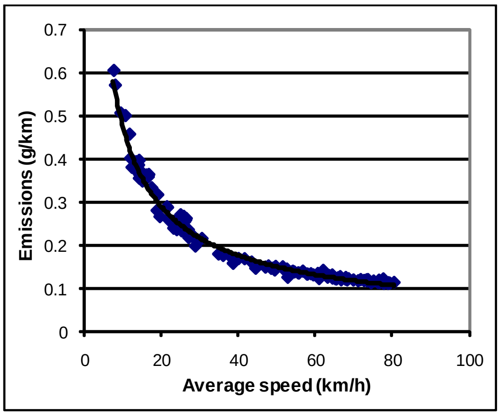


Carbon dioxide (CO_2)

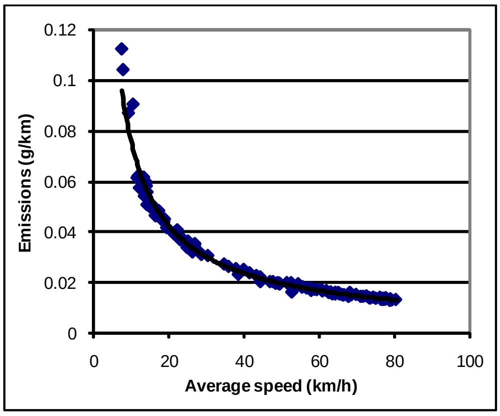


Fuel consumption (FC)

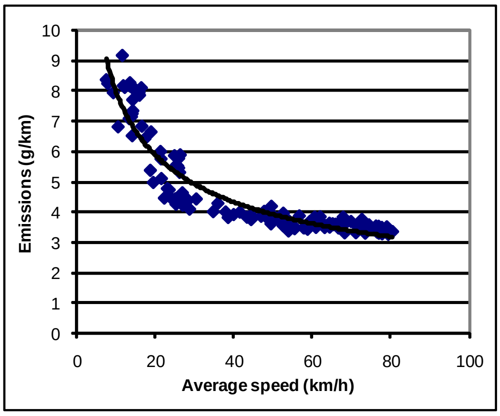
PHEM emissions: Vehicle 4
Existing Artic Double (3+3)
Euro class: 5
typical load



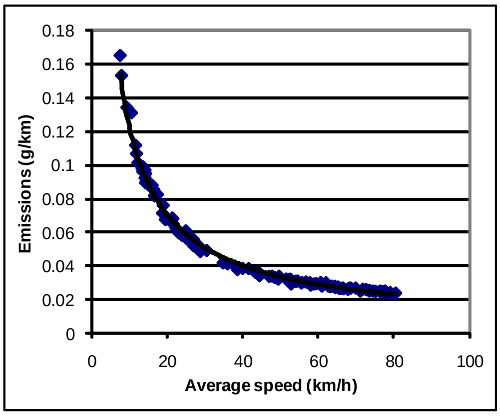
Carbon monoxide (CO)



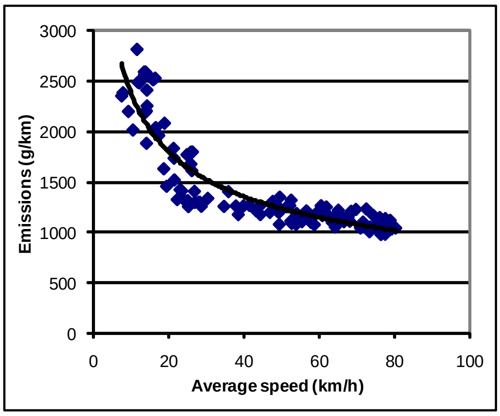
Hydrocarbons (HC)



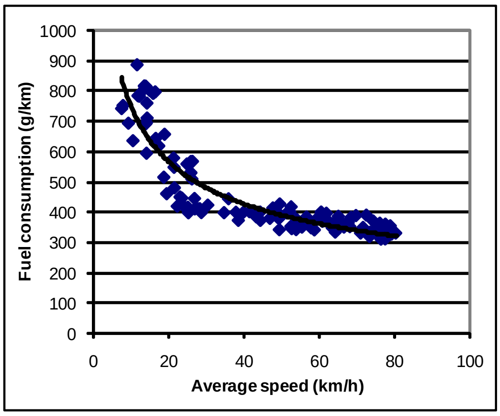
Oxides of nitrogen (NO_x)



Particulate matter (PM)

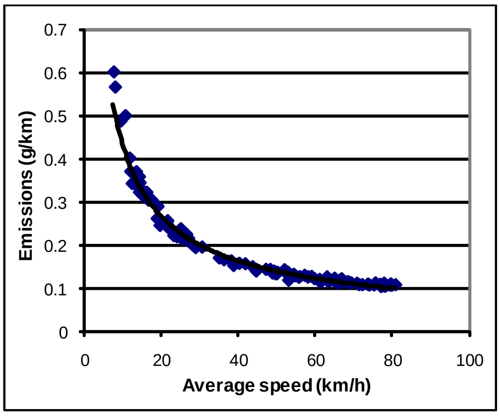


Carbon dioxide (CO_2)

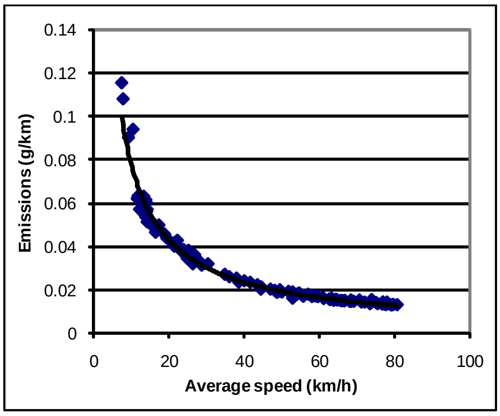


Fuel consumption (FC)

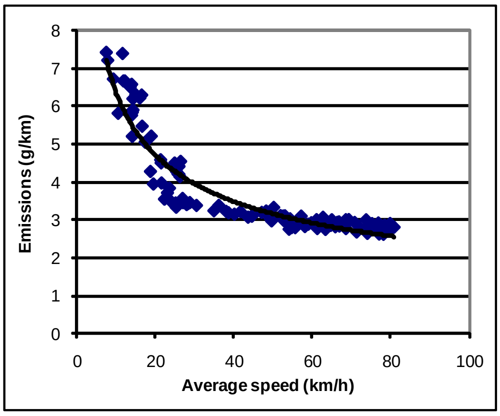
PHEM emissions: Vehicle 5
Existing Trawbar (3+3)
Euro class: 5
typical load



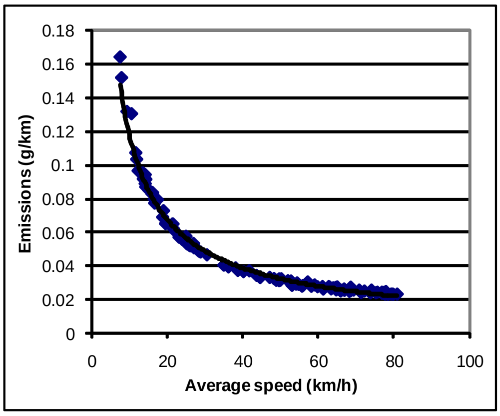
Carbon monoxide (CO)



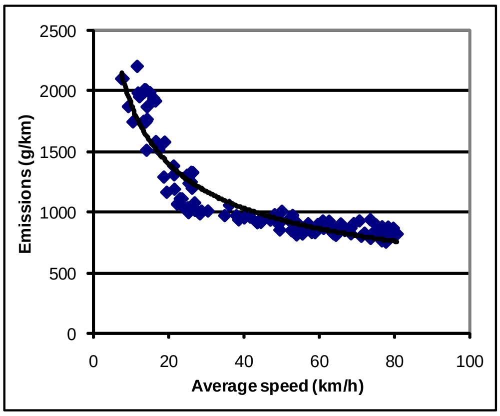
Hydrocarbons (HC)



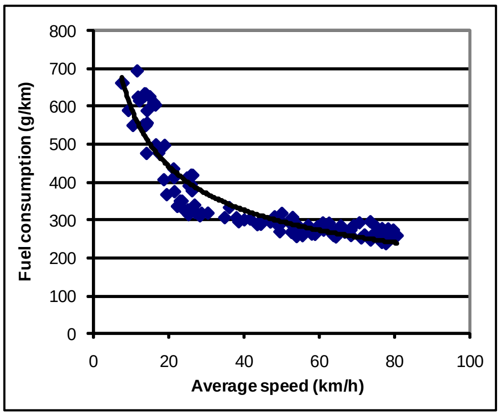
Oxides of nitrogen (NO_x)



Particulate matter (PM)

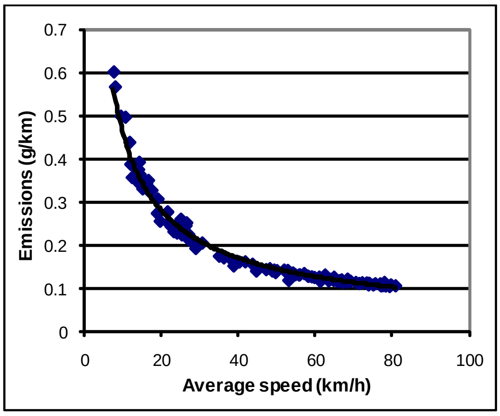


Carbon dioxide (CO_2)

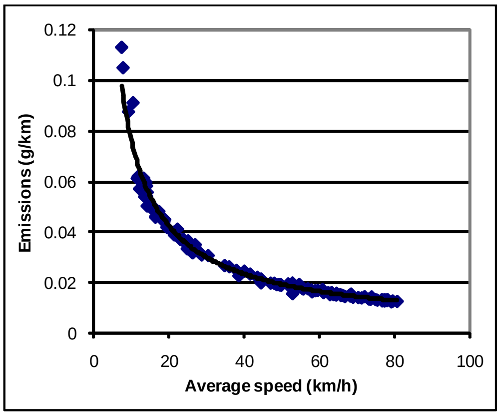


Fuel consumption (FC)

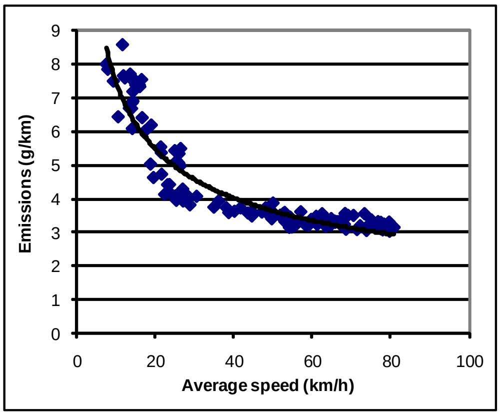
PHEM emissions: Vehicle 6
Longer Vehicle Artic Single (3+3) Self Steer
Euro class: 5
typical load



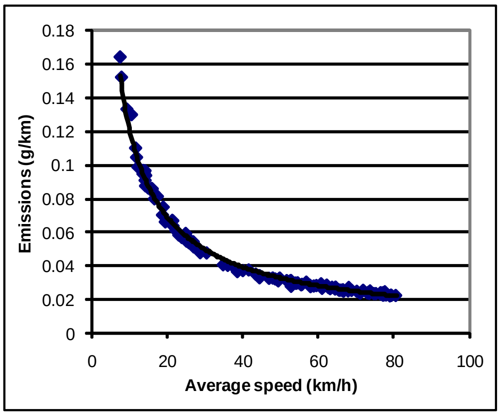
Carbon monoxide (CO)



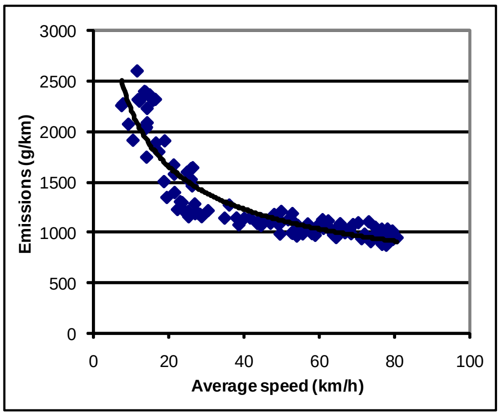
Hydrocarbons (HC)



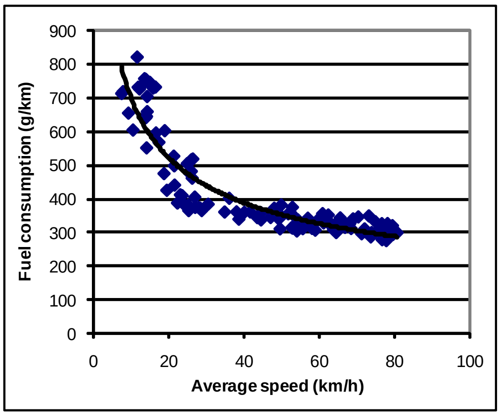
Oxides of nitrogen (NO_x)



Particulate matter (PM)

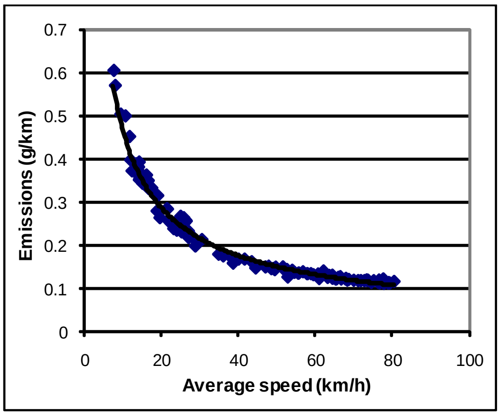


Carbon dioxide (CO_2)

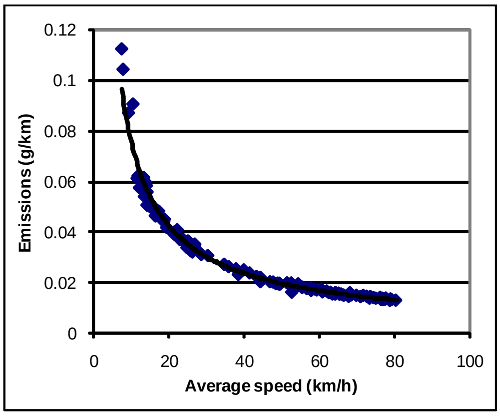


Fuel consumption (FC)

