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Safer aerodynamic frontal structures for trucks: final report

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Transport Research Laboratory



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Safer aerodynamic frontal structures for trucks: final report

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Executive summary

Background

Approximately 1% of all road vehicles registered in GB are Heavy Goods Vehicles (HGVs) but they account for approximately 6% of all motor vehicle traffic and are involved in accidents that result in approximately 15% of all road traffic fatalities. The Stern review (2006) showed that in 2000 freight trucks were responsible for approximately 23% of global transport CO_2 emissions, which in turn represented 14% of ALL global CO_2 emissions. Thus, freight trucks were responsible for approximately 3% of ALL global CO_2 emissions.

Most trucks are currently designed to maximise the load space that can be achieved within the legally permitted maximum dimensions. This usually means that the front of the truck approximates a flat vertical surface where the cab is positioned above the engine. This design has a number of disadvantages:

- The tall, flat, vertical structure has an inherently high drag co-efficient;
- The relative position of the driver's eyes and the lower edge of the windscreen leaves a significant blind spot in front of the vehicle, which is a contributory factor in fatal collisions with pedestrians where the vehicle is pulling away from rest;
- In collisions with pedestrians, the flat vertical surface distributes the loads quite evenly, which is good, but tends to push the pedestrian over which increases the chance of injuries caused by contact with the ground and of being run over by the wheels. The interaction with pedal cyclists is likely to be similar;
- There is little space available between the driver and the front of the vehicle with which to provide a "crumple zone" to protect the driver in the event of a collision with another heavy vehicle or rigid fixed object;
- There is little space available between the front of the vehicle and the front axle with which to provide energy absorbing structure in order to better protect light vehicle occupants (mainly car occupants but possibly also van occupants) in head-on collisions with the front of the truck.

It is possible to re-design the frontal shape of trucks in a way that all of the above disadvantages could be reduced or eliminated, thus reducing the fuel consumption and the numbers of pedestrian, truck occupant, car occupant and other casualties. Robinson & Chislett (2010) suggested that when estimated costs and implementation dates were considered, this "nosecone" concept (to introduce a curved profile at the front of a truck) was one of the top heavy vehicle safety priorities. Feist & Gugler (2009) suggested that aerodynamic improvements resulting from changes to the frontal shape of trucks could result in a reduction of fuel consumption of up to 5% to 10%.

The DfT decided that, in parallel with its research into the feasibility and likely effects of permitting longer semi-trailers, research should also be undertaken into the merits of allowing additional length, irrespective of load space, for the purposes of the safety and environmental objectives described above. TRL were commissioned to undertake this work in conjunction with MIRA.

Objectives

The objective of the research was to draw together the various strands of safety and environmental research in this area to produce an initial assessment of the likely feasibility, regulatory implications, costs and benefits of introducing an integrated frontal design for trucks. The scope included potential benefits for the safety of light vehicle occupants, heavy vehicle occupants, and vulnerable road users, potential improvements in aerodynamics and potential disbenefits in terms of manoeuvrability and unladen mass.

A range of different frontal geometries and lengths (up to 2.25m, which would take articulated vehicles up to the existing maximum permitted length for drawbar

combinations of 18.75m) have been analysed and modelled in various ways, to estimate:

- The energy absorption and casualty reduction potential in frontal collisions with light vehicles;
- The energy absorption and casualty reduction potential in frontal HGV impacts with other large, heavy vehicles and objects;
- The energy absorption, impact kinematics, forward field of view and casualty reduction effects in frontal HGV impacts with pedestrians and pedal cyclists;
- The effects on approach angles, ramp angles and ability to comply with the turning requirements of 97/27/EC;
- The effects on aerodynamic drag, fuel consumption and emissions;
- The overall costs and benefits of the defined options.

All analyses were based on a modified vehicle towing a standard 13.6m semi-trailer.

Conclusions

In general, the analyses show the biggest casualty savings are for pedestrians. For example, before changes in exposure to risk (e.g. increased HGV traffic as a result of reduced payload mass) are considered, it was found that a 1m pedestrian-friendly nosecone applied to all tractor units would be likely to save 10 pedestrian fatalities per year in GB and 2 pedal cyclists. Designing a 1m nosecone just for truck to car/car derived van impacts would probably save 2 car/car derived van occupants per year, and designing purely for HGV to HGV impacts would be likely to save around 1 HGV occupant death every other year (assuming all HGV drivers wear seat belts).

The aerodynamic effects were found to be in the region of 3% to 6%, which is somewhat less than quoted in the literature. It was also found that for longer nosecones there was a trade-off between aerodynamic improvements to the tractor unit and the characteristics of the semi-trailer. The indication is that if a standard tractor unit is simply modified to include a nosecone (designed to give very good aerodynamic performance for the tractor), but it is then coupled to a standard semi-trailer, the overall vehicle drag (and, therefore, fuel consumption and emissions) may actually increase slightly. The effect seems to get worse as nosecone length increases. Conversely, if an articulated vehicle combination is designed as a single package, with optimised and matched aerodynamic features on both the tractor and semi-trailer, then longer nosecone lengths can produce reductions in whole vehicle aerodynamic drag, and not just in the drag of the tractor unit.

Modelling the combined effect, over realistic duty cycles, of these changes to aerodynamic drag and unladen mass showed only small effects on fuel consumption and emissions. For example a 1% reduction in fuel consumption was evident with a 500mm nosecone on a vehicle laden to its maximum authorised mass.

Considering specific length increases, it was found that:

- 1. A 0.2m length increase could allow two different approaches:
 - a. An "add-on" approach where the front-end would be designed to protect pedestrians and other vulnerable road users (VRUs) in frontal impacts with articulated HGVs in a manner similar to the steel and foam "safety-bar" concept developed by the APROSYS FP6 project. This would be expected to save around 4 lives per year in Great Britain, have no significant effects on manoeuvrability or aerodynamics and minimal effects on traffic generation through reduced payload mass capacity. The limited benefit of this approach for vehicle operators (i.e. no aerodynamic effect) meant that it was not considered in the full cost benefit analysis.

- b. An "integrated" approach where a mildly shaped front end would be expected to save around 5 lives per year but could also produce small aerodynamic benefits at the cost of a small increase in unladen mass and a consequent small increase in HGV traffic for the same loads transported. This would be expected to produce net benefits, excluding congestion costs, of around £18.7million per year.
- 2. An increase of about 0.5m would allow a shaped front end that could offer substantially improved field of view, deflect VRUs away from the front of the truck in an impact and have an outer skin of foam to absorb energy in collisions with VRUs. In addition to this it could have short sections of crumple zone intended to protect car occupants and truck occupants. This would be expected to reduce fatalities by about 9 per year at the same time as reducing fuel consumption and emissions per vehicle km. If appropriately shaped this would be unlikely to cause significant manoeuvrability difficulties. However, unladen mass and, thus, HGV traffic would be increased further. The net benefit, excluding congestion costs, would be expected to be around £30.5million/year.
- 3. An increase of approximately 1m would allow a front end that was optimised for safety in terms of field of view, VRU kinematics and energy absorption, and car occupant protection. It would also allow an improved capacity for HGV occupant protection. Some manoeuvrability difficulties would be likely but could be overcome with relatively straightforward modifications such as making the rearmost trailer axle self-steered. This would be expected to reduce fatalities by about 14 per year. However, other effects would depend on how the aerodynamics were controlled:
 - a. If the optimised tractor towed a standard trailer there would be an increase in unladen mass and, thus, in HGV traffic. There would be very little effect on aerodynamic drag. The increased mass would combine with the increased traffic to produce a significant increase in emissions (e.g. c.97k tonnes of CO_2), resulting in net costs of about £65million/year
 - b. If the tractor and trailer aerodynamics were optimised as a combination then the aerodynamic drag would be improved as would the fuel consumption and emissions. However, this would be expected to require additional aerodynamic aids, and hence unladen mass, on the trailer, further reducing payload and generating additional HGV traffic. The beneficial effect on aerodynamics would not be expected to outweigh the disbeneficial effect of the mass resulting in a net annual cost of about \pounds 43.5million/year.
- 4. If a 2.25m length increase were applied solely to the front of the cab, the additional safety benefits over the 1m nose length would be limited to 1 or 2 more HGV occupant fatality savings per year. Manoeuvrability problems would be significant making compliance with Directives 97/27/EC (turning requirements) and 2000/40/EC (front underrun protection) difficult. Aerodynamically, the effects of such a nosecone are difficult to predict and likely to be highly dependent on the aerodynamic characteristics of the whole vehicle combination. Coupling such a tractor unit to a conventional semi-trailer (rather than one designed to be aerodynamically highly efficient) could actually lead to increased fuel consumption and emissions. The mass implications of such a front end are likely to be significant. For all these reasons the cost benefit of such a change was not analysed in detail.
- 5. The analyses were based on a limited set of policy options and assumptions of how the industry would react. A range of subtle variations would be possible and could influence the results. In particular, investigating the following possibilities could identify further optimisation of the concept:
 - a. Extending application of the policy to rigid goods vehicles

- b. Restricting application of the policy to vehicles carrying loads not constrained by mass, possibly approximated by excluding tipping and tank bodied vehicles.
- c. Removing consideration of requirements for car and truck occupants, potentially allowing lower mass solutions which may (or may not) improve net benefits when both safety and environment are considered.
- d. Investigating the potential for advanced engineering and materials to offer solutions with a mass lower than that assumed in this analysis.
- 6. The results described above would be equally valid if semi-trailers of up to 15.65m in length were to be permitted, except for manoeuvrability where further analysis may be required if the overall combination length exceeded 18.75m. They are also based on applying the principles of safer aerodynamic fronts to articulated vehicles only. Further casualty reductions, particularly for vulnerable road users, could be achieved if the measures were also applied to rigid vehicles. This has been quantified in the main body of the report.

1 Introduction

Approximately 1% of all road vehicles registered in GB are Heavy Goods Vehicles (HGVs) but they account for approximately 6% of all motor vehicle traffic and are involved in accidents that result in approximately 15% of all road traffic fatalities. The Stern review (2006) showed that in 2000 freight trucks were responsible for approximately 23% of global transport CO_2 emissions, which in turn represented 14% of ALL global CO_2 emissions. Thus, freight trucks were responsible for approximately 3% of ALL global CO_2 emissions.

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- There is little space available between the front of the vehicle and the front axle with which to provide energy absorbing structure in order to better protect light vehicle occupants (mainly car occupants but possibly also van occupants) in head-on collisions with the front of the truck.

It is possible to re-design the frontal shape of trucks in a way that all of the above disadvantages could be reduced or eliminated, thus reducing the fuel consumption and the numbers of pedestrian, truck occupant, car occupant and other casualties. Robinson & Chislett (2010) suggested that when estimated costs and implementation dates were considered, this "nosecone" concept (to introduce a curved profile at the front of a truck) was one of the top heavy vehicle safety priorities. Feist & Gugler (2009) suggested that aerodynamic improvements resulting from changes to the frontal shape of trucks could result in a reduction of fuel consumption of up to 5% to 10%.

The DfT decided that, in parallel with its research into the feasibility and likely effects of permitting longer semi-trailers, research should also be undertaken into the merits of allowing additional length, irrespective of load space, for the purposes of the safety and environmental objectives described above. TRL were commissioned to undertake this work in conjunction with MIRA.

This report summarises the results from analyses of the all the different potential safety and aerodynamic benefits and manoeuvrability disbenefits from integrated changes to the frontal design as a whole. A range of different frontal geometries and lengths (up to 2.25m, which would take articulated vehicles up to the existing maximum permitted length for drawbar combinations of 18.75m) have been analysed and modelled in various ways, to estimate:

- The energy absorption and casualty reduction potential in frontal collisions with light vehicles;
- The energy absorption and casualty reduction potential in frontal HGV impacts with other large, heavy vehicles and objects;

- The energy absorption, impact kinematics, forward field of view and casualty reduction effects in frontal HGV impacts with pedestrians and pedal cyclists;
- The effects on approach angles, ramp angles and ability to comply with the turning requirements of 97/27/EC;
- The effects on aerodynamic drag, fuel consumption and emissions;
- The overall costs and benefits of the defined options.

All analyses were based on a modified vehicle towing a standard 13.6m semi-trailer.

2 Light vehicle occupants

This section describes an analysis of the additional energy absorption and casualty prevention potential from extra frontal truck cab structures being placed at a height suitable for interaction with the crumple zones of passenger cars and small vans (typically 400mm to 500mm from the ground).

The results of the VC-COMPAT project on front underrun protection systems (FUPs) and other recent research are reviewed to identify the appropriate force-deflection characteristics (to absorb any residual energy over and above that which can be safely absorbed by the car's crumple zone). Based on these results, energy calculations are used to plot the estimated critical impact speeds for a range of cars against the length of the energy-absorbing front overhang of the truck needed to provide that level of protection for the car occupants. Distributions of collision speeds in actual fatal head on accidents (derived from the Heavy Vehicle Crash Injury Study database) are then used to estimate the casualty reduction effects of this additional energy absorbing material.

2.1 Analytical method

When two vehicles collide head on, as in a typical frontal car to truck accident, a proportion of the initial (kinetic) energy of the vehicles is converted into work done to deform the vehicles' structures. When the truck is fitted with a rigid FUP system, only the car structure can deform and so all the impact energy is absorbed by deformation of the car's front crumple zone. As the impact speed increases, the kinetic energy also increases (proportional to the square of the velocity) and there is inevitably a speed at which the crumple zone has absorbed all the energy it possibly can and any more must come from deforming the car's occupant compartment. Severe and/or fatal injuries can occur as a result of the occupant contacting intruding parts of the car's occupant compartment during the impact. They can also occur as a result of the higher forces involved in deforming this much stronger part of the car's structure (and thus compartment accelerations which can lead to bottoming out of the restraint system and high loads on the occupants).

The extent of injuries, particularly whether or not they prove fatal, depends on many variables and not just the efficacy of the car's crumple zone and occupant protection systems, e.g. the age and general health of the occupants and the time taken for them to receive expert medical attention. To assess the "survivability" of a specific impact configuration, standardised test dummies (such as the Hybrid III) are used; the injury criteria on various critical body regions are measured and compared with threshold levels defined in crash safety legislation and test procedures. These thresholds are set at points where, generally speaking, an otherwise fit and healthy adult receiving expert medical attention within a normal timeframe would be likely to survive if they sustained injuries just below those levels. For any given car design, impacting any given mass of truck, it is therefore possible to define a "critical impact speed" as that at which the car's crumple zone absorbs all the impact energy it can and above which occupant injuries, as recorded by test dummies, would be likely to exceed the critical threshold levels defined.

The VC-COMPAT project and other research have been used to estimate the critical energy absorption capabilities of a range of typical passenger cars. For given masses of cars and trucks, these energy levels are used to work out the critical closing speeds for occupants of those cars when impacting those trucks fitted with a rigid FUP. To allow higher closing speeds to result in no increase in the energy absorbed by the car, the extra impact energy must be entirely absorbed through deformation of the truck structure, i.e. an energy-absorbing FUP (ea-FUP). For a given crush force (determined by the force generated by the car's deforming crumple zone), the amount of energy absorbed by the ea-FUP is proportional to the distance the ea-FUP deforms, so as the depth of the ea-FUP increases, so does the energy it can absorb. The more energy the ea-FUP can absorb, the higher the critical (equivalent energy) closing speed becomes.

2.1.1 Basic impact and energy equations

For a vehicle of mass m_1 , travelling at velocity v_1 and colliding head-on with a second vehicle of mass m_2 and travelling in the opposite direction at velocity v_2 , the initial total kinetic energy is given by $\frac{1}{2}(m_1v_1^2 + m_2v_2^2)$.

If we assume that after the collision, both vehicles move together at a velocity v_3 , by the conservation of momentum principle, $m_1v_1 - m_2v_2 = (m_1+m_2)v_3$.

So $v_3 = (m_1v_1 - m_2v_2) / (m_1 + m_2)$

After the impact, the two vehicles have the residual kinetic energy given by $\frac{1}{2}(m_1+m_2)v_3^2$, and the overall amount of energy lost in the impact, E (i.e. used to deform the structures), is thus $\frac{1}{2}(m_1v_1^2 + m_2v_2^2) - \frac{1}{2}(m_1+m_2)v_3^2$.

Substituting for v_3 ,

$$E = \frac{1}{2}(m_1v_1^2 + m_2v_2^2) - \frac{1}{2}(m_1v_1 - m_2v_2)^2/(m_1+m_2)$$

= $\frac{1}{2}m_1m_2(v_1 + v_2)^2 / (m_1+m_2)$

The energy is thus proportional to the pre-impact closing speed of the vehicles and to simplify for the case when $v_1=0$ (the truck is assumed stationary), the energy to be absorbed is $\frac{1}{2}m_1m_2v^2$ / (m_1+m_2), where m_1 if the mass of the truck, m_2 is the mass of the car and v is the impact velocity of the car.

2.1.2 Modelling a car's energy absorption

When a structure deforms, the work done (i.e the energy absorbed) is given by the area under the force-deflection curve. Vehicle impact tests typically show quite complex force-deflection curves, as different parts of the structures (e.g. engine blocks, suspension units and chassis components) collapse and interact with each other. Typical curves are shown at Figure 2-1.





For a basic, first-order calculation, we can approximate this curve to a linear forcedisplacement relationship, where the force increases up to a peak, F, corresponding to a maximum deflection, d, and where the energy absorbed is ½Fd. Using, for example, Huibers and de Beers Phase 4 results (for large passenger cars), this approach would approximate the Figure 2-1 curve to a peak force, F, of 400kN and a maximum deflection, d, of 1.3m, giving an expected total energy absorption of 260kJ. These results relate to cars of typical mass 1650kg impacting at 64 km/h (17.8 ms⁻¹), thus having a kinetic energy transfer of roughly 261kJ, so there is very good agreement between the actual results and the simplified model. In each of the tests, the deformable barrier itself was reported to have deflected by about 400 mm before bottoming out, having absorbed about 40 kJ. The balance between this figure and the initial kinetic energy of the car is absorbed by the car structure, and the deflection of the car is 400 mm less than the maximum deflections shown in Figure 2-1.

2.1.3 Modelling a truck's energy absorption

To absorb the required energy, the ea-FUP must collapse at a force level commensurate with that the collapsing car can provide. In general, the larger the car, the greater is the force that it can provide to collapse the ea-FUP (Figure 2-1 shows this, with Phases 4 and 6 relating to impact tests with large passenger cars and MPVs having much higher peak forces than the smaller cars tested in phases 3 and 7). This means that for a given crush depth, an ea-FUP designed to collapse at the forces provided by a large car would absorb more energy than one designed for a lower (small car) force level. However, if a small car were to impact such a strong ea-FUP, it would not be able to generate the force needed to fully collapse it and it would, therefore, not absorb as much energy and not provide as much protection for the occupants of that car as a less stiff FUP.