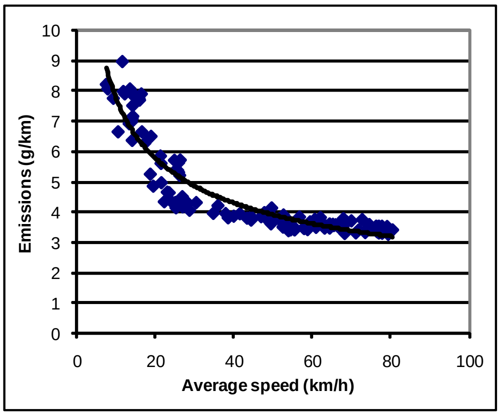
PHEM emissions: Vehicle 7
Longer Vehicle Artic Double (3+3) Self Steer
Euro class: 5
typical load



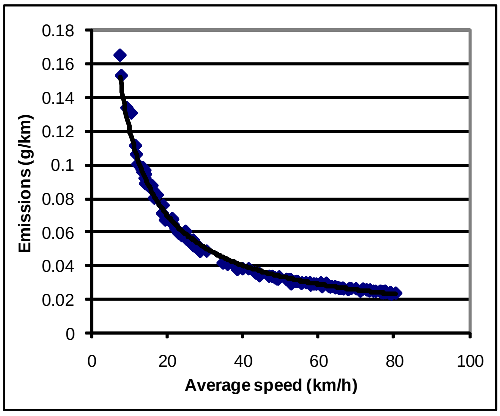
Carbon monoxide (CO)



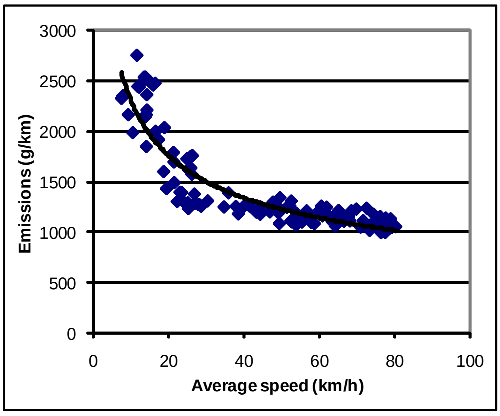
Hydrocarbons (HC)



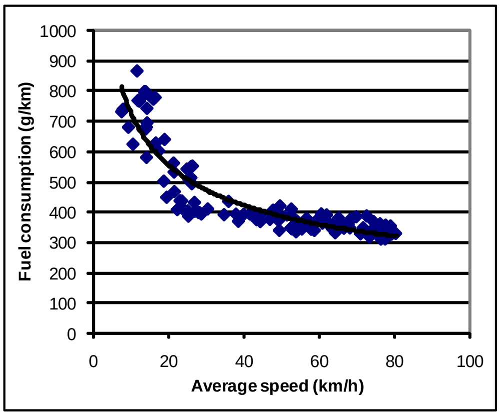
Oxides of nitrogen (NO_x)



Particulate matter (PM)

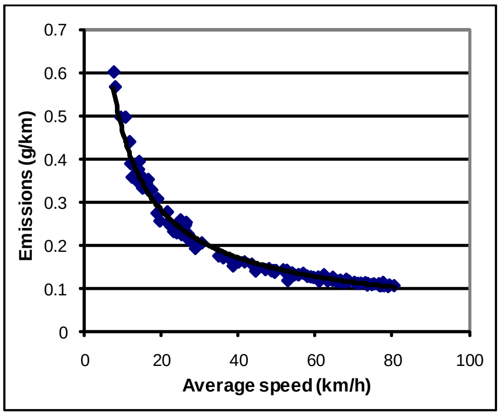


Carbon dioxide (CO_2)

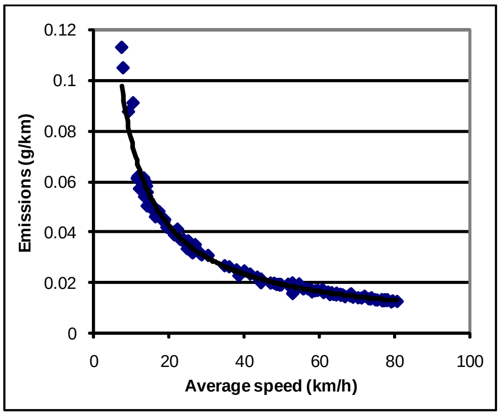


Fuel consumption (FC)

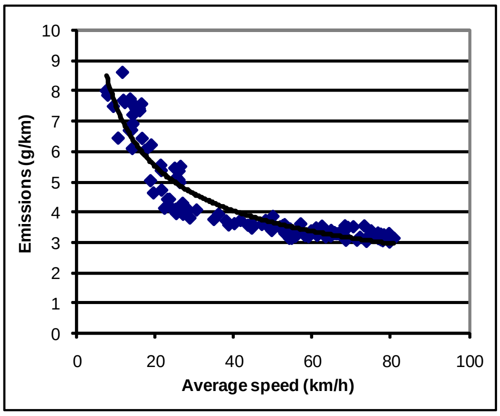
PHEM emissions: Vehicle 8
Longer Vehicle Artic Single (3+3) Command Steer
Euro class: 5
typical load



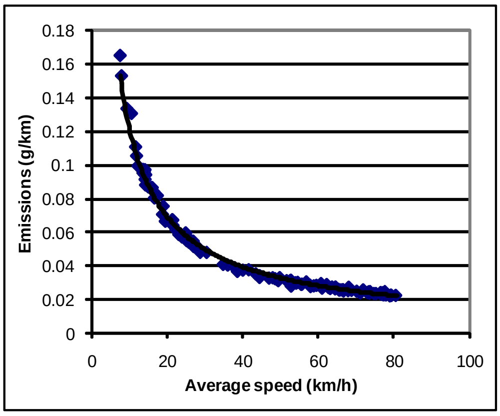
Carbon monoxide (CO)



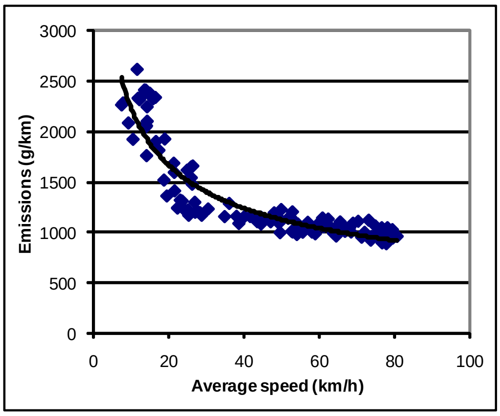
Hydrocarbons (HC)



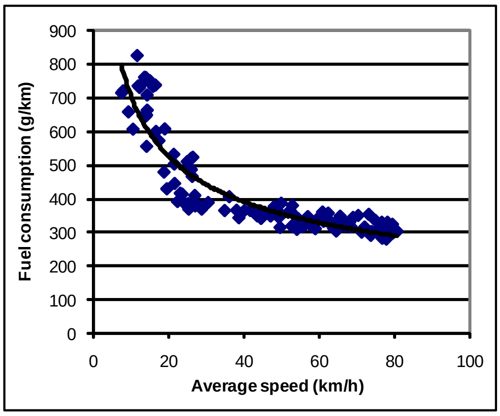
Oxides of nitrogen (NO_x)



Particulate matter (PM)

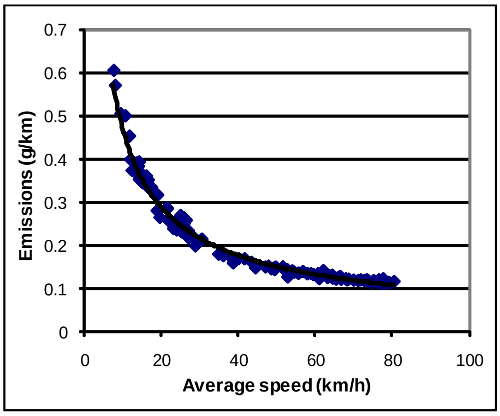


Carbon dioxide (CO_2)

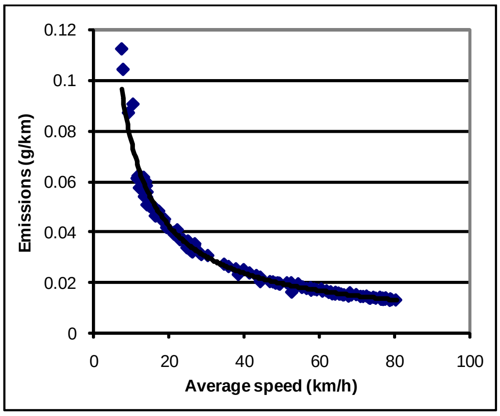


Fuel consumption (FC)

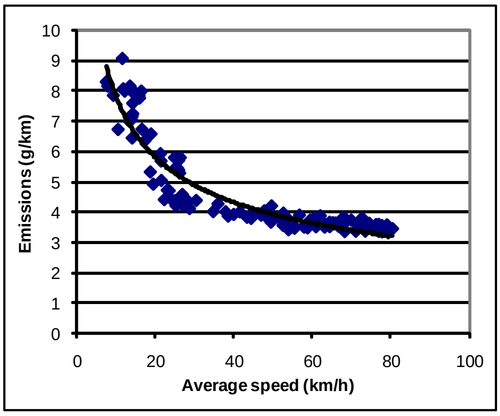
PHEM emissions: Vehicle 9
Longer Vehicle Artic Double (3+3) Command Steer
Euro class: 5
typical load



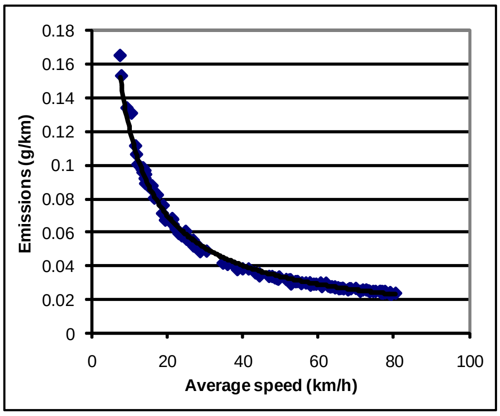
Carbon monoxide (CO)



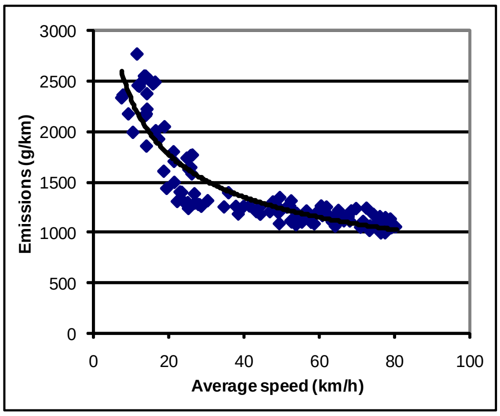
Hydrocarbons (HC)



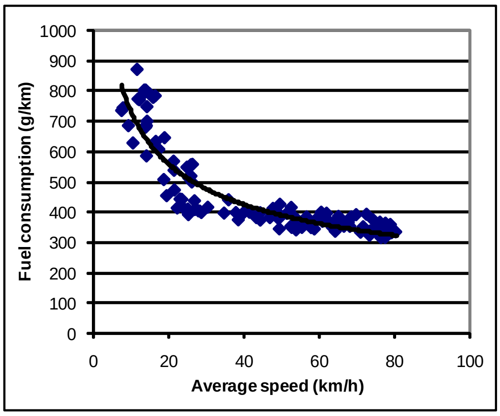
Oxides of nitrogen (NO_x)



Particulate matter (PM)

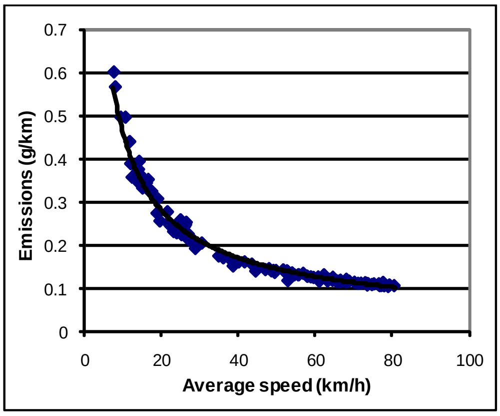


Carbon dioxide (CO_2)

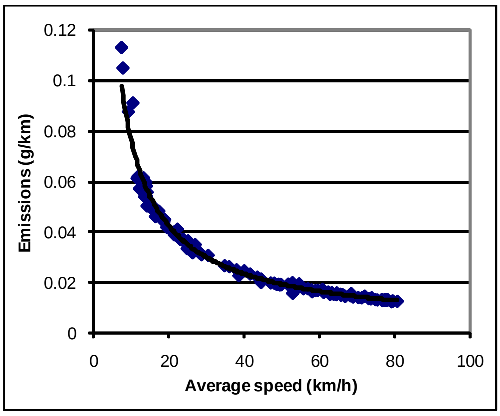


Fuel consumption (FC)

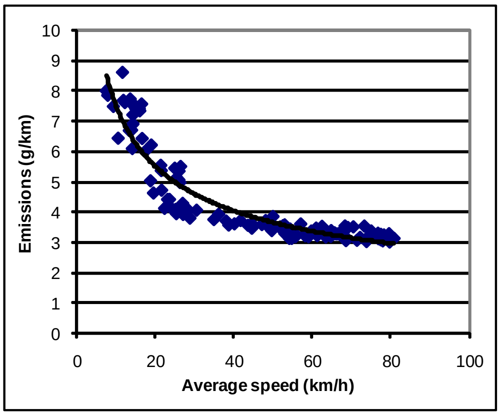
PHEM emissions: Vehicle 10
Longer Vehicle Artic Single (3+3) Active Steer
Euro class: 5
typical load