For this reason, an ea-FUP has to be designed carefully to collapse at a low enough force level to protect small car occupants. An impacting larger car would still be able to fully collapse such a guard, and therefore get it to absorb all the energy it can, but it is not possible (with simple conventional technology) to design an ea-FUP that can fully collapse at different force levels depending on the force available from the impacting car.

In the modelling work for this project, it has been assumed that an energy absorbing FUP is designed to collapse linearly with deflection at a constant force level commensurate with that consistently available from a small car impacting at what would be the critical impact speed for such a car into a rigid FUP. The energy that the ea-FUP can absorb is thus modelled as being equal to F_sD , where F_s is the steady force generated by small cars impacting at their critical speed and D is the crush depth of the ea-FUP. The VC-COMPAT project reports that the small cars impacted into trucks fitted with rigid FUPs at speeds of 64-75 km/h generated steady forces of 200 - 300 kN. The Huiber and de Veers data (Figure 2-1) confirms that even small cars (Phase 7) can generate peak forces of 300 kN in deformable barrier impacts at 64 km/h. For the purposes of the modelling for this project it has been assumed that an ea-FUP designed to collapse at 250 kN is an appropriate choice, as this would be highly likely to collapse fully (and therefore absorb all the energy it can) for all the impact scenarios considered. As car crashworthiness and compatibility continues to improve, it is likely that somewhat higher force levels will be generated, even by small cars, so this approach is considered to be a conservative estimate of the energy absorption potential of future ea-FUPs.

2.2 Input parameter selection

To model a range of different impact scenarios and assess a range of different nosecone configurations, the following main parameters are needed:

- Mass of truck, m₁
- Mass of car, m₂

- Impact velocity, v
- Peak force of car crumple zone in just-survivable impact, F
- Peak force of small car crumple zone in just-survivable impact, F_s
- Maximum survivable crumple zone crush distance of car, d
- Crushable depth of ea-FUP, D

Using the equations and models described in the preceding section, by defining appropriate values of m_1 , m_2 , F and d, the critical (equivalent energy) velocity, v, (velocity at which the car absorbs the same energy as the same car colliding with a rigid FUP at its critical speed, and the ea-FUP absorbs the rest) for each impact configuration and for any given depth of ea-FUP, D, can be calculated.

2.2.1 Car parameters $(m_{2r} F and d)$

Both the car frontal stiffness research described by Huibers and de Beer and the VC-COMPAT research project crash tested a range of common passenger cars. The masses of those cars tested ranged from 1100-1200kg for small cars like the Citroen C2, VW Polo and Renault Clio, to 1650-1900kg for large saloon cars and MPVs (e.g. Audi A6, BMW 520 and Vauxhall Sintra). For the purposes of this project, we have modelled three sizes of car (m_2); small (1200kg), medium (1400kg) and large (1700kg).

The Huiber and de Beers research impacted a wide range of cars, but all at 64 km/h into a loadcell barrier with a deformable element. The purpose of their research was simply to obtain the force-deflection (stiffness) characteristics of the cars at this impact speed so they do not quote any injury data from the crash dummies. Their research was, though, based entirely on tests undertaken by the European New Car Assessment Programme (NCAP), and so the injury levels can be found from the NCAP web site. In summary, almost all the cars tested provided a reasonable degree of protection for their occupants. The majority of the cars tested, of whatever size, achieved at least 3 stars and more often 4 stars (out of a maximum of 5 stars). It can therefore be concluded that car impacts into trucks with rigid FUPS at 64 km/h would be likely to be below the critical impact speeds regardless of the size of car.

The VC-COMPAT project (Edwards et al, 2007) involved crash testing a narrow range of cars, but at a range of different impact speeds, into 12t trucks fitted with differing FUP systems. For the purposes of this project, the tests at 75 km/h into a rigid FUPS system are particularly useful. When a Citroen C2 was impacted into a 12t truck fitted with a rigid FUP at 64 km/h, the occupant injury levels were severe – just above the critical threshold levels. When the same car was impacted at 75 km/h, the injury levels were much more severe, and much higher than the threshold values. It can therefore be deduced that the critical speed for a small car like the C2 (a 4 star EuroNCAP performer) is somewhere just below 64 km/h.

The Huiber and de Beers (TNO) research shows that for a small car, weighing about 1150kg, impacting at 64 km/h, the peak force generated is about 360kN (F) and the maximum deflection (d) is about 1100mm. This suggests a total energy absorption of about 200 kJ, and 40 kJ being absorbed by the deformable barrier leaves 160 kJ to have been absorbed by the car. As 64 km/h is known to be near the critical limit for such a car, this is the critical energy absorption value chosen for the model of a typical small car. This also corresponds very well to the 157 kJ reported to have been absorbed by the Citroen C2 in the 64 km/h VC-COMPAT test.

VC-COMPAT also crash tested a medium size car (Vauxhall Astra) at both 64 km/h and 75 km/h into a rigid FUP system. For this size of car (about 1400kg), the recorded injury levels were below the threshold values, even at the higher impact speed. A 75 km/h closing speed into a 12t rigid FUPs implies an energy absorption capacity from the car's crumple zone of about 270 kJ. No testing was performed at speeds over 75 km/h, so no data are available to confirm a closing speed at which the injury levels as measured by

the test dummy would exceed threshold values. For the purposes of the modelling, it is assumed that the car's structure could absorb 10% more energy than was the case at 75 km/h (300 kJ) and still maintain injury levels at or just below threshold values. This would put the critical speed in an impact with a 12t rigid-FUPs truck at about 79 km/h.

The VC-COMPAT project did not involve impact testing of any large passenger cars (>1600kg), and no data for such cars impacting at 75 km/h has been identified for this project. It is known from EuroNCAP results, however, that such cars generally provide similar levels of protection for their occupants at 64 km/h as is the case with medium sized cars (both commonly achieve 4 stars). We can therefore postulate that if the critical speed for a medium sized car is about 79 km/h, it is likely to be about the same (or maybe slightly higher still) for a larger car. A critical impact speed into a rigid FUPs of 79 km/h for a large (1700kg) car implies a maximum energy absorption capacity of the car's crumple zone of about 360kJ.

		-		
Car size Mass		Maximum	Critical impact	
	(m ₂)	absorption	FUPs)	
Small	1150 kg	160 kJ	63 km/h	
Medium	1400 kg	300 kJ	79 km/h	
Large	1700 kg	360 kJ	79 km/h	

Table 2-1. Modelled car parameters

Table 2-1 summarises the car parameters used in the impact energy model.

2.2.2 Truck parameters $(m_1, F_s \text{ and } D)$

As the impact energy equations described above show, when the mass ratio between two colliding vehicles is high (i.e. the truck is much heavier than the car), and the truck is stationary or only moving slowly at impact, virtually all the initial, pre-impact kinetic energy (mostly of the car) has to be absorbed by collapse of the vehicle structures. At lower mass ratios, the impacting car has sufficient momentum to cause the (stationary) truck to move backwards slightly in the impact, thus allowing it to retain some of the kinetic energy and meaning slightly less energy has to be absorbed by the collapsing car structure. To model an appropriate range of HGV masses, three truck sizes have been chosen; small (12 tonnes), medium (25 tonnes) and large (44 tonnes). This range covers the full spectrum of vehicles in category N3 permitted on UK roads.

For the reasons explained earlier, the ea-FUP system modelled for these trucks is assumed to have a constant force-deflection characteristic equivalent to that able to be generated by a small car impacting at its critical speed for a rigid FUP, 250 kN. The ea-FUP is assumed to collapse and absorb energy at that constant force, regardless of the size of car impacting it.

Existing rigid FUP systems take up space under the front of the truck's cab and do not project forward from the standard truck's front edge. When modelling the replacement of these systems by energy absorbing versions, it has been assumed that there is at least 400mm of space available under the existing cab structure and that 200mm of this would be available for some energy absorption. It has been assumed that the other 200mm would be needed to hold the fully collapsed ea-FUP structure. A brief review of existing cab designs indicates that there is commonly at least 800mm between the front of a truck's cab and the front-most edge of the front tyres, so the 400mm availability assumption for an ea-FUP seems reasonable.

The consequence of this assumption is that the modelled crush depth of an ea-FUP is always 200mm more than the extra front projection (nosecone length) needed. To cover

the full range of possible length increases, ea-FUP crush depths (D) have been modelled ranging from 0 (i.e. the baseline rigid FUP) to 2450mm (corresponding to a length increase of 2250mm; the maximum conceivable if 16.5m articulated vehicles were to be allowed to go to 18.75m as is already the case for drawbar combinations). Intermediate crush depths of 100mm, 200mm, 300mm, 600mm and 1000mm have been modelled to allow the graphical assessment of any crush depth within the 2.45m range.

Table 2-2 summarises the truck parameters used in the impact energy model.

Truck size	Truck mass (m ₁)	EA-FUP Crush Force (F _s)	Maximum Crush Depth (D)	Maximum Energy Absorption (F _s D)
Small	12000 kg	250 kN	0 mm	0 kJ
			100 mm	25 kJ
			200 mm	50 kJ
			300 mm	75 KJ
			600 mm	150 kJ
			1000 mm	250 kJ
			2450 mm	612 kJ
Medium	25000 kg	250 kN	As above	As above
Large	44000 kg	250 kN	As above	As above

2.3 Modelling results

An Excel spreadsheet was developed to use the various parameters and equations and relate the ea-FUP depths, D, to the critical (equivalent energy) impact speed for each car to truck impact configuration. With 3 different car sizes and 3 different truck sizes, there are 9 basic configurations in the model. For each of these, the model has been used to plot critical impact speed against the ea-FUP crush depth needed to just absorb all the impact energy at that speed that is not absorbable by the car's crumple zone (set out in Table 2-1).

The results are shown in full in Figure 2-2. The critical speeds rise from about 68-81 km/h for the rigid FUP condition (0 mm of crush depth) up to about 117-129 km/h if the full 2450mm of crush depth is available.



Figure 2-2. Critical (equivalent energy) impact speeds at various ea-FUP crush depths

The effects of optimising the ea-FUP for the small car are evident from the fact that at the lower speeds it is the larger cars that have the highest critical speeds, but at higher impact speeds the ea-FUP provides optimum protection for the small car occupants (by crushing at a constant force of 250kN) and so the critical speed for the small car is modelled as being higher than that for the larger cars.

To summarise the results:

- Simply including 200mm of ea-FUP crush depth under the front of existing cab structures, without needing to increase any overall length allowances, is likely to increase critical impact speeds from about 60-80 km/h (depending on the size of car and truck) to about 70-85 km/h.
- If 400mm of additional truck length is used (and 600mm of ea-FUP crush depth), critical speeds would be likely to rise to 85-95 km/h. This is in good agreement with work by Scania (APROSYS, 2008) who suggested that a 600mm "semibonneted" truck could take manageable impact speeds from 56 to 80 km/h; the required energy absorption (about 145 kJ for a 1150 kg car) is very close to that modelled for a 600mm crush depth in this study (150 kJ).
- If 800mm of additional truck length is used (and 1000mm of ea-FUP crush depth), critical speeds would be likely to rise to 95-105 km/h.
- If the full 2250mm of extra length is used (and 2450mm of ea-FUP crush depth), critical speeds would be likely to rise to 125-135 km/h.

2.4 Fatality reduction potential

Figure 2-3 shows the cumulative frequencies of car occupant fatalities at different closing speeds from the Heavy Vehicle Crash Injury Study (HVCIS). The three lines relate to:

the 54 fatalities in the database (which covers accidents from the period 1997-2007) where both the car and articulated HGV impact speeds were known (or could at least be estimated with a reasonable degree of confidence);

- the 122 such fatalities for car to any form of HGV where the speeds were known;
- a modelled distribution of car to articulated HGV impact speeds based on averaged known relationships between impact speeds, travel (pre-impact) speeds and speed limits. These 160 cases include all the 54 where the closing speed was known and a further 106 cases where the impact speed could be estimated from known travel speed information or, where that was also unknown, from the known speed limit information.



Figure 2-3. Car occupant fatalities by closing speed in frontal car to truck collisions (from HVCIS)

It can be seen that very few fatalities occur at closing speeds of less than about 70 km/h, but most (around 60%) occur in the range 110-150 km/h.

At a given impact speed, an ea-FUPS can help to improve the chances of survival for the car occupants, over and above those provided by a rigid FUPs. Combining the data in Figure 2-2 and Figure 2-3 allows the assessment of the proportion of existing fatalities that might be saved by differing lengths of ea-FUP crush depth. For example, Figure 2-2 indicates that at a maximum crush depth of 2450mm, impacts at 125-135 km/h would be the same, from an energy perspective, for the car occupants as an impact at 65-75 km/h into a rigid FUPS and so are quite likely to produce injuries below the critical threshold levels. Figure 2-3 shows that about one third of existing car occupant fatalities occur at closing speeds of 125 km/h or less, so potentially a 2450mm ea-FUPs could save one third of all car fatalities in frontal car to HGV impacts. This figure, though, would be a "best case" scenario; a more realistic estimate should exclude fatalities of unbelted or very elderly car occupants, who would still be unlikely to survive even with an ea-FUPS, and fatalities below the critical speed for a rigid FUPs (assumed to be 75 km/h), because they would be likely to be saved anyway by having rigid FUPs (most of the HGVs in the HVCIS sample are not fitted with rigid FUPs); about 30% of the frontal impact fatalities in the HVCIS database were either not wearing their seat belt or were elderly (over 65 years of age), or both, so a correction factor of 0.7 is appropriate, and about 10% of the fatalities occurred at impact speeds below 75 km/h, and are excluded from the casualty savings estimates for ea-FUPs.

Figure 2-4 provides such an estimate for various different ea-FUP crush depths (converted to nosecone lengths by subtracting 200mm to allow for some energy absorption under the existing truck structure), for both all HGVs and if fitted only to articulated HGVs. The casualty savings are derived from assumed overall annual fatality rates of 152 car occupants killed in car to HGV impacts, of which 55 car occupants killed in frontal impacts with HGVs (front of car to front of HGV) per year, 24 of which involve artics, based on published data and more detailed STATS19 data for the three years 2006-2008 and the HVCIS database for 1997-2007.



Figure 2-4. Estimated annual GB car occupant fatality savings

To summarise:

- A modest 200mm increase in overall length of articulated HGVs would be likely to save 1 fatality per year in the UK if ea-FUPs were incorporated (5% of all fatalities in front of car to front of artic impacts);
- A longer increase of 800-1000mm would be likely to save 2 fatalities per year (10% of fatalities in frontal car to artic impacts);
- An even longer ea-FUPS, adding up to 2250mm to the length of articulated HGVs would be likely to save around 5 fatalities per year (22% of frontal car to artic fatalities. For this to happen, though, no other structure could be above the ea-FUPS, at least not for the first 1.5 2 metres or so of its stroke, to avoid intrusion of that structure through the car's windscreen);
- These savings would be likely to double if the ea-FUPS were fitted to all HGVs.

3 HGV Occupants

This section describes an analysis of the additional energy absorption and casualty prevention potential from extra frontal truck cab structures being placed at a height suitable for interaction with the (very stiff) rear chassis of other HGVs (typically 700mm to 1100mm from the ground), to better protect the HGV occupants when impacting the rear of another HGV.

The results of international research into HGV occupant protection and cab strength have been reviewed to estimate appropriate force-deflection/stiffness characteristics for cab structures. Based on these results, energy calculations have been used to assess the extra impact speeds at which additional stiff structures in front of the HGV occupants would be able to prevent unacceptable levels of intrusion (and hence injury) into the occupant compartment. To protect the HGV occupants in this way, it has been assumed that the HGV occupants would be wearing seat belts; without seat belts, the likelihood of serious or fatal injuries from interior contacts or ejection would not be substantially lowered through extra frontal cab structures. It is further assumed that the additional structures are designed to ensure good structural interaction with the impact partner.

3.1 Analytical method

The basic approach is very similar to that described above for Front Underrun Protection. Whereas, though, the car to truck impact was modelled with energy being absorbed by both the car (via its crumple zone) and the truck (via its ea-FUP), for the HGV to HGV impact it has been assumed that the rear of the impacted HGV is essentially rigid and so all the impact energy needs to be absorbed by the front of the impacting HGV. The existing cab structure can absorb some energy without leading to an unacceptable risk of severe/fatal injuries to a belted HGV occupant, which has been estimated based on published research findings. To provide a similar level of protection in higher speed (and thus higher energy) impacts, additional frontal cab structure (effectively a crumple zone for the truck) will be required. In a similar way as the ea-FUP was modelled, the peak force level that causes the existing cab structure to collapse by its maximum permissible amount also determines the peak force at which the extra crumple zone must have fully crushed and thus absorbed its maximum energy capacity.

3.1.1 Modelling the existing cab structure

The main international standard for HGV cab strength is the UNECE Regulation R29, and various international research studies have assessed the appropriateness of that test (a pendulum impactor) and the wider issue of HGV cab strength. Sukegawa and Oki (2004) report that in a low speed cab frontal impact test (into the back of another HGV) in Japan, the 31kJ of absorbed energy produced a cab crush of 200 mm. Assuming the structure collapses according to the linear force-displacement model described in the FUP section of this report, such that the energy absorbed is equal to ½Fd (where F is the peak force and d the crush distance), then this indicates a peak force of about 310kN at that 200mm crush. No allowance is made in this analysis for differing amounts of energy absorption between the cab structure and the truck's chassis because to do so properly would require detailed modelling of the interactions between the different parts of the colliding HGVs which is beyond the scope of this project.

Sukegawa et al (2001) and Sukegawa and Oki (2002) report crush distances of about 700mm when they impacted a 9.5 tonne truck into the back of another 9.5 tonne truck at 40 km/h. This equates to an impact energy of about 290kJ and implies a peak force of about 840kN at the 700 mm crush depth. They also describe 9.5 tonne truck impact tests into various rigid barrier configurations at 30 km/h (330 kJ of energy), which produced deformations of about 740 mm, implying a peak force of 880kN at that crush depth. Based on over 50 truck to barrier impacts, they suggested that an HGV to HGV

impact energy of about 105kJ would generate a cab crush of about 375mm, equating to a peak force of 525kN.



Figure 3-1 plots the various peak force to crush displacement values calculated from these Japanese studies.