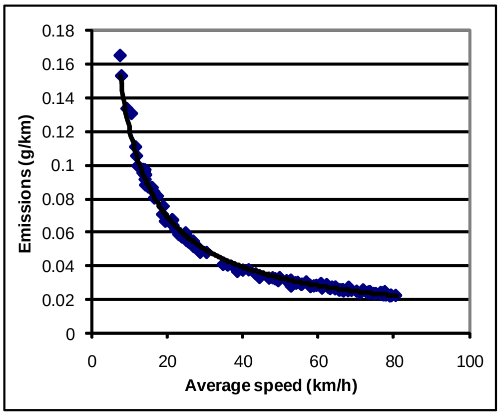
Carbon monoxide (CO)



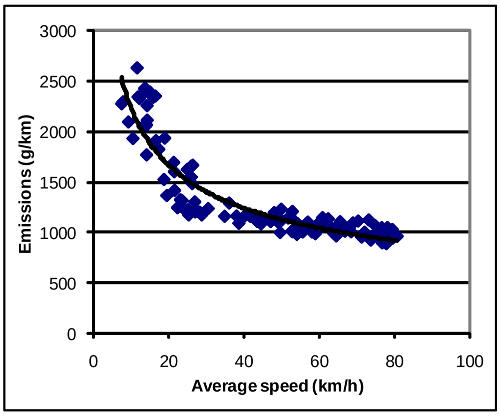
Hydrocarbons (HC)



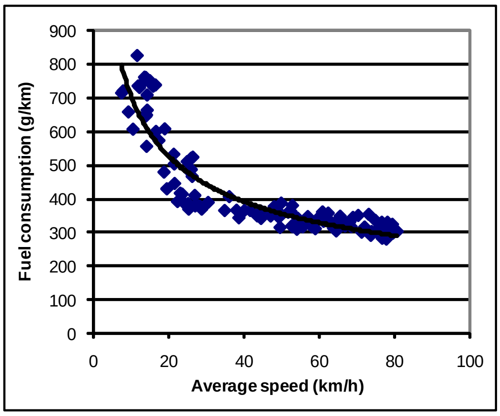
Oxides of nitrogen (NO_x)



Particulate matter (PM)

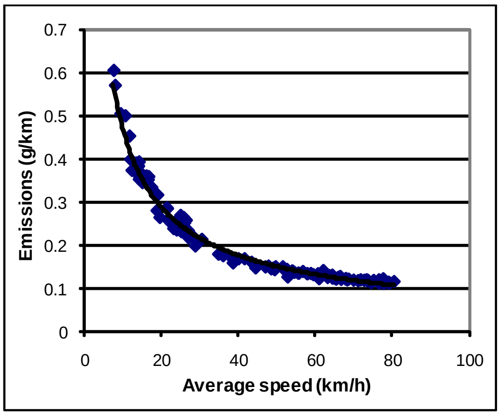


Carbon dioxide (CO_2)

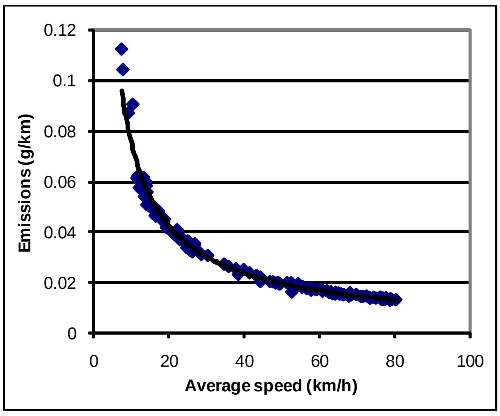


Fuel consumption (FC)

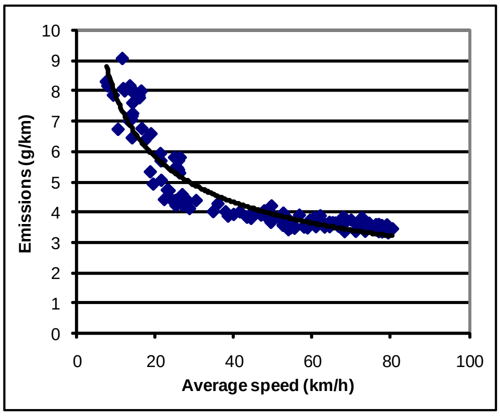
PHEM emissions: Vehicle 11
Longer Vehicle Artic Double (3+3) Active Steer
Euro class: 5
typical load



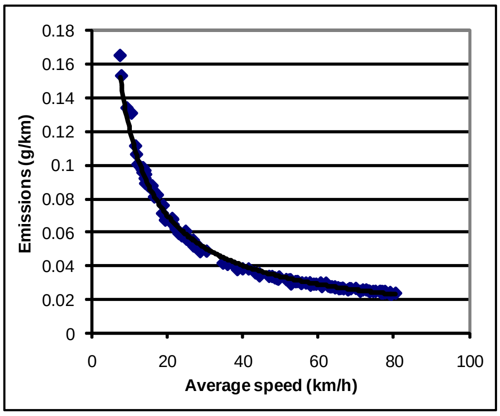
Carbon monoxide (CO)



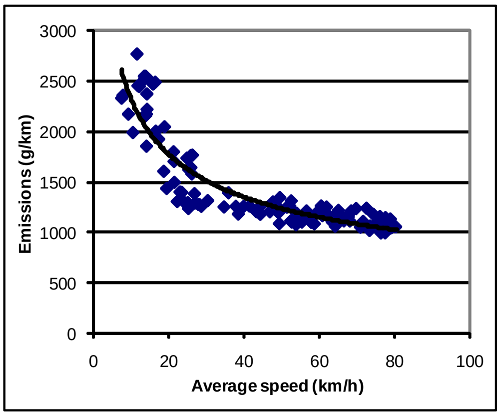
Hydrocarbons (HC)



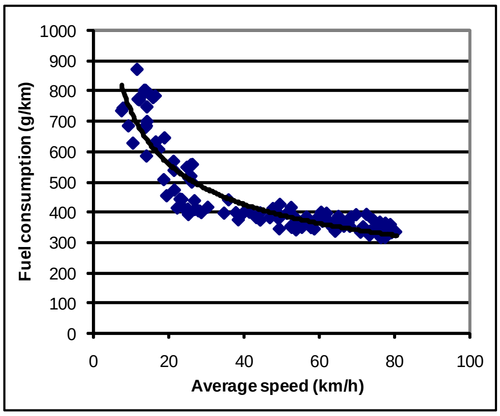
Oxides of nitrogen (NO_x)



Particulate matter (PM)

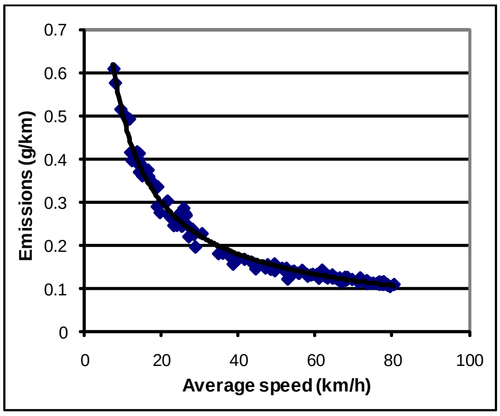


Carbon dioxide (CO_2)

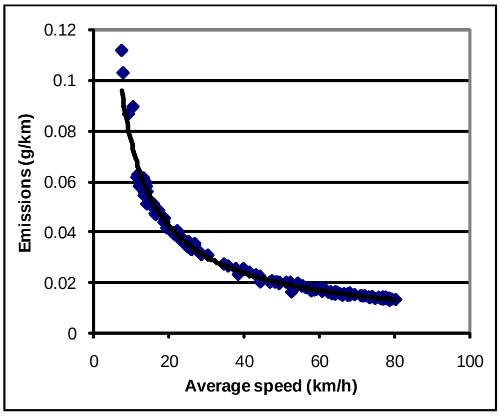


Fuel consumption (FC)

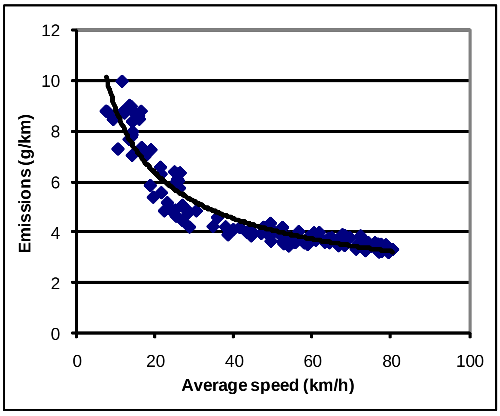
PHEM emissions: Vehicle 1
Existing Artic Single (2+3)
Euro class: 5
fully-laden



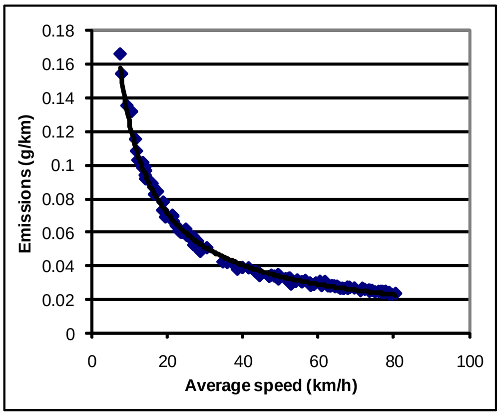
Carbon monoxide (CO)



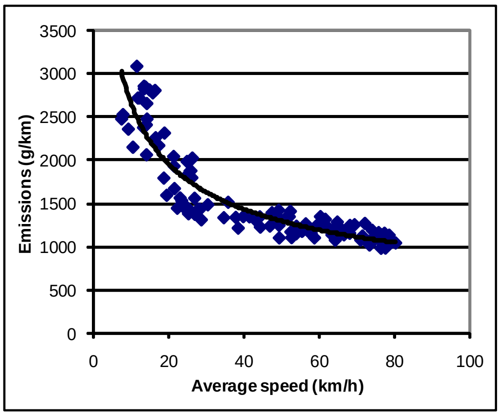
Hydrocarbons (HC)



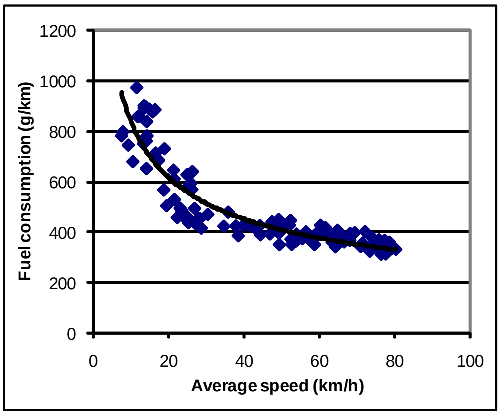
Oxides of nitrogen (NO_x)



Particulate matter (PM)

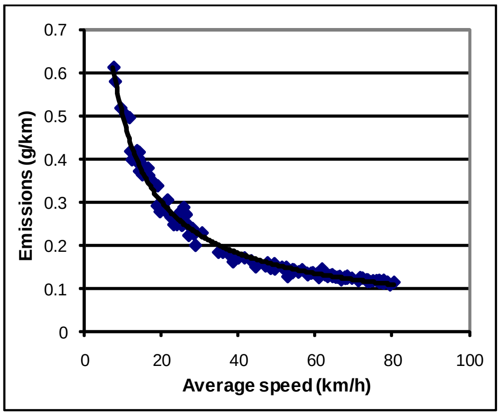


Carbon dioxide (CO_2)

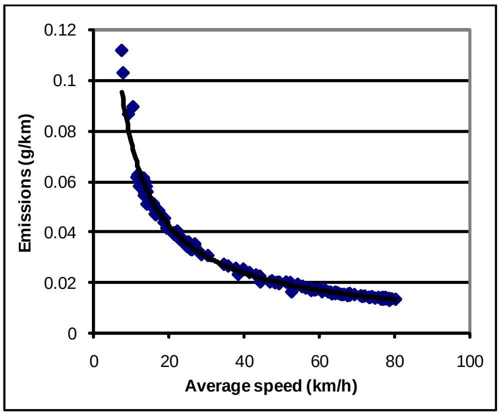


Fuel consumption (FC)

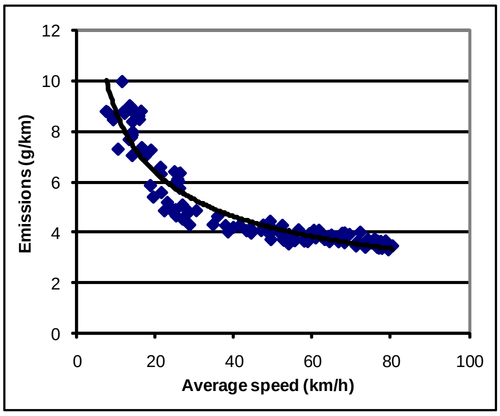
PHEM emissions: Vehicle 2
Existing Artic Double (2+3)
Euro class: 5
fully-laden



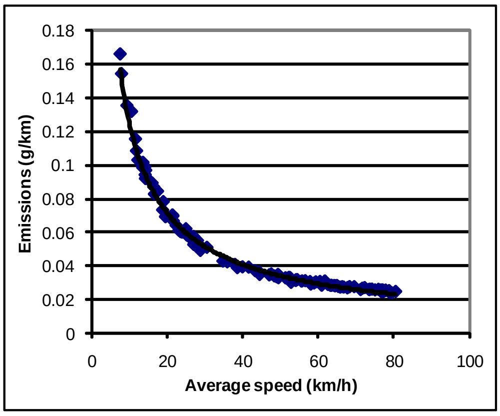
Carbon monoxide (CO)



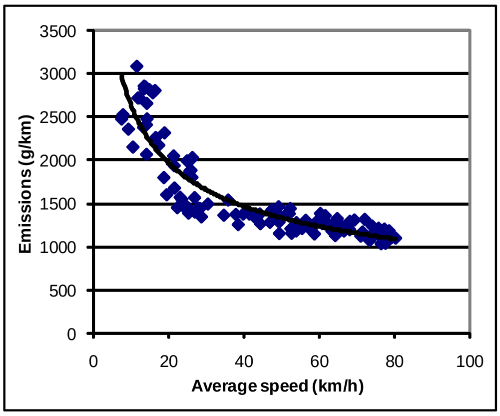
Hydrocarbons (HC)