Figure 3-1. Force-displacement characteristics for truck frontal structures, based on Japanese research

Anderson (2003) reports the results of research carried out for the UK Department for Transport. This included a pendulum impact test causing the cab structure to absorb 20kJ of energy, and during which it crushed by about 240mm. This suggests a peak force of about 167kN. This is somewhat below the force level suggested for that depth of crush by the Japanese research, but the UK test involved just a truck cab, so no energy could be absorbed by the truck's chassis. It is likely that if the chassis had absorbed some energy the resultant deformation of the cab would have been less than 240mm and the peak force therefore somewhat higher than 167kN, and more in line with the Japanese data.

Sukegawa and Oki (2004) also report that based on their analysis of real accidents involving belted HGV occupants (86% of truck drivers in Japan wear their seat belts), cab deformations above 900mm are very likely to result in fatal injuries, whereas crush depths in the range 600-900mm are likely to cause serious (but not fatal) injuries. Figure 3-1 shows that a 900mm crush would be likely to generate a peak force of about 1100kN, and thus absorb about 495kJ of impact energy. For the purposes of modelling the effects of additional cab structure (crumple zone), it has, therefore, been assumed that the existing cab structure can absorb up to 495kJ of energy without presenting an unacceptable risk of fatal injury to the truck's occupants. Impact energies over and above that number have to be absorbed by the extra crumple zone to maintain the same level of protection.

3.1.2 Modelling additional truck structure (crumple zone)

In order to allow the existing cab structure to absorb its full 495kJ, the additional crumple zone structure must collapse linearly up to the same peak force level (1100kN). The energy absorbed by this structure is then calculated using the $\frac{1}{2}$ Fd formula

explained previously (see section 2.1.2). For a given overall impact energy, the crush distance, d, can thus be calculated with F fixed at 1100kN.

It should be emphasised that this method is appropriate for the case where the additional structure is assumed to be simply added on to the existing cab structure. To provide optimum protection for HGV occupants, it would be more sensible to combine a crumple zone with a much stronger cab (occupant compartment). In this way, the crumple zone can absorb much higher forces, and thus more energy for a given crush depth, without affecting the structural integrity of the cab. The design complexities and additional material weight and costs that may be needed to provide such a stiff occupant compartment are considered beyond the scope of this project. The more simple approach we have taken can therefore be assumed to provide somewhat conservative estimates of the energy absorption and casualty reduction benefits that a properly designed cab and crumple zone system could provide for belted occupants.

3.2 Input parameter selection

Table 3-1 shows the main parameters used to calculate the increases in impact speed that various depths of truck front crumple zone would be able to maintain protection for the HGV's occupants (such that the cab deformation was no more than the 900mm critical limit suggested by Sukegawa and Oki).

It has been assumed that truck cabs are basically the same, at least in their frontal impact characteristics, regardless of the gross vehicle weight they are used for. For N3 vehicles (of more than 12 tonnes) this seems reasonable because the main variables affecting gross weight are overall chassis length and the number of axles, not the cab design. The assumption that the cabs are the same in all cases means that it makes no difference to the energy calculations which truck hits which for a given mass pairing (i.e. a 25t truck hitting the back of a 12t truck would need exactly the same amount of crush depth to protect its occupants as a 12t truck hitting the back of a 25 tonner). This simplification means that 9 impact configurations can be reduced to 6.

Truck sizes	Truck masses	Peak Force of cab and crumple zone	Maximum cab crush (energy absorbed)	Maximum Crush Depth	Maximum energy absorption by crumple zone
Small	12000 kg	1100 kN	900 mm	0 mm	0 kJ
			(495kJ)	100 mm	55 kJ
				200 mm	110 kJ
				300 mm	165 KJ
				600 mm	330 kJ
				1000 mm	550 kJ
				2250 mm	1238 kJ
Medium	25000 kg	1100 kN	900 mm (495kJ)	As above	As above
Large	44000 kg	1100 kN	900 mm (495kJ)	As above	As above

Table 3-1	. Modelled	truck to	truck	impact	parameters
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The modelled crumple zone crush depths cover the full range of options from zero (the existing baseline case) to the 2.25 metres of extra structure that would be made possible if the maximum allowable length for 16.5m articulated vehicles was increased to match the 18.75 metre length already allowed for drawbar combinations.

In making these calculations, it has been assumed that there would be sufficient space at the front of the existing cab structure to hold the fully collapsed crumple zone material, thus allowing the crumple zone to collapse fully through the modelled distance without the need to protrude any further than that from the front of the existing cab prior to being impacted.

3.3 Modelling results

As with the car to truck modelling, an Excel spreadsheet was developed to use the various parameters and equations and relate the crumple zone depths to the impact speeds for each truck to truck impact configuration. For each of the six mass configurations, the model has been used to plot impact speed against the crumple zone crush depth needed to just absorb all the impact energy at that speed that cannot be absorbed by the existing cab structure.

The results are shown in full in Figure 3-2. The critical speeds rise from about 25-45 km/h for the baseline condition (0 mm of extra crumple zone) up to about 45-85 km/h if the full 2250mm of crush depth is available.



Figure 3-2. Critical impact speeds at various crumple zone crush depths

The much greater mass, and therefore energy, involved with the larger trucks, means that there is a substantial lowering of critical speeds when large trucks are involved than is the case for much smaller trucks.

It is also noticeable that the speed increases that a crumple zone might allow for are much less for the larger vehicles than the same depth of crush allows for the lower overall mass impacts. This is again a function of the much higher energy levels and also reflects the assumption that the cab of a 44 tonne truck would be essentially the same design, and have the same maximum energy absorption capability as a smaller (12 tonne) truck cab.

To summarise the results:

• Simply including 200mm of crumple zone in front of existing cab structures, is likely to increase critical impact speeds for belted occupants only marginally, from about 24-46 km/h with existing cab designs (depending on the sizes of trucks) to about 27-51 km/h.

- If 600mm of additional truck length is used, critical speeds would be likely to rise to 30-60 km/h.
- If 1000mm of additional truck length is used, critical speeds would be likely to rise to 35-65 km/h.
- If the full 2250mm of extra length is used, critical speeds would be likely to rise to 45-85 km/h.

3.4 Fatality reduction potential

Figure 3-3 shows the cumulative frequencies of HGV occupant fatalities in front to rear impacts at different closing speeds from the Heavy Vehicle Crash Injury Study (HVCIS), involving accidents during the period 1997-2007. The three lines relate to:

- The 103 HGV occupant fatalities from all HGV frontal impacts into other large vehicles or road-side objects ("all HGV frontals");
- The 53 of those fatalities from HGV frontal impacts into the back of another HGV;



• The 31 of those that were articulated HGV occupants.

Figure 3-3. HGV occupant fatalities by closing speed in frontal collisions with other large vehicles and objects (from HVCIS)

It can be seen that most of the fatalities occur in the speed range 50-80 km/h. Figure 3-4 combines the data from Figure 3-3, the energy absorption potential from various nosecone lengths shown in Figure 3-2 and annual GB casualty rates to estimate the likely casualty reductions (fatalities prevented) from the fitment of nosecones designed to protect HGV occupants. These calculations are based on assuming that all HGV occupants do wear their seat belts and that the truck occupant compartments are of a similar structural strength and integrity to existing designs. The casualty savings assume 38 HGV occupant fatalities in all accidents per year in Great Britain (Department for Transport statistics show only 23 fatalities in 2008, but 52 in 2007 and 39 in 2006, so a

three year average has been used), and use proportions from HVCIS to estimate that of those, 18 stem from frontal impacts with other large vehicles or objects and 8 of those relate to articulated HGV occupants.



Figure 3-4. Estimated annual UK HGV occupant fatality savings

To summarise:

- A modest 200mm increase in overall length of articulated HGVs would be likely to save 1 HGV occupant fatality every other year in GB if designed to offer protection in frontal impacts with other large heavy objects and if HGV occupants wore seat belts (6% of all HGV occupant fatalities in such impacts);
- A longer increase of about 800mm would be likely to save 1 fatality per year (12% of all HGV occupants killed in frontal impacts with other large objects);
- An even longer ea-FUPS, adding up to 2250mm to the length of articulated HGVs would be likely to save around 2.5-3 fatalities per year (38% of the fatalities. For this to happen, though, any structure below the crumple zone, e.g. a FUPs, would need to be essentially rigid, at least after the first half metre or so of its stroke, to avoid intrusion of the truck structure through the car's windscreen);
- These savings would be likely to double if the crumple zone were fitted to all HGVs, not just tractor units.

3.5 Effects of proposals to amend UNECE R29 (cab strength)

The main existing Regulation affecting HGV cab strength in frontal impacts is UNECE Regulation 29 (R29). This currently includes a pendulum impactor test which imparts an impact energy of 44kJ and the cab deflection must be such that no part of the cab shall intrude within a survival space defined for a manikin positioned in the driver's seat. A recent proposal from Russia within GRSP has been made to increase this energy to 55kJ for all N2 and N3 vehicles over 7.5 tonnes GVW. The effects of this proposal more generally on safety are discussed in more detail by Robinson (2010).

It is beyond the scope of this project to establish to what extent existing cab designs pass UNECE R29; it is possible that they generally pass very easily and that, therefore,

increasing the energy absorption requirement from 44kJ to 55kJ would not necessarily lead to a change (strengthening) of cab designs. For the purposes of an initial assessment of the maximum potential benefits, though, if it is assumed that existing cabs only just pass R29, then the additional strength needed to just pass the 55kJ test can be estimated, as can the additional casualty reduction benefits.

It is known from the Japanese tests described above that a 44kJ frontal impact would be likely to produce a cab deflection of about 250mm. Assuming that this deflection is just sufficient to pass the current R29 test, then if 55kJ of energy needed to be absorbed with the same maximum deflection, then the peak force would need to be something like 440kN (up from 350kN with the existing cab). This increase in stiffness would take the energy absorption for a 900mm deflection (the critical limit used in the energy modelling) from 495kJ for the existing cab design (peak force of 1100kN) to about 675kJ for the strengthened design, corresponding to a peak force of about 1500kN.

This extra energy absorption capacity within the cab, along with a commensurate increase in the peak force at which the additional crumple zone provided by a nosecone could collapse, means that the critical speeds would be higher than those modelled above. For example, the critical speeds for a typical 25t to 25t HGV to HGV impact would increase by about 6-8 km/h for nosecone lengths up to about 1000mm.

Applying these higher critical speeds to the casualty estimates increases the likely casualty savings by about 50%. For example, an 800mm nosecone with this higher stiffness and energy absorption capacity would be likely to save about 1.5 lives per year, compared to the 1 life per year estimated for the standard strength design, if all articulated HGV occupants wore seat belts.

4 Vulnerable Road Users (VRUs)

The first part of this section describes an analysis of the effects that various nosecone depths might have on the forward field of view (FFOV) for HGV drivers - to better see pedestrians standing or walking close to the front of their cab.

This is followed by a review of recent research into the potential casualty reduction benefits from adding a thin layer of energy absorbing foam or other material to the front-most structure of a truck cab. It also assesses fitting nosecone-type geometries to modify the impact kinematics for pedestrians and other VRUs (e.g. cyclists) involved in frontal collisions with HGVs.

4.1 Forward Field of View

4.1.1 Analytical method

A CAD model of a tractor unit (a Scania Series 4) was combined with a range of modelled pedestrians (of varying heights) to assess how far from the front of the cab the pedestrian would need to be standing/crossing for the HGV driver (assumed to be a 50th percentile male) to be able to see them. The software used was the SAMMIE-CAD package which has been specifically developed for ergonomic analysis and field of view studies. For each run of the model, two visibility criteria were used:

- Just visible (JV) defined as the top of the pedestrian's head being just visible as he/she moved fully across the whole front of the HGV at a fixed distance from that front. To actually be seen by the HGV driver, it would be necessary for that driver to be paying full and careful attention to what is going on in front of his vehicle.
- Head visible (HV) defined as the whole of the pedestrian's head being visible to the driver at all stages as the pedestrian moves across the front of the truck. Even a moderately alert driver should be able to see the pedestrian in these circumstances.

"Visibility" here means direct line of sight; the effects of different mirror options were not assessed.

4.1.2 Input parameter selection

Initially, three pedestrian models were created within the SAMMIE programme – a 50^{th} percentile adult male (height 1.76m), a 5^{th} percentile adult female (1.53m) and a 50^{th} percentile 2 year old female child (0.85m). These were chosen to represent both the typical accident case, involving an elderly pedestrian and the most extreme conceivable case, where a small toddler is involved, walking or running across the front of the HGV unseen by its parents or guardians.

On placing these models at the front of the standard truck, standing close to the front but not touching it, the 50th percentile male was already fully (whole head) visible to the driver. This pedestrian was thus excluded from any further analysis because anybody of this height walking in front of the truck modelled would be fully visible to an attentive driver whether or not an extra nosecone was fitted. The 5th percentile female was just visible (top of head only) when placed in this position and was therefore suitable for assessing what length of nosecone would be needed to ensure such a pedestrian would be fully visible. The child pedestrian, unsurprisingly, was completely invisible when placed near to the front of the standard truck. This child was thus suited to modelling the extreme case, both for the length of nosecone to ensure even the top of her head was visible and what more would be needed to have her fully visible to the HGV driver.

The SAMMIE-CAD software allows the rapid creation of some fairly simple 3D shapes, but is not a full-blown CAD package. For the purposes of this research, therefore, very

complex nosecone geometries could not be modelled, but some representative shapes were created and attached to the truck's front. In determining the FFOV for the HGV driver, the modelling work strongly suggested that it is the height of the front most part of the "nose" that has the greatest single effect on pedestrian visibility, rather than the intricacies of the nose shape. It is suggested, therefore, that the basic modelling capabilities of the SAMMIE programme were perfectly adequate for the task. More complex nosecone shapes certainly do have an effect on pedestrian impact kinematics (see later section), but for FFOV assessments, the simpler model is adequate.

Three basic models were assessed:

- The baseline, standard vehicle without a nosecone. The two pedestrian models were placed at varying distances from the truck (and moved across the front of the truck at that fixed distance from it) and their visibility to the HGV driver recorded;
- A conical-section nosecone geometry (see Figure 4-1), with the base diameter set to match the width of the truck front, the top diameter varied between 400mm and 800mm, and of a depth set according to the length of nose being modelled. Vertically, this nose was placed such that the bottom of the top edge of the cone lined up with the bottom of the truck's bumper (450mm from the ground), which also allowed the top-most part of the base of the nose to be just below the line of the bottom of the truck's windscreen. The 800mm top diameter was used to simulate a nose optimised for HGV occupant protection, by providing plenty of stiff structure at a similar height to the rear of an HGV semi-trailer (up to 1250mm from the ground). The 400mm diameter was chosen to minimise the aggressive flat front for pedestrian impacts, but to retain structure at a height of 450-850mm from the ground for car to truck impacts. To ensure that pedestrians could not walk in a curved path around the front of the nose, and to produce a completed overall nosecone shape more in keeping with the pedestrian impactoptimised designs described later in this section (from the APROSYS research), an additional bumper beam was modelled across the whole front of the truck, 400mm high and placed 450mm from the ground.
- A prism-section nosecone geometry (see Figure 4-2), with a two dimensional triangular shape projected as a solid across the whole of the truck front on top of a bumper bar as described for the conical-section nosecone. The height of the bumper section was varied between 400mm and 800mm (again to simulate optimisation strategies for car and HGV occupant impacts), and the top-most part of the triangle was set just below the base of the truck's windscreen.

Nosecone lengths starting at 400mm and rising in 200mm increments to 1400mm were modelled. For each nosecone, and for each pedestrian, the pedestrian was moved in 50mm increments away from the front-most part of the truck until first, the top of the head could be seen by the driver and second, to the point at which the whole head came into view.

For some geometries with the more pointed conical-sections, it was noticeable that the limiting distance from the truck front was determined by the tip of the nose. This meant that the pedestrian was much more highly visible when standing/walking either side of the nose (centre line of truck), but was obscured by the nose itself when near to the centre line. This would have the effect that the pedestrian could be standing somewhat nearer to the front of the truck and still be visible, but only while near to the far left or right hand edges of the truck's front. In the real world, in these circumstances, only if the driver happened to quickly check what was in front of his vehicle at the instant that the pedestrian was obscured by the nose, but not look immediately before or after (when the pedestrian came back into view) would a pulling-away accident still be likely. To assess this effect more closely, some additional model runs were carried out with the pedestrian standing at the left hand edge of the truck (which would simulate a pedestrian waiting to cross the road from the near-side).



Figure 4-1. Conical-section nosecone geometry (800mm front height shown)



Figure 4-2. Prism-section nosecone geometry (400mm front height shown)

4.1.3 Modelling results

Table 4-1 presents the results, as distances from the front of the truck at which the 5^{th} percentile adult female ("Adult") and/or the 50^{th} percentile 2 year old child ("Child") were in the direct line of sight (forward field of view) of the HGV driver.

Nose length	Adult/ Child	Nose height	Standard truck (no nosecone)		Conical-section nosecone *		Prism-section nosecone	
mm		mm	Just Visible	Head Visible	Just Visible	Head Visible	Just Visible	Head Visible
			metres	metres	(left edge)	(left edge)	metres	metres
					metres	Metres		
0	Adult		0	0.40				
	Child		1.15	1.35				
400	Adult	400			-	0	-	0
	Adult	800			-	0	-	0
	Child	400			0.80	1.00	0.75	0.90
	Child	800			0.80 (0.75)	1.00 (0.95)	0.75	0.90
600	Child	400			0.60	0.80	0.55	0.70
	Child	800			0.60 (0.55)	0.80 (0.75)	0.55	0.70
800	Child	400			0.40	0.60	0.35	0.55
	Child	800			0.40 (0.35)	0.60 (0.55)	0.40	0.60
1000	Child	400			0.20	0.40	0.15	0.30
	Child	800			0.25 (0.15)	0.45 (0.35)	0.50	0.70
1200	Child	400			0	0.20	0	0.10
	Child	800			0.30 (0)	0.50 (0.15)	0.60	0.80
1400	Child	400			0	0.15	-	0
	Child	800			0.35 (-)	0.55 (0)	0.65	0.90

Table 4-1. Distances from truck front at which Adult and Child pedestriansbecame just or fully visible

* Figures in brackets refer to the visibility distance when the pedestrian was standing at the left edge of the truck, and so not obscured by the nosecone.

The adult (5th percentile female) pedestrian became fully (whole of head) visible when placed 0.4m from the standard truck and, not surprisingly, her head was still fully visible to the driver in this position when a 400mm nosecone was added. Any nosecones longer than 400mm were thus not modelled for the adult pedestrian, because all would be bound to allow full visibility with the pedestrian stood just in front of the front edge.