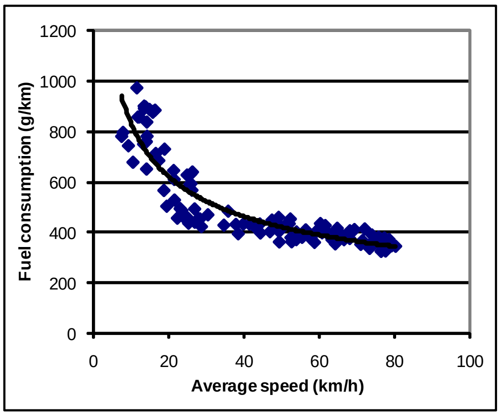
Oxides of nitrogen (NO_x)



Particulate matter (PM)

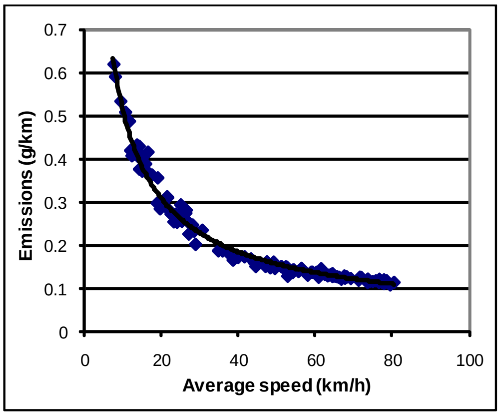


Carbon dioxide (CO_2)

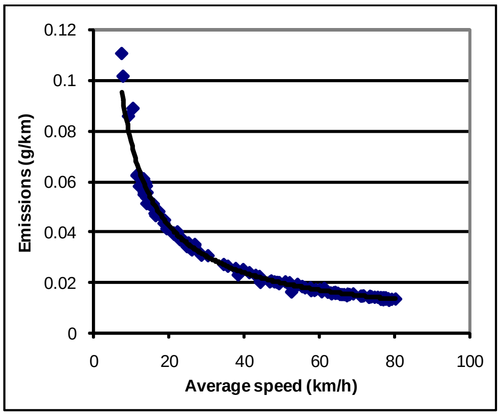


Fuel consumption (FC)

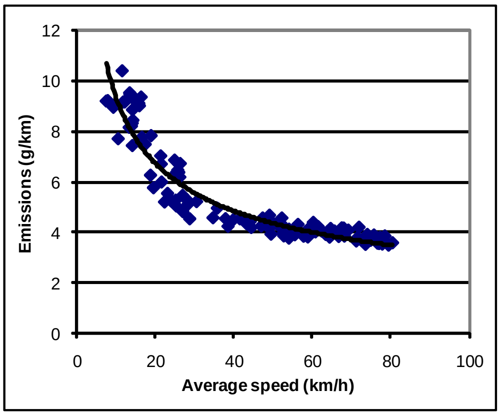
PHEM emissions: Vehicle 3
Existing Artic Single (3+3)
Euro class: 5
fully-laden



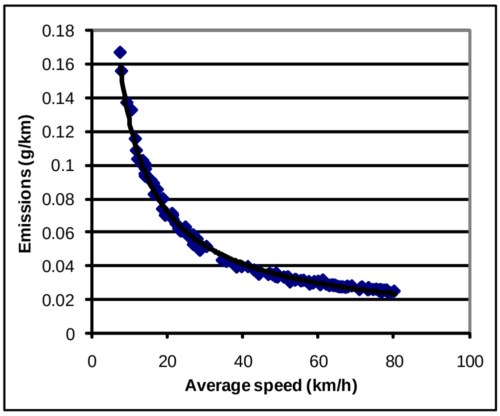
Carbon monoxide (CO)



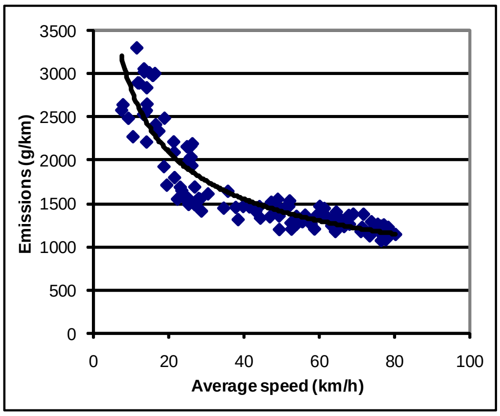
Hydrocarbons (HC)



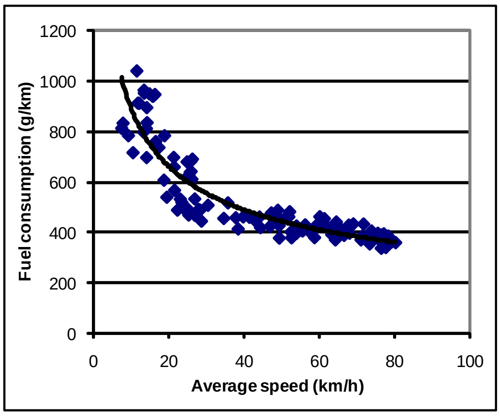
Oxides of nitrogen (NO_x)



Particulate matter (PM)

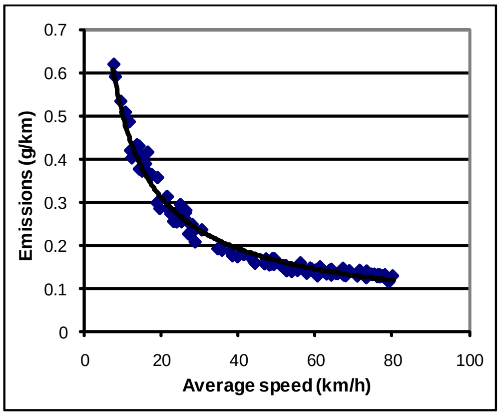


Carbon dioxide (CO_2)

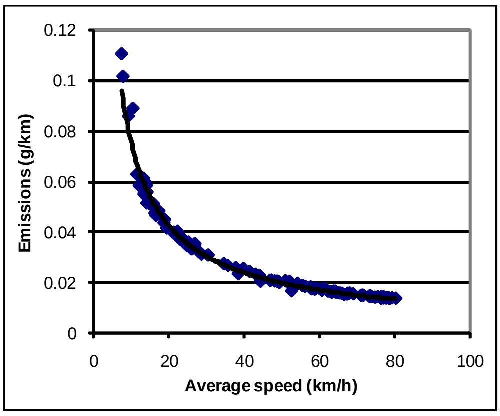


Fuel consumption (FC)

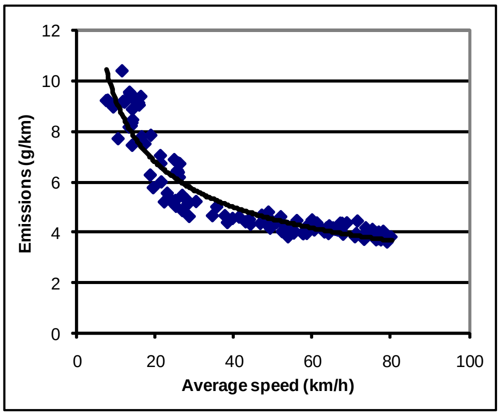
PHEM emissions: Vehicle 4
Existing Artic Double (3+3)
Euro class: 5
fully-laden



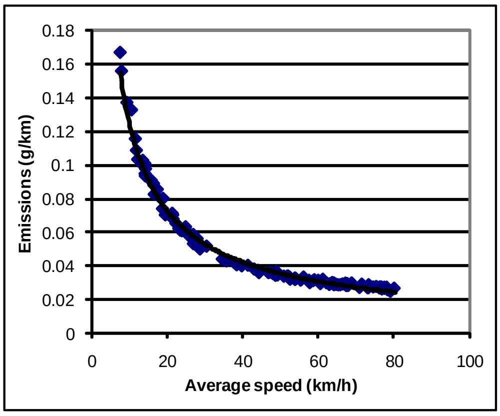
Carbon monoxide (CO)



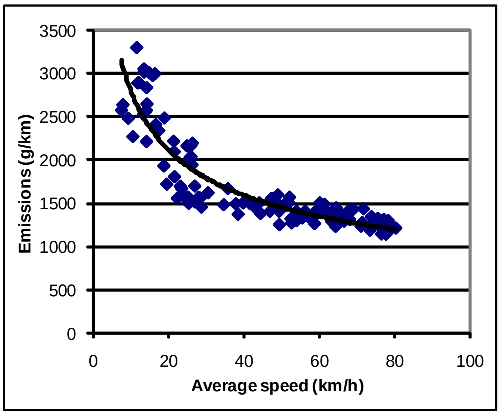
Hydrocarbons (HC)



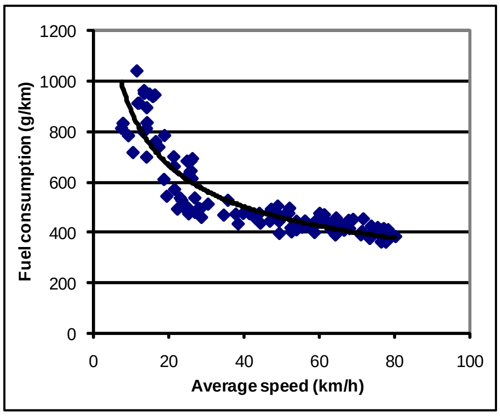
Oxides of nitrogen (NO_x)



Particulate matter (PM)

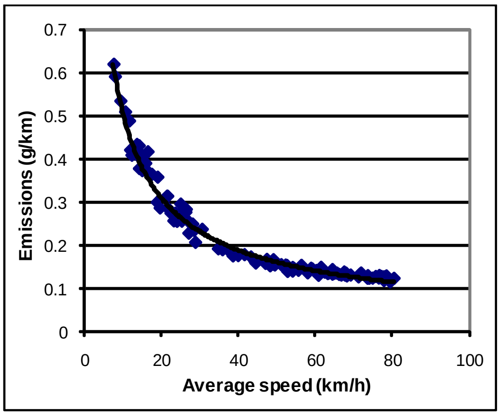


Carbon dioxide (CO_2)

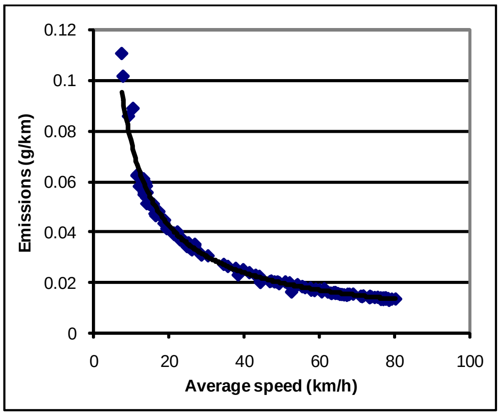


Fuel consumption (FC)

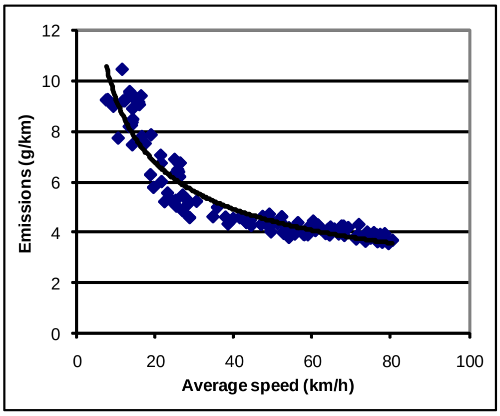
PHEM emissions: Vehicle 5
Existing Trawbar (3+3)
Euro class: 5
fully-laden



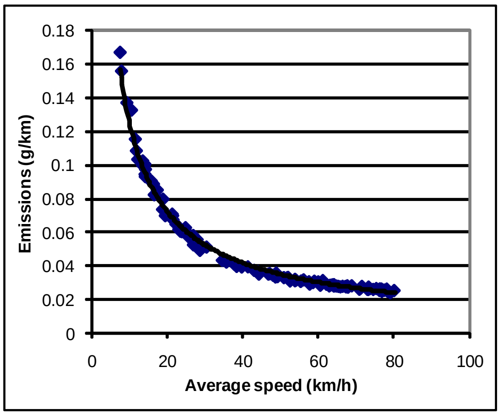
Carbon monoxide (CO)



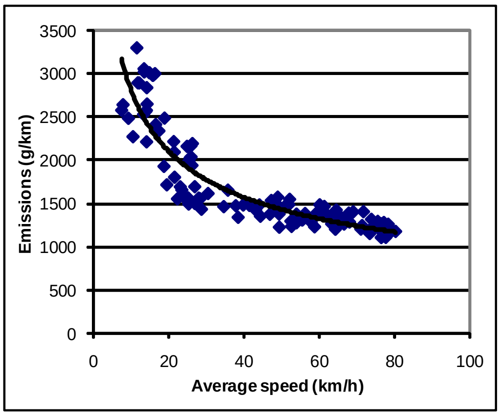
Hydrocarbons (HC)



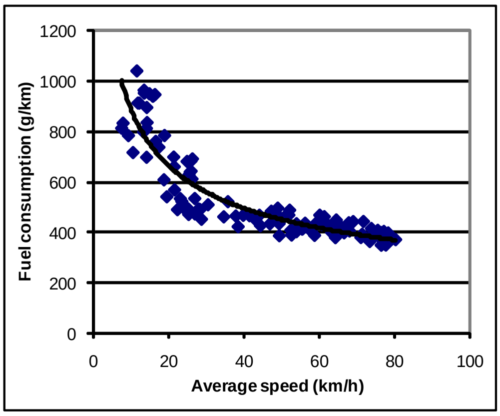
Oxides of nitrogen (NO_x)



Particulate matter (PM)

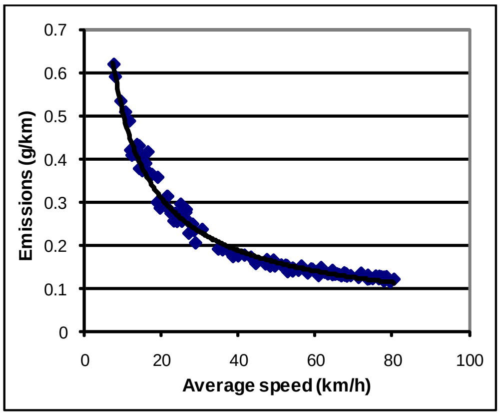


Carbon dioxide (CO_2)

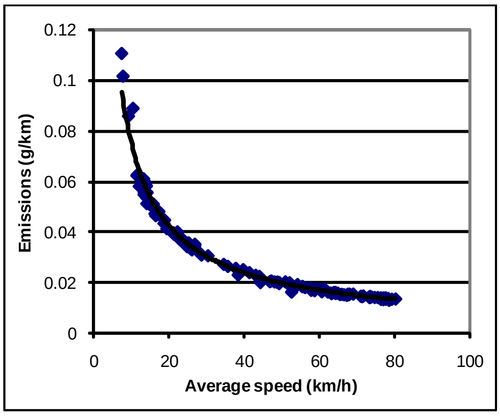


Fuel consumption (FC)

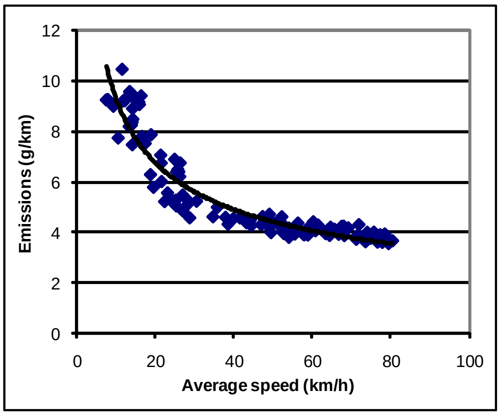
PHEM emissions: Vehicle 6
Longer Vehicle Artic Single (3+3) Self Steer
Euro class: 5
fully-laden



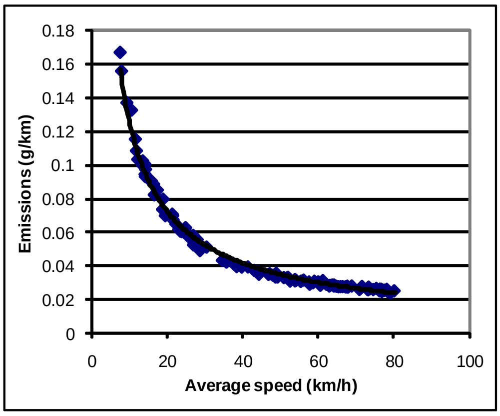
Carbon monoxide (CO)



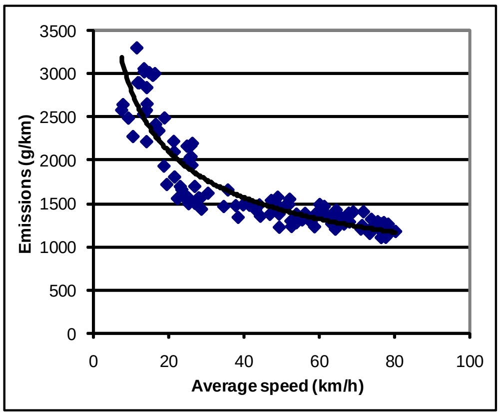
Hydrocarbons (HC)



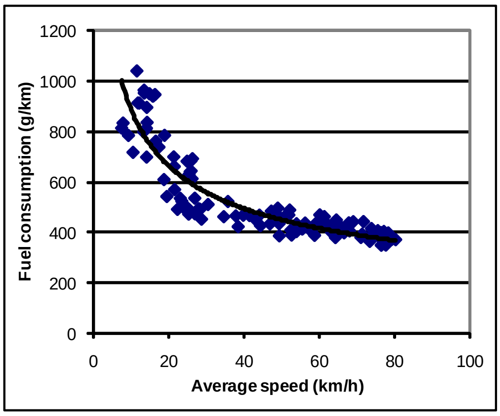
Oxides of nitrogen (NO_x)



Particulate matter (PM)

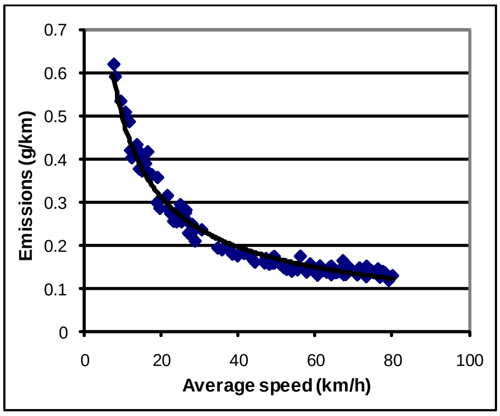


Carbon dioxide (CO_2)

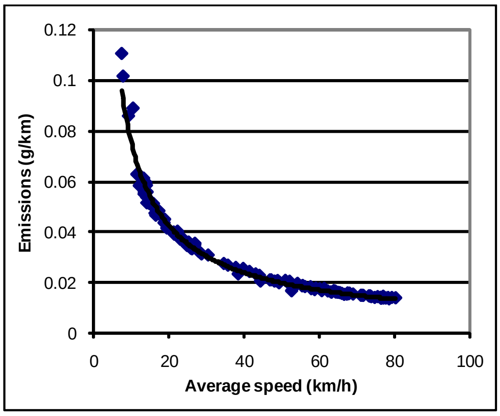


Fuel consumption (FC)

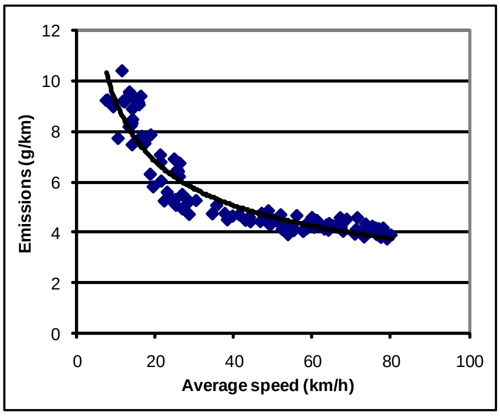
PHEM emissions: Vehicle 7
Longer Vehicle Artic Double (3+3) Self Steer
Euro class: 5
fully-laden



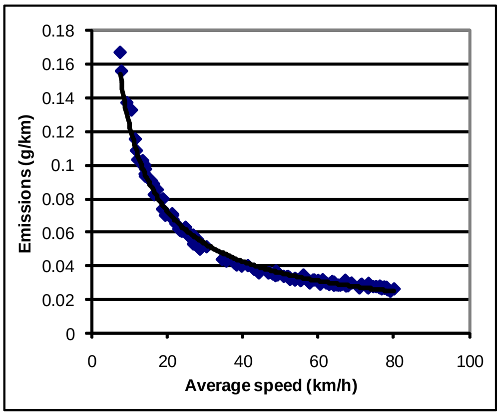
Carbon monoxide (CO)



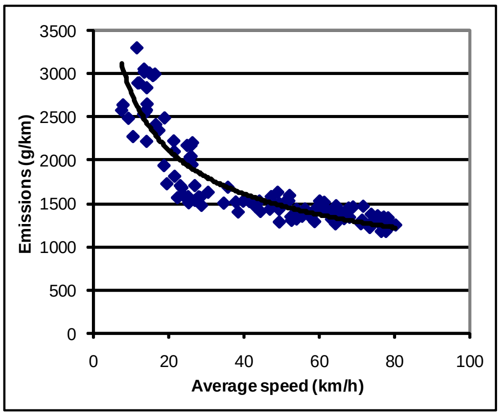
Hydrocarbons (HC)



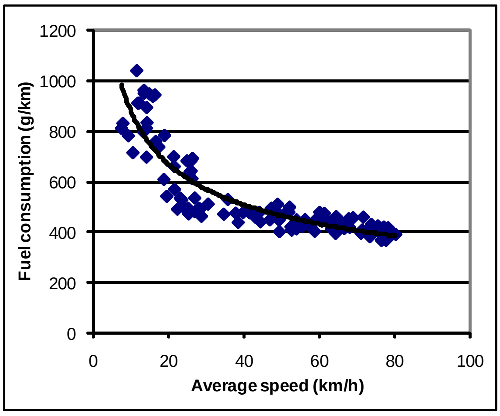
Oxides of nitrogen (NO_x)



Particulate matter (PM)

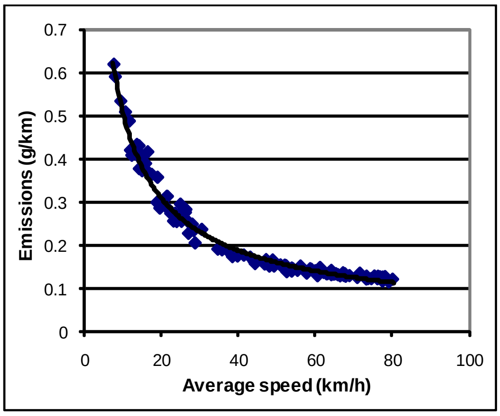


Carbon dioxide (CO_2)

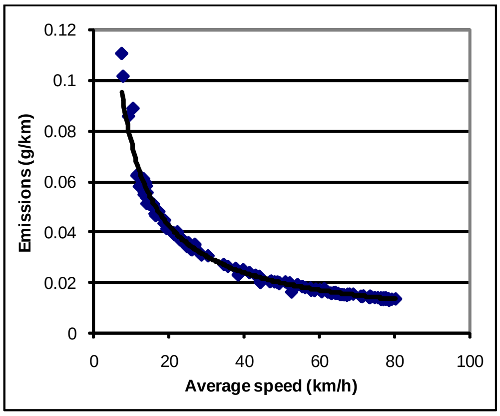


Fuel consumption (FC)

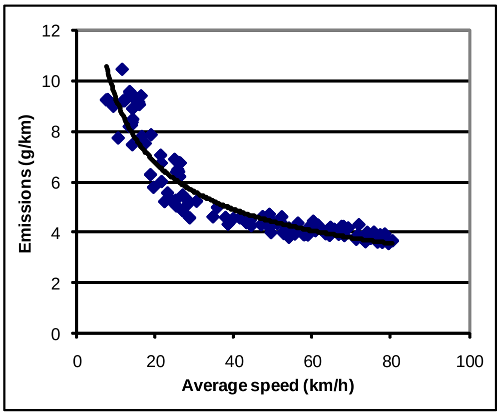
PHEM emissions: Vehicle 8
Longer Vehicle Artic Single (3+3) Command Steer
Euro class: 5
fully-laden



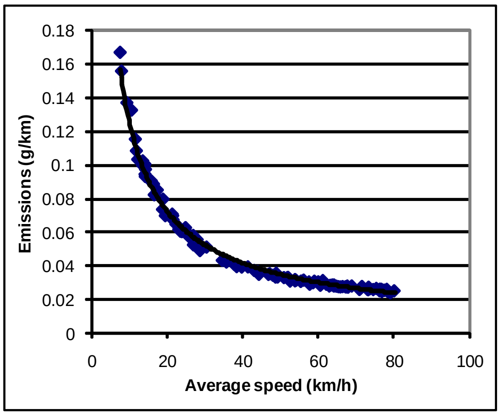
Carbon monoxide (CO)



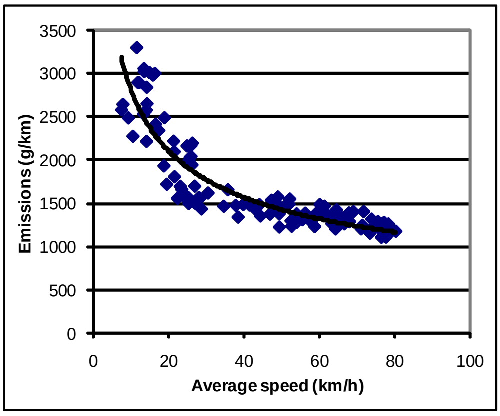
Hydrocarbons (HC)



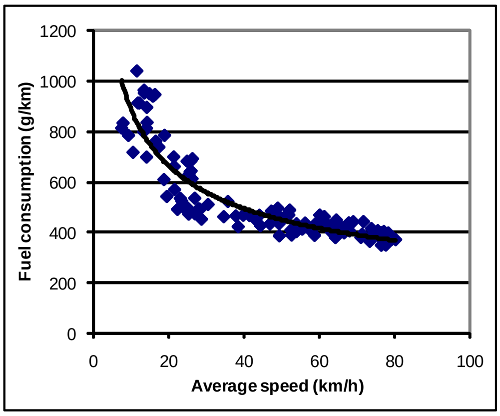
Oxides of nitrogen (NO_x)



Particulate matter (PM)

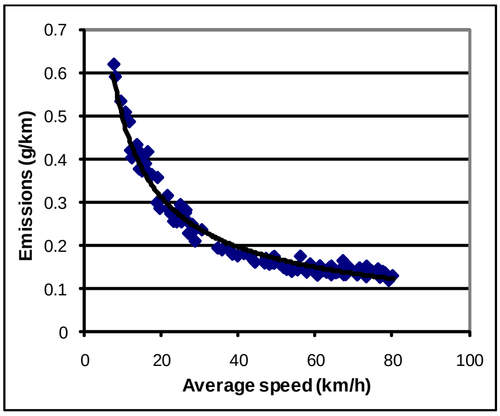


Carbon dioxide (CO_2)

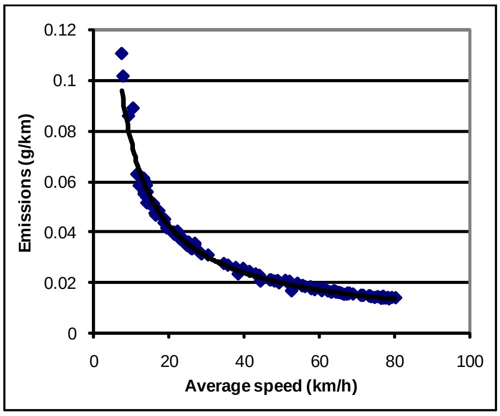


Fuel consumption (FC)