The child only became visible when placed 1.15m away from the standard truck, and needed to be 1.35m away before the whole of its head came into the driver's field of view. Nosecone depths up to 800mm had very little effect on the field of view, even with the 800mm nose height, so the distances simply reduced in line with the increases in nosecone lengths, i.e by about 0.2m for each 200mm increase in nose length.

At nosecone lengths of 1000mm and above, the effect of nose height becomes increasingly evident. With the larger (800mm) nose height, the nose itself obscures the child from the driver's view and thus the child has to be standing further back to be seen

than with the standard truck. The longer the nose, the further away from the front of the truck the child has to be to be seen. For the longest prism-section nose modelled, 1400mm, the child needs to be standing fully 0.9m back from the front edge (i.e. 2.3m back from the original front of the truck) for the whole of her head to be visible to the driver. For the 1400mm conical nosecone this distance decreased slightly to 0.55m away from the truck front.

The visibility for the conical nosecone depended on where the child was placed across the width of the truck. The figures in brackets in Table 4 show that with the longer, conical nosecones, the child could be seen even when standing right up close to the front of the truck when placed at the left hand edge.

For the prism-section nosecone, the structure of the nose would obscure the child from the driver's view wherever the child was standing across the width of the truck, so the left edge distances would be the same as the centre line.

With the lower (400mm) nose height, these effects were greatly reduced; the child became just visible when standing/crossing close to the 1200mm nosecones, and fully visible when doing so with the 1400mm prism-section nose.

To summarise the results:

- Nosecones of 400mm or longer eliminated the current blind-spot (for the modelled truck and driver) for adult pedestrians of height 1.53m (5th percentile female) or taller; even when standing or crossing right up against the front of the cab, the whole of their head at least should be visible to the driver at all times.
- For very young children, such as the 0.85m tall (50th percentile 2 year old girl) pedestrian modelled, only nosecones of 1200mm length or more would allow any visibility for the modelled truck driver if that child were standing or crossing close to the truck's front edge.
- For intermediate nosecone lengths, the blind-spot area in front of the cab reduces in line with increases in nose length.
- For nosecone lengths of 1000mm or more, nosecone height also had an effect; with a high nose (800mm, i.e. tip of nose 1250mm from the ground) obscuring the child pedestrian. Even in the most extreme case modelled, however, the overall blind-spot area was still reduced, i.e. the child could stand slightly closer to the truck's front edge and remain visible to the driver than was possible with the standard truck.

Figure 4-3 shows pictorially the approximate reductions in blind-spot area for the 2 year old child provided by the various nosecone geometries and for two nosecone lengths.



Figure 4-3. Blind-spot areas for 2 year old child with 600mm and 1200mm nosecones (whole of head not visible in shaded areas)

4.2 Pedestrian impact protection

This section reviews the results of the APROSYS (Advanced Protection Systems) project and other research into the provision of energy absorbing materials and other less aggressive structures onto the front of HGVs to provide some protection for pedestrians and other VRUs in frontal impacts.

Chirwa and Ashton (2002) analysed vehicle front-end geometry as a function of injury severity for pedestrian frontal impacts. They concluded that vehicles with a high incidence angle of between 80 and 90 degrees (i.e. with a flat rather than a sloping front) such as trucks and buses provide the most intense loading conditions on the pedestrian. The first points of impact tend to be spread over the whole body, from head down to legs and often cause fatal injuries, almost independent of speed.

With slightly lower incidence angles $(60^{\circ}-80^{\circ})$, such as with SUVs and LCVs) the first points of impact tend to be confined to a smaller area and cause slightly less severe injuries, depending on impact speed, especially for adult pedestrians where head impacts can be avoided in this first phase of the accident.

For even lower angles $(30^{\circ}-60^{\circ})$, such as found with most passenger cars), adults and even quite small children can avoid a direct head impact and so injury severities are still further reduced, again depending on the impact speed.

Chirwa et al (2006) built upon the earlier research to test the stiffness/aggressiveness, and hence energy-absorption capabilities, of various frontal components of a truck, with the aim of developing a "Structural Aggressivity Index". They found that the front bumper was the most injurious, particularly for child pedestrians.

Feist et al (2008) contributed to the EU's APROSYS project by analysing the benefits of a retrofittable, energy-absorbing structure for enhanced protection of VRUs. Various concepts were assessed using MADYMO and other modelling software, including foam, inflated rubber tubes, and combinations of steel and plastic, and steel and foam. Headform impactor tests were also carried out on steel-plastic/foam combinations and one of the concepts (the foam-steel structure) was also crash tested when fitted to a real truck and impacting a Hybrid III standing dummy at 30km/h.

All the concepts studied gave greatly reduced injury criteria levels when modelled in impacts at both 30 and 40km/h, for pedestrians and cyclists. The steel-foam structure that produced the best overall results was lightweight, low cost, added no more than

200mm to the overall length of the truck, yet could absorb sufficient energy to provide protection for VRUs in frontal impacts at speeds of between 30 and 40 km/h. Figure 4-4 shows the steel-foam (safety bar) concept.



Figure 4-4. APROSYS steel-foam safety bar concept

The APROSYS project also examined various nosecone geometries, to ascertain their effectiveness in protecting VRUs in frontal impacts with trucks. Hamacher et al (2009) summarised the results. The objective was to develop a tapered nosecone that could reduce the risk of post-impact run over by deflecting the pedestrian sideways, away from the front of the truck. The researchers concluded that a convex truck front significantly reduces this risk, particularly in impacts of more than 20km/h, and the additional deformation space (energy absorption) also allows the contact forces at primary impact to be reduced.

The modelling work to assess the optimised design was based on 95th and 50th percentile male pedestrians, a 5th percentile female and 6 year old child model, and only looked at the post-impact kinematics, i.e. whether or not the pedestrian was run over, and not at injury levels. To find the "optimised" design, 90 different geometries were first assessed only with the 50th percentile male pedestrian.

The optimised design, which was able to reduce the risk of run over for all the pedestrians modelled in both straight-ahead driving and cornering impacts, is shown in Figure 4-5. This nosecone adds about 850mm to the overall length of the truck. Increasing this length was found not to have any further positive influence on the pedestrian kinematics, but the detailed geometry of the nose did have a strong influence. At nosecone lengths of about 500mm or less, there was insufficient structure to adequately deflect the pedestrian. At longer lengths, it was found that using a gently sloping design allowed the pedestrian to be pushed upwards and thereby reduced the risk of run over more than was the case with steeper (flatter) nosecone shapes. This upward movement was also encouraged with a lower plateau at around truck bumper height, with deflection sideways optimised when the upper section of the nosecone had a convex shape.



Figure 4-5. APROSYS optimised nosecone geometry

To prove the MADYMO simulations, a full scale impact test was also carried out. A truck fitted with the optimised nosecone, made of expanded polypropylene (EPP) foam was driven at 30 km/h straight into the side of a 50th percentile male dummy. The dummy was successfully deflected to the side and not run over.

4.3 Fatality reduction potential

For the ea-FUP and truck crumple zone analyses described earlier, it could be assumed that there was a fairly straightforward relationship between the length of nosecone and the potential casualty savings, because as nosecone length increases, so does the energy it can absorb. For VRU impacts, however, such a relationship is not appropriate because there are optimal nosecone lengths after which no additional casualty savings are likely to arise in particular accident scenarios. For example, the field of view modelling indicated that once a nose is above about 1400mm long, then all pedestrians, even very small children, come into view. Having a 2000mm long nosecone, in this scenario, would make no further difference. To assess the VRU casualty reduction potential, three nosecone lengths were examined:

- 200mm. This nosecone would correspond to something like the safety bar concept described above. It would absorb enough of the impact energy to protect the VRU (pedestrian or pedal cyclist) when a truck impacts at up to 40 km/h, but only if that person is not too elderly (<70 is assumed). Such a guard would only help to prevent post-impact run over if the truck stops before reaching the casualty (who is thrown forward and/or over by the impact), which it is assumed is only possible in half of the impacts. For pulling away accidents, where field of view is the crucial factor, such a guard would make only a slight improvement (allowing the driver to see pedestrians over 1.7m tall was assumed);
- 900mm. This nosecone would be similar to the APROSYS optimised geometry described above. As well as protecting non elderly VRUs in the same way as the 200mm safety bar, it would also help to deflect them away, so full protection can be assumed because post-impact roll-over will be unlikely. Such a guard would also greatly reduce the forward blind-spot, but not eliminate it altogether; the modelling work indicates that it would prevent pulling away accidents for pedestrians 1.2m tall or taller.
- 1400mm. This nosecone would have all the benefits of the 900mm version, but is assumed to eliminate the forward blind-spot, so even very young children can be seen and thus not killed in pulling away type accidents.

HVCIS contains details of 312 pedestrian and pedal cyclist fatalities from frontal impacts with HGVs during the period 1997-2007. An analysis has been carried out to quantify the

proportions of these fatalities that the three nosecones, with their assumed capabilities, would be likely to save. These proportions are then applied to the numbers of VRUs killed in such impacts in GB, from STATS19. These statistics show that 72 pedestrians and 27 pedal cyclists were killed in impacts with HGVs on average between 2006 and 2008, of which 50 pedestrians and 10 pedal cyclists per year were in frontal impacts. It has been estimated from HVCIS data that 22 of those pedestrians and 4 of the pedal cyclists were in impacts with articulated HGVs. Figure 4-6 shows the likely annual casualty savings as nosecone length increases.

Most of the estimated casualty savings stem from low speed "pulling away" accidents (which account for about 38% of all pedestrian fatalities in frontal impacts with HGVs in HVCIS) where improving the forward field of view is the main countermeasure and can save lives regardless of the age of the pedestrian because the accidents are completely avoided; about 20% of the casualties in this type of accident in the HVCIS sample were over 1.7m tall and could thus be saved by a 200mm safety-bar type concept, 96% were over 1.2m tall and therefore suitable for the 900mm nosecone and just an additional 4% were very young children that only the full 1400mm nosecone could avoid.

The second biggest group of potential savings come from higher speed "going ahead" impacts (which account for the highest proportion of fatalities – 57% of all pedestrians killed in frontal impacts with HGVs, 46% of pedal cyclists). About one third of those pedestrian impacts occur at speeds below 40 km/h, and half of the pedal cyclist impacts, and half of those involve pedestrians under the age of 70 (all the pedal cyclists were under 70) and are thus suitable for protection from a 200mm nosecone (saving half of them) or a 900mm (or 1400mm) nosecone (assumed to save all of them).

The remaining savings come from low speed turning accidents, which account for just 5% of all pedestrian fatalities in frontal impacts with HGVs in HVCIS and, of those, only one third involve pedestrians under the age of 70, but account for 38% of the pedal cyclist fatalities, all under the age of 70.



Figure 4-6. Estimated annual UK pedestrian and pedal cyclist fatality savings

To summarise:

- A modest 200mm increase in overall length of articulated HGVs would be likely to save 3 pedestrian fatalities and one pedal cyclist every year in GB if designed to absorb impact energy in a way similar to the APROSYS safety bar concept (15% of VRUs killed in frontal impacts with articulated HGVs);
- Longer increases of about 900mm or more would be likely to save 12 fatalities per year (10 pedestrians and 2 pedal cyclists) if the nosecones were shaped like the APROSYS optimised geometry (46% of all VRU fatalities from frontal impacts with artics);
- These savings would be likely to double if the VRU friendly structures were fitted to all HGVs, not just tractor units.

5 Manoeuvrability

This section assesses the effects of various nosecone geometries on the approach angles, ramp angles and slow speed turning ability of articulated HGVs.

5.1 Approach and ramp angles

A vehicle's approach angle is defined (by ISO 612:1978) as the maximum slope that the vehicle could be driven up if the slope started suddenly from a horizontal approach. It is usually dictated by the ground clearance of the front bumper and the distance from the front of the bumper to the front of the contact patch of the front tyre (see Figure 5-1). It therefore reflects the maximum negotiable slope of, for example, a ramp up to a ferry; if the slope were any steeper, the front of the bumper would hit the slope first, before the tyre had touched it and the vehicle would not be able to move up the slope.

The ramp angle (also shown in Figure 5-1) is the angle of ground slope change above which the underside of the vehicle would scrape the ground after the front wheels have passed but before the rear wheels have arrived at the same point. It is dictated by the wheelbase and ground clearance of the vehicle between the front and rear wheels. It reflects the maximum negotiable sudden change in ground slope, from positive to negative, e.g. when driving over a hump-backed bridge.



Figure 5-1. Approach and Ramp Angles

There are two plausible options for adding a nosecone structure to the front of a tractor unit; first, to simply bolt the new nose onto the existing truck structure, without changing the position of the front axle and second, to integrate the nose into the cab design and move the front axle forward. These two options are illustrated in Figure 5-2 The "bolt-on" option would not affect the ramp angle at all, but might affect the approach angle (because the bumper to tyre distance might increase), whereas the "integrated" option would allow the approach angle to remain the same but might affect the ramp angle (because the wheelbase might increase).



Figure 5-2. "Bolt-on" (top) and "Integrated" (bottom) nosecone concepts (sources: Scania, MAN and Daf)

A survey of published tractor unit specifications indicates that existing vehicles have approach angles of about $10^{\circ}-14^{\circ}$ and ramp angles of $16^{\circ}-26^{\circ}$. The objectives of this part of the project are to quantify the effect that bolt-on and integrated nosecones might have on in-use approach and ramp angles, and establish whether these effects would significantly (and adversely) affect the manoeuvrability of the vehicles.

5.1.1 Effect of "bolt-on" nosecones on approach angles

Two scenarios are assessed; first, to quantify how nosecone length reduces the approach angle if the ground clearance is fixed and second, to quantify how the ground clearance of the nosecone influences the approach angle if the nosecone length is fixed.

For the first scenario, the starting point is a typical tractor unit, with an approach angle of 14°, achieved by having a bumper ground clearance of 325mm and a horizontal distance from the lower edge of the bumper to the front of the tyre contact patch (front overhang) of 1300mm. Table 5-1 shows how the approach angle decreases as the nose length increases from zero (the standard truck) to 2250mm (the maximum possible length increase to allow 18.75m artics, as is already permissible for drawbar combinations). The Table also shows how the ground clearance would have to increase for the longer nose lengths if a minimum approach angle of 10° was required, as suggested by the survey of existing vehicles.

Nose length	Approach angle with 325mm ground clearance	Ground clearance* to achieve a 10° approach angle
0	14.0°	-
200mm	12.2°	-
400mm	10.8°	-
600mm	9.7°	335mm
800mm	8.8°	370mm
1000mm	8.0°	405mm
2250mm	5.2°	625mm

Table 5-1. Effects of nosecon	e length and ground	clearance on approach angle
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At front-most edge of nosecone

For the second scenario, the base vehicle is a tractor unit with a 10° approach angle, achieved with a bumper ground clearance of 220mm and front overhang of 1250mm. Table 5-2 shows how the nosecone front edge ground clearance would need to rise in order to retain the 10° approach angle as nosecone length increases.

Nose length	Ground clearance* for 10° approach angle
0	220mm
200mm	255mm
400mm	290mm
600mm	325mm
800mm	360mm
1000mm	395mm
2250mm	615mm

Table 5-2. Effects of nosecone length on ground clearance to achieve 10°
approach angle

* At front-most edge of nosecone

The maximum permissible ground clearance for (rigid) front underrun systems is currently set at 400mm (under any loading condition), so even a 1000mm long nosecone (on a 17.5m overall length artic) could be fitted to the existing 10° approach angle tractor unit without risking contravention of this requirement, assuming that the front of the truck is not raised excessively when the rear axle is loaded, e.g. through active suspension. Longer nosecones would dictate lower approach angles to remain in compliance with the FUPD legislation; in the modelled case, an approach angle of 7.3° would be the maximum possible for a 2250mm nosecone.

5.1.2 Effect of "integrated" nosecones on ramp angles

In these scenarios, the effects of increasing wheelbase on ramp angles are examined, assuming that as the nosecone length increases, the front overhang distance remains the same as for an existing truck, and thus the front axle is assumed to move forwards relative to the rear axle by an amount equal to the nose length.

The lowest ramp angle identified in the brief survey of published tractor unit specifications was 16°, with 19° being a more typical figure. The minimum acceptable ramp angle, though, is more likely to be determined by the distance from the back of the

rear tractor tyre to the front of front trailer tyre and the ground clearance of the trailer, e.g. of the sideguards. The survey of articulated vehicle sideguard heights described by Whitehead and Knight (2002) found the average sideguard ground clearance to be 444mm, with a minimum of 350mm. Assuming a tractor to trailer "wheel base" (distance between tyre contact patches) of 6 metres, this suggests that ramp angles of 14° were then quite common, and with recent trends towards lower, aerodynamic side-skirts, even lower ramp angles are likely to be possible (see Figure 5-3 for an example).

Table 5-3 shows how a tractor unit currently operating with a 16° ramp angle (ground clearance of 250mm and wheelbase of 3.6m) would be affected by increasing the wheelbase.



Figure 5-3. Example of low ground clearance, low ramp angle HGV

Nose length (= wheelbase increase)	Ramp angle
0	15.8°
200mm	15.0°
400mm	14.3°
600mm	13.6°
800mm	13.0°
1000mm	12.4°
2250mm	9.8°

Table 5-3. Effects of nosecone length on ramp angle

Only with very long nosecone lengths do ramp angles start to become low enough to cause concern (below, say 12°). In practice, these effects could quite easily be mitigated by, for example, raising the ground clearance slightly or bringing the 2nd tractor axle forward slightly (as would in all likelihood be necessary anyway to provide adequate weight distribution when laden), or some combination of the two.

5.2 Turning ability

This section describes the results of an analysis of the effects of increasing tractor unit length on an articulated vehicle's ability to meet the low speed turning requirements set out in Directive 97/27/EC.

5.2.1 Analytical methods

The AutoTrack vehicle manoeuvrability software package was used for this analysis. It allows a realistic simulation of a vehicle's low speed turning and cornering paths and is widely used in, for example, designing car parks, roundabouts and road junctions. The software has an extensive library of different vehicle types, including a maximum length (16.5m) artic. This was thus chosen as the base model for assessment. The software also allowed various changes to be made to the shape of the tractor unit, e.g. to increase its length and introduce a tapered nose. For vehicle configurations (with a flat or tapered front) that the model indicated could not meet the 97/27/EC requirements, the option of allowing the rear-most semitrailer axle to self-steer was also explored. This was to check whether this change alone would be sufficient to allow the vehicle to then meet the turning requirements.

5.2.2 Input parameter selection

The base vehicle modelled was a 5.79m long Leyland DAF 95.400 6X4 tractor unit coupled to a 13.5m, tri-axle semitrailer. The overall length was 16.5m and the width was 2.5m. The front overhang was 1.39m. For the flat-front nosecone