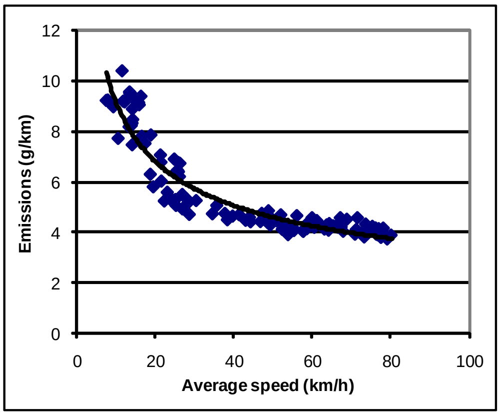
PHEM emissions: Vehicle 9
Longer Vehicle Artic Double (3+3) Command Steer
Euro class: 5
fully-laden



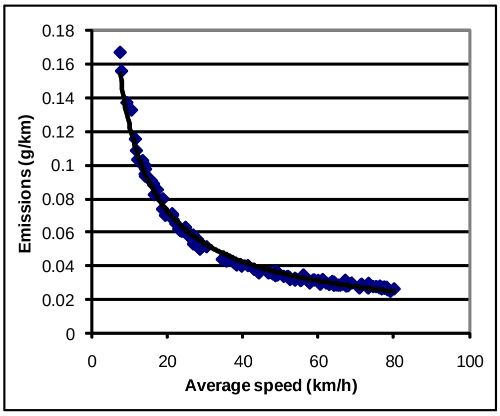
Carbon monoxide (CO)



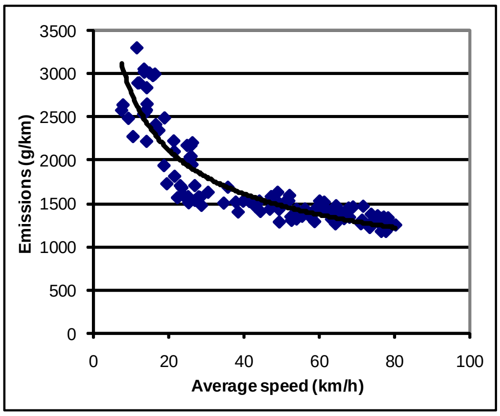
Hydrocarbons (HC)



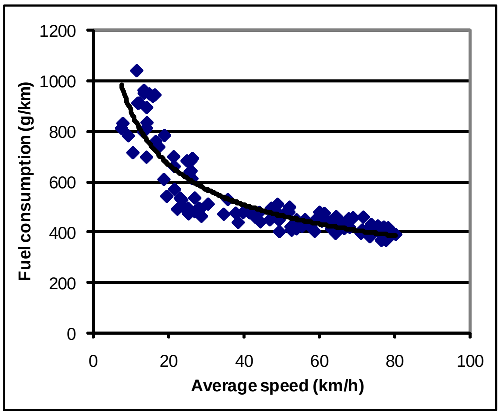
Oxides of nitrogen (NO_x)



Particulate matter (PM)

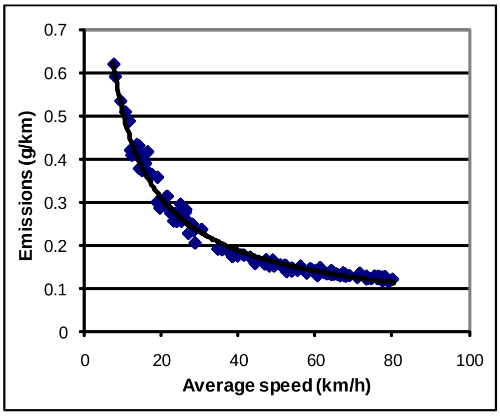


Carbon dioxide (CO_2)

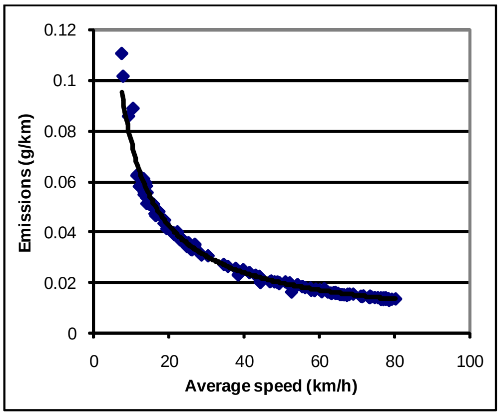


Fuel consumption (FC)

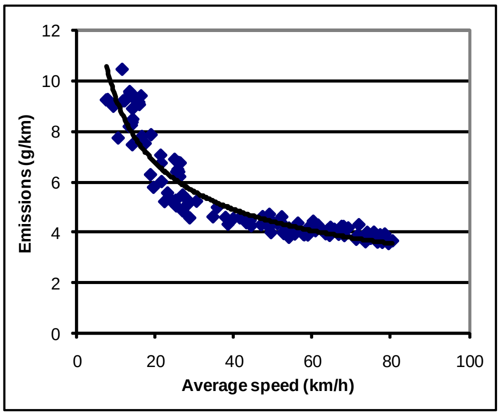
PHEM emissions: Vehicle 10
Longer Vehicle Artic Single (3+3) Active Steer
Euro class: 5
fully-laden



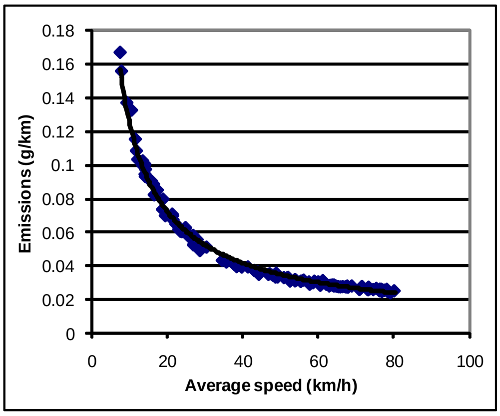
Carbon monoxide (CO)



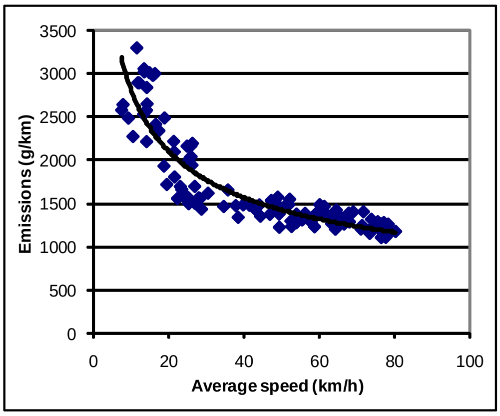
Hydrocarbons (HC)



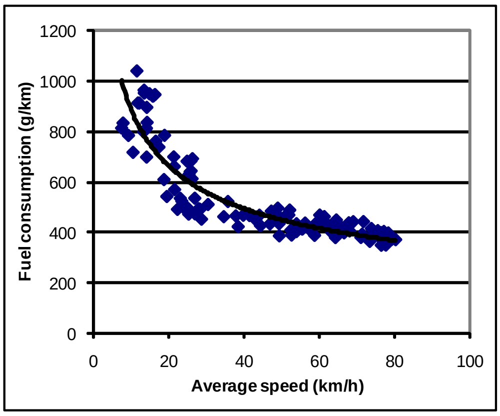
Oxides of nitrogen (NO_x)



Particulate matter (PM)

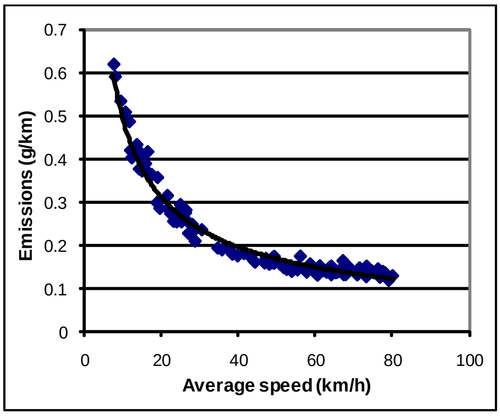


Carbon dioxide (CO_2)

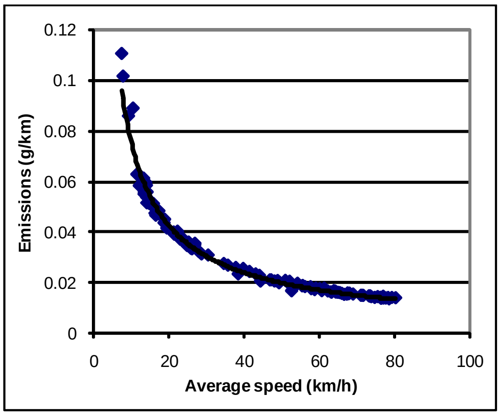


Fuel consumption (FC)

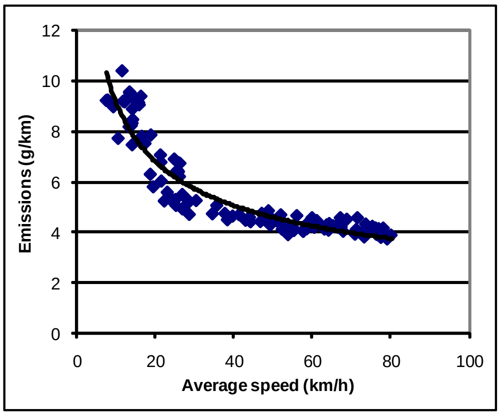
PHEM emissions: Vehicle 11
Longer Vehicle Artic Double (3+3) Active Steer
Euro class: 5
fully-laden



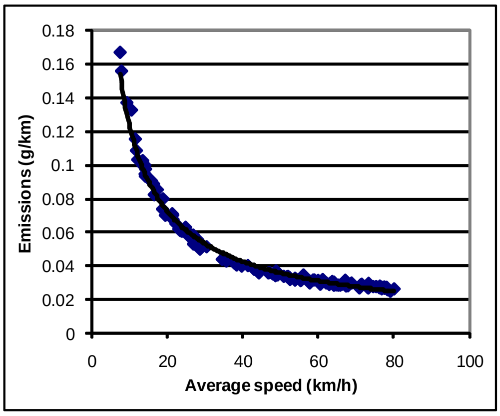
Carbon monoxide (CO)



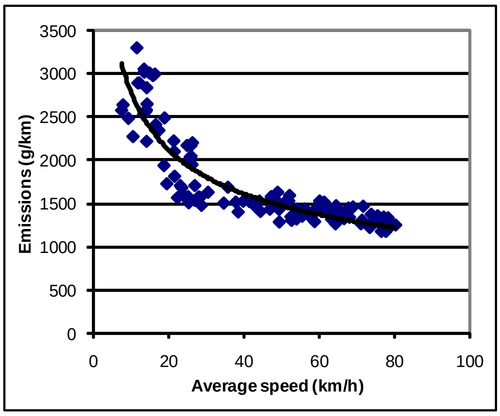
Hydrocarbons (HC)



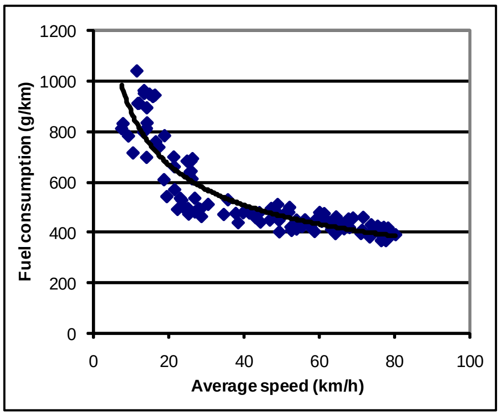
Oxides of nitrogen (NO_x)



Particulate matter (PM)



Carbon dioxide (CO_2)



Fuel consumption (FC)

Appendix C LHV emission functions

Function form: $E = a.v^b$

Where:

v is speed in km/h

a & b are the coefficients contained in the tables below

E is the emissions in g/km

Table 28: CO emission functions

		Euro V		
Load	**Veh**	**a**	**b**	**r^2**
Typical load	1	2.3435	-0.72	0.990
	2	2.38	-0.715	0.989
	3	2.4901	-0.724	0.989
	4	2.4711	-0.714	0.987
	5	2.1747	-0.699	0.989
	6	2.4137	-0.717	0.989
	7	2.3674	-0.703	0.988
	8	2.424	-0.717	0.989
	9	2.3845	-0.704	0.988
	10	2.4238	-0.717	0.989
	11	2.3974	-0.706	0.987
Maximum Load	1	2.7842	-0.742	0.986
	2	2.6863	-0.729	0.987
	3	2.8245	-0.738	0.986
	4	2.463	-0.69	0.979
	5	2.6304	-0.713	0.984
	6	2.6613	-0.717	0.985
	7	2.3037	-0.667	0.971
	8	2.6637	-0.717	0.984
	9	2.3035	-0.667	0.971
	10	2.6637	-0.717	0.984
	11	2.3035	-0.667	0.971

Table 29: HC emission functions

		Euro V		
Load	**Veh**	**a**	**b**	**r^2**
Typical load	1	0.5526	-0.853	0.991
	2	0.5551	-0.856	0.992
	3	0.5456	-0.851	0.992
	4	0.5265	-0.839	0.993
	5	0.5798	-0.867	0.992
	6	0.5525	-0.855	0.992
	7	0.5306	-0.842	0.993
	8	0.5519	-0.855	0.992
	9	0.5291	-0.84	0.993
	10	0.5516	-0.855	0.992
	11	0.5289	-0.84	0.993
Maximum Load	1	0.5215	-0.836	0.993
	2	0.518	-0.833	0.993
	3	0.5129	-0.829	0.994
	4	0.5153	-0.83	0.994
	5	0.5128	-0.829	0.994
	6	0.5133	-0.829	0.994
	7	0.5159	-0.831	0.994
	8	0.5132	-0.829	0.994
	9	0.5159	-0.831	0.994
	10	0.5133	-0.829	0.994
	11	0.5159	-0.831	0.994

Table 30: NO_x emission functions

		Euro V		
Load	**Veh**	**a**	**b**	**r^2**
Typical load	1	20.971	-0.485	0.919
	2	20.311	-0.446	0.897
	3	22.359	-0.462	0.904
	4	22.23	-0.443	0.899
	5	17.47	-0.437	0.896
	6	20.974	-0.448	0.898
	7	20.792	-0.427	0.891
	8	21.126	-0.448	0.898
	9	20.99	-0.428	0.892
	10	21.149	-0.448	0.898
	11	21.014	-0.428	0.892
Maximum Load	1	27.093	-0.484	0.914
	2	25.56	-0.463	0.907
	3	27.984	-0.475	0.914
	4	25.648	-0.443	0.900
	5	26.84	-0.46	0.909
	6	27.041	-0.462	0.910
	7	24.675	-0.429	0.893
	8	27.048	-0.463	0.910
	9	24.676	-0.429	0.893
	10	27.048	-0.463	0.910
	11	24.676	-0.429	0.893

Table 31: PM emission functions

		Euro V		
Load	**Veh**	**a**	**b**	**r^2**
Typical load	1	0.7729	-0.811	0.994
	2	0.7852	-0.811	0.995
	3	0.7997	-0.814	0.995
	4	0.7822	-0.803	0.995
	5	0.752	-0.802	0.993
	6	0.7945	-0.813	0.995
	7	0.7683	-0.798	0.995
	8	0.7962	-0.814	0.995
	9	0.7693	-0.798	0.995
	10	0.7962	-0.814	0.995
	11	0.7696	-0.798	0.995
Maximum Load	1	0.825	-0.816	0.995
	2	0.802	-0.806	0.995
	3	0.8105	-0.806	0.995
	4	0.754	-0.78	0.993
	5	0.7782	-0.791	0.994
	6	0.7835	-0.794	0.994
	7	0.7322	-0.77	0.991
	8	0.7839	-0.794	0.994
	9	0.7321	-0.77	0.991
	10	0.7839	-0.794	0.994
	11	0.7321	-0.77	0.991

Table 32: CO_2 emission functions

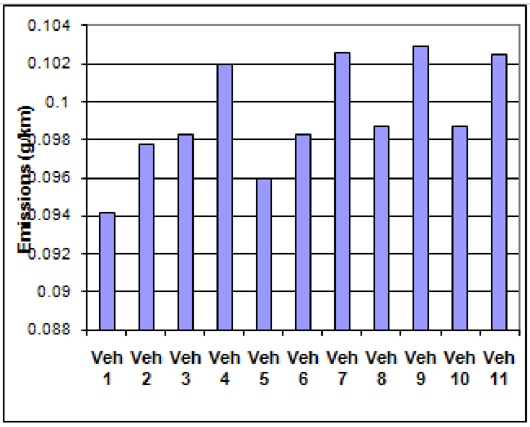
		Euro V		
Load	Veh	a	b	r^2
Typical load	1	6105.2	-0.476	0.896
	2	5814.9	-0.429	0.865
	3	6361.1	-0.44	0.869
	4	6130	-0.409	0.849
	5	5236.9	-0.44	0.882
	6	5979	-0.428	0.864
	7	5746.9	-0.394	0.839
	8	6020.1	-0.428	0.863
	9	5788.7	-0.394	0.840
	10	6026.3	-0.428	0.863
	11	5793.4	-0.394	0.840
Maximum Load	1	7528.5	-0.449	0.865
	2	7057.6	-0.425	0.854
	3	7745.9	-0.435	0.858
	4	7225.5	-0.409	0.845
	5	7480.6	-0.422	0.852
	6	7528.2	-0.425	0.853
	7	7001.3	-0.398	0.838
	8	7528.6	-0.425	0.853
	9	7001.5	-0.398	0.838
	10	7528.6	-0.425	0.853
	11	7001.5	-0.398	0.838

Table 33: FC functions

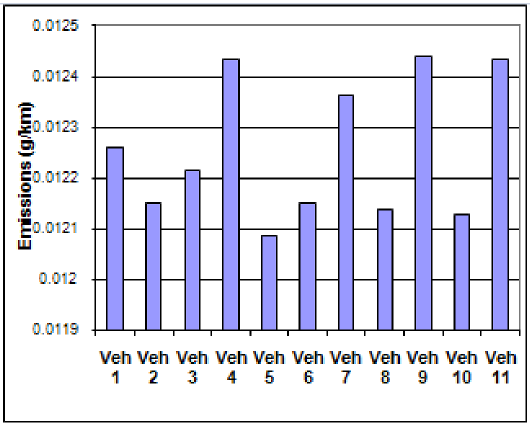
Load	Veh	Euro V a	Euro V b	Euro V r^2
Typical load	1	1926.4	-0.476	0.896
	2	1834.8	-0.429	0.865
	3	2007	-0.44	0.869
	4	1934.1	-0.409	0.849
	5	1652.5	-0.44	0.882
	6	1886.5	-0.428	0.864
	7	1813.2	-0.394	0.840
	8	1899.5	-0.428	0.863
	9	1826.4	-0.394	0.840
	10	1901.4	-0.428	0.863
	11	1827.9	-0.394	0.840
Maximum Load	1	2375.2	-0.449	0.865
	2	2226.7	-0.425	0.854
	3	2443.8	-0.435	0.858
	4	2279.6	-0.409	0.845
	5	2360.1	-0.422	0.852
	6	2375.1	-0.425	0.853
	7	2208.8	-0.398	0.838
	8	2375.2	-0.425	0.853
	9	2208.9	-0.398	0.838
	10	2375.2	-0.425	0.853
	11	2208.9	-0.398	0.838

Appendix D Emission rates for the various categories at a speed of 86.9 km/h

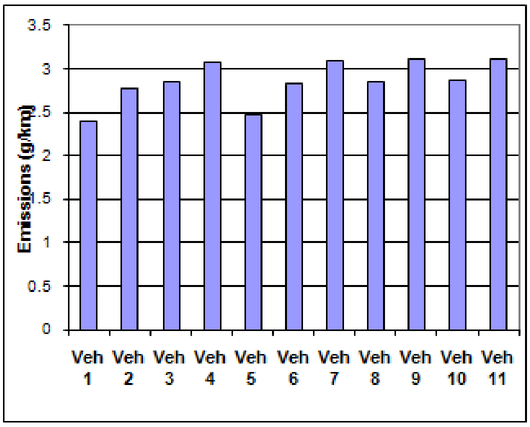
Emissions rates for the various vehicle types
Typical laden weight
Euro 5



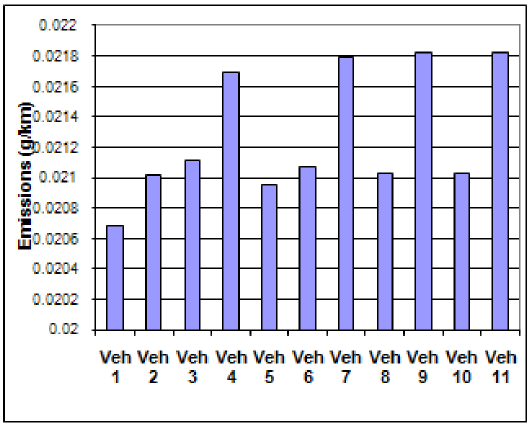
Carbon monoxide (CO)



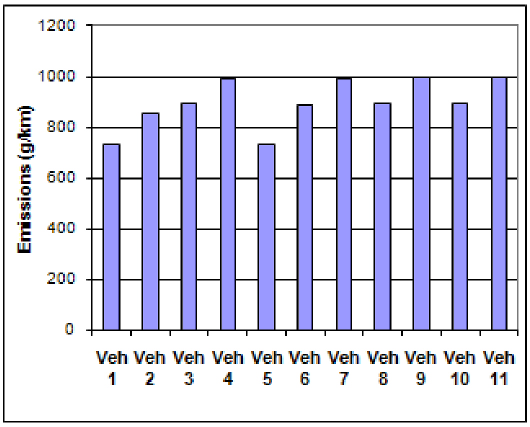
Hydrocarbons (HC)



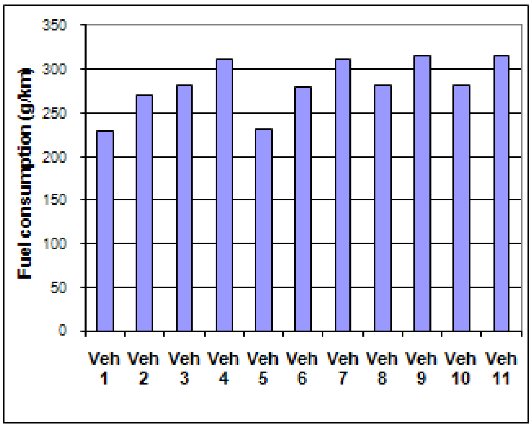
Oxides of nitrogen (NO_x)



Particulate matter (PM)

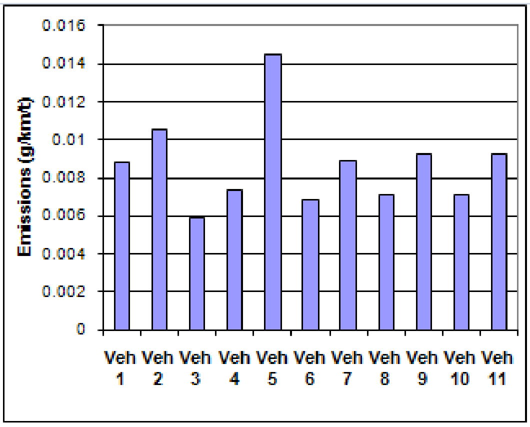


Carbon dioxide (CO_2)

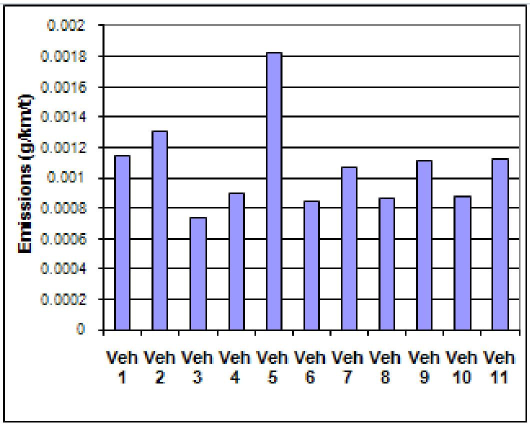


Fuel consumption (FC)

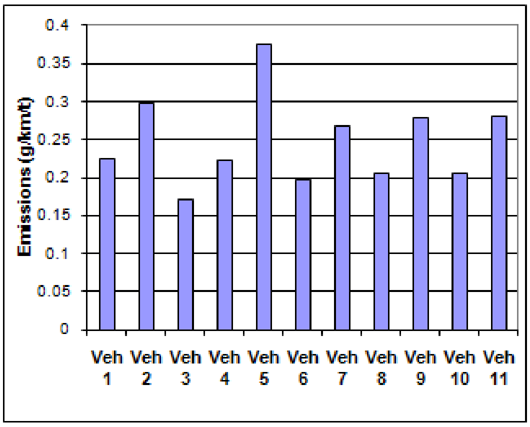
Emissions rates per tonne of payload for the various vehicle types
Typical laden weight
Euro 5



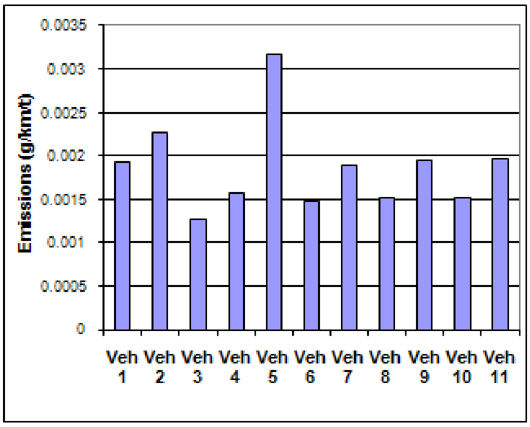
Carbon monoxide (CO)



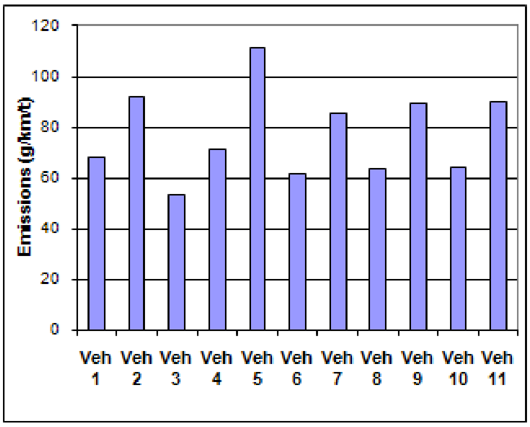
Hydrocarbons (HC)



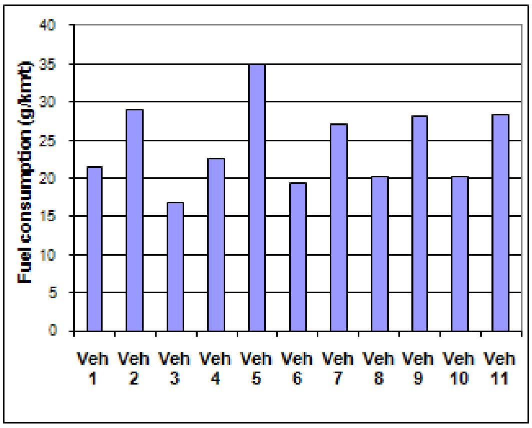
Oxides of nitrogen (NO_x)



Particulate matter (PM)

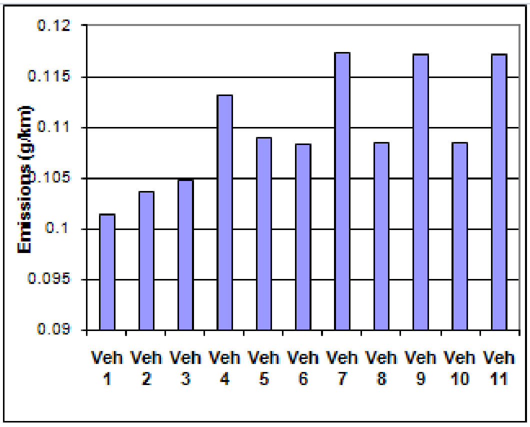


Carbon dioxide (CO_2)



Fuel consumption (FC)

Emissions rates for the various vehicle types
Maximum laden weight
Euro 5



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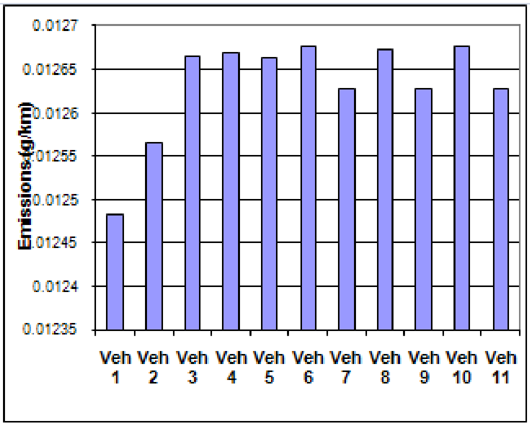

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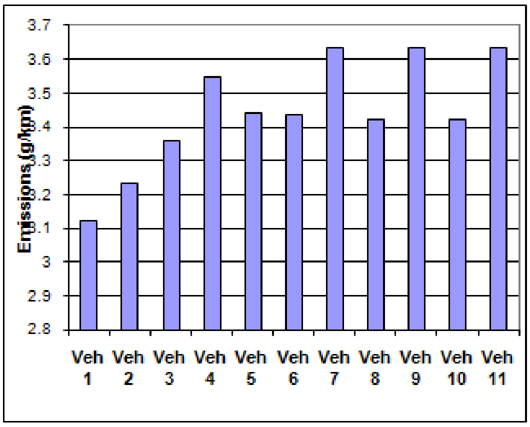
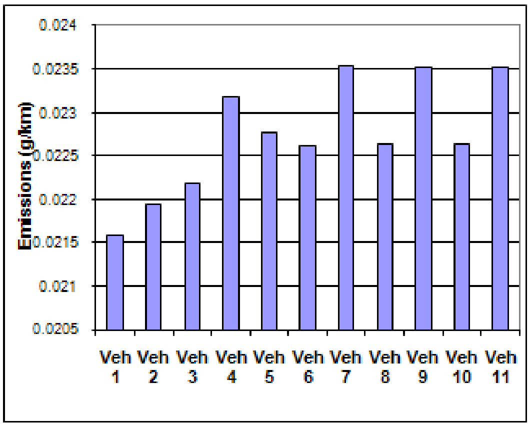
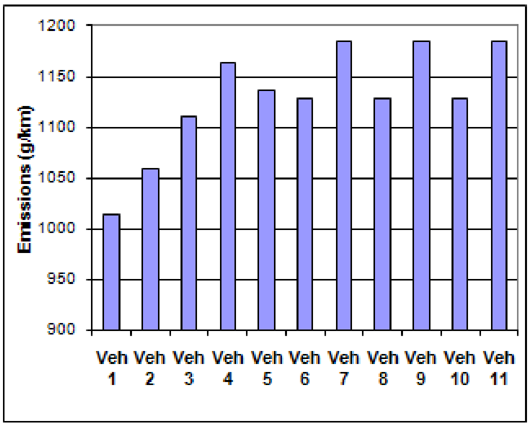


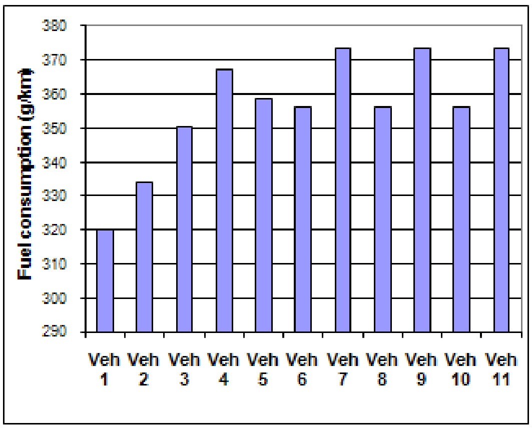
Oxides of nitrogen (NO_x)



Particulate matter (PM)

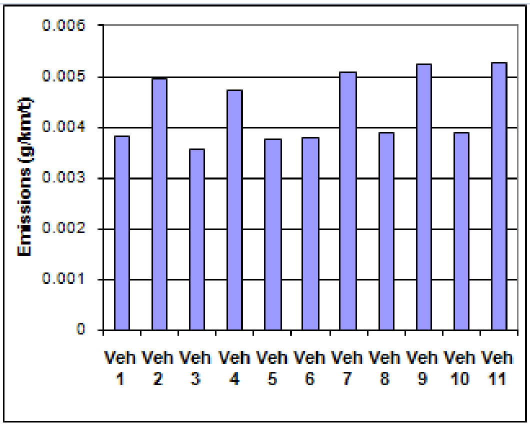


Carbon dioxide (CO_2)

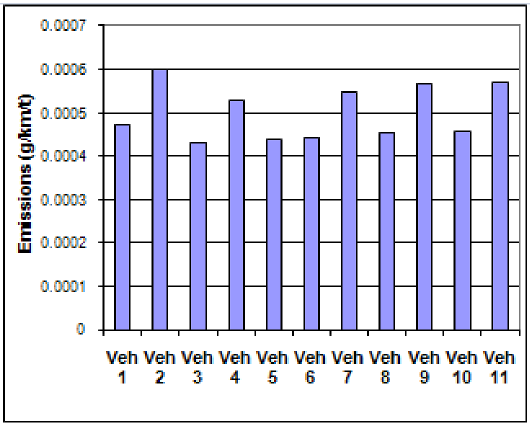


Fuel consumption (FC)

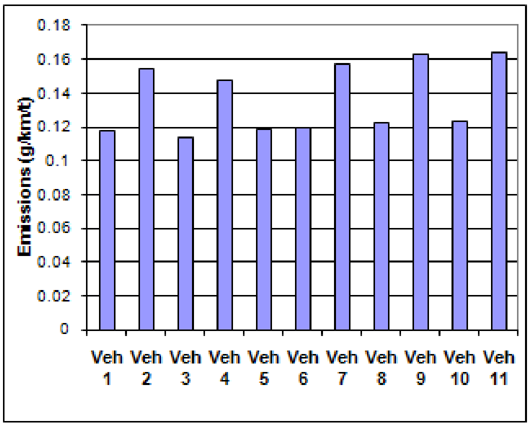
Emissions rates per tonne of payload for the various vehicle types
Maximum laden weight
Euro 5



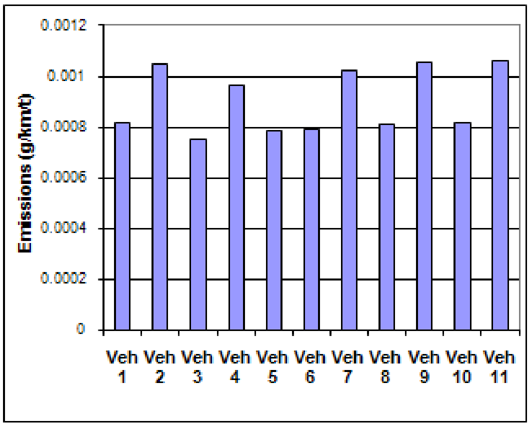
Carbon monoxide (CO)



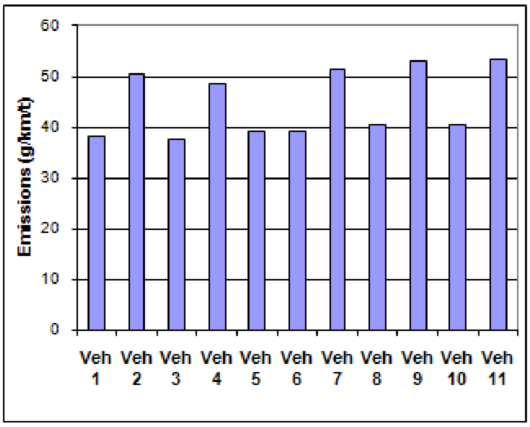
Hydrocarbons (HC)



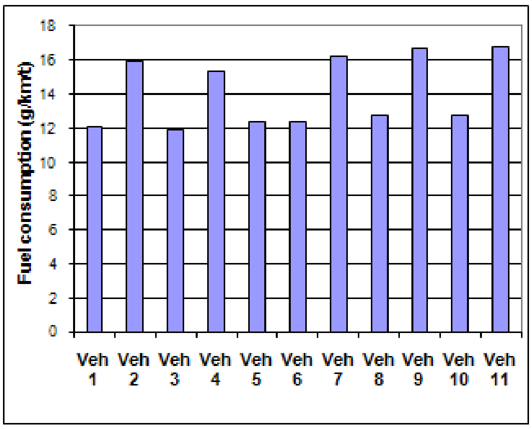
Oxides of nitrogen (NO_x)



Particulate matter (PM)



Carbon dioxide (CO_2)



Fuel consumption (FC)

Appendix E Analysis of accidents involving drawbar combinations

E.1 Previous analyses

Knight *et al* (2008) used accident data from the Stats 19 national accident database, linked to the DVLA database in order to derive accident data for different types of HGV. There are several different ways in which vehicles can be classified within these data sets. Within the Stats 19 database there is a field called towing and articulation. The codes permitted in this field are:

0. No tow or articulation
1. Articulated vehicle
2. Double or multiple trailer
3. Caravan
4. Single trailer
5. Other tow

Stats 20 (DfT, 2005) is the document forming the coding instructions for Stats 19. These instructions state that code number 1 is for a tractor semi-trailer combination and should thus be the same definition as considered in this report. It is stated that a rigid vehicle towing a drawbar trailer should be coded as 4.

The DVLA database contains a field titled “wheel-plan”, which allows the following entries:

- 2-axle rigid
- 3-axle rigid
- 4+ -axle rigid
- 2-axle + artic
- 3-axle + artic
- 4+ -axle + artic
- 2+2 artic
- 2+3 artic
- 3+2 artic
- 3+3 artic

No document equivalent to Stats 20 could be traced that identified the meaning of these codes, in particular the difference between for example the 2-axle plus artic and the 2+2 artic. Cross referencing with the towing and articulation field in Stats 19 did not provide an obvious correlation that explained the data, with many vehicle records where the articulation recorded by Stats 19 and by the DVLA database did not match. Most of these conflicts were treated as unknowns and thus excluded from the analysis. However, it was considered likely that a vehicle recorded by DVLA as being a rigid vehicle would genuinely be a rigid vehicle because the data comes from manufacturers. However, Stats 19 forms are often completed by the police officer first attending the scene, only a day or two after the accident. Such officers do not necessarily have any specialist, accident vehicle or traffic training. It was, thus considered likely that they could misinterpret the relatively subtle distinction between a tractor semi-trailer articulated vehicle (code 1) and a drawbar combination (code 4). Thus, it was considered that drawbars were most likely to be identified where the DVLA wheelplan code was one of the “rigid” ones and the Stats 19 code was anything except 0 for “no tow or articulation” – i.e. the rigid vehicle was towing something. This led to an estimated casualty rate around 4 times greater than for articulated vehicles.

E.2 Using HVCIS to evaluate coding accuracy

TRL designed, populate and analyse the HVCIS fatal accident database, under contract to the DfT. This database involves experienced TRL technical staff coding information from police fatal accident files onto a purpose designed database. These staff are well briefed on vehicle design and understand the difference between articulated and drawbar combinations so this database is expected to be more reliable than either the Stats 19 or DVLA databases when it comes to the detailed vehicle codes. The HVCIS database contains the stats 19 reference number for almost all accidents and can thus be linked to the combined Stats 19 and DVLA databases. However, because the HVCIS database is only a sample of fatal accidents the number of linked records is relatively low.

Linking the data sets for accidents involving HGVs identified 373 HGVs involved in fatal accidents that were recorded in all three data sets. It was found that the definition of vehicle type agreed in all three data sets in just 74% of cases. Of these 373 HGVs only 9 were recorded by the HVCIS fatal database as being drawbar combinations. In all of these cases, the DVLA database recorded the vehicles as rigid vehicles. However, the tow and articulation field in Stats 19 was very variable. In two cases, the vehicle was correctly coded (4), a further two were coded as no tow or articulation (0), one was coded as towing a double or multiple trailer (2) and the remaining four were coded as articulated vehicles (1). This analysis supports the earlier hypotheses that the DVLA data would be more accurate than the Stats 19 data.

Considering the criteria used in the previous analyses (DVLA rigid vehicles and Stats 19 any code except 0) identifies 20 HGVs, of which 7 are also recorded as drawbars by HVCIS, whereas a further 7 are solo rigid vehicles, 5 are articulated vehicles and one is of unknown type in HVCIS.

Selecting only those HGVs recorded in Stats 19 as towing a single trailer (4), which according to Stats 20 is how drawbar combinations should be recorded, identified 8 vehicles. Two of these were recorded as drawbars by HVCIS, five were recorded as articulated vehicles and one as a rigid. This suggests that if HVCIS data is treated as accurate reference data then using Stats 19 as intended only accurately identifies drawbars in approximately 25% of the cases identified by the right code.

Given that HVCIS identifies 9 genuine drawbars, the method combining DVLA and Stats 19 coding appears to overestimate by a factor of more than two. Relying on Stats 19 alone identifies 8 vehicles which is nearly the right number but this is coincidental because many of the vehicles identified are not in fact drawbars. There is some chance that this method might get close to the right answer but it would be by random luck and cannot be considered reliable.

The only conclusion possible, is therefore, that there is no reliable means to identify the number of accidents or accident rates where drawbar HGVs are involved.

The logical corollary of this conclusion is that the accuracy with which articulated vehicles are identified in Stats 19 could also be questioned. Undertaking similar analysis shows that the combined data set contained 183 HGVs recorded in HVCIS as articulated. Of these, 161 (88%) were also recorded as articulated in the DVLA data. Stats 19 correctly identified them as articulated vehicles in 134 cases (73%).

Relying only on Stats 19 data, as much of the analysis in section 5 of this report did, records 161 articulated vehicles, of which 149 were also recorded as articulated vehicles by HVCIS. The conclusion here is that although there are still substantial amounts of misclassification of articulated vehicles, it is considerably less than for drawbars. This will have an effect on the absolute values of the accident and casualty numbers and rates presented in the report but the effect on the relative change will be much less affected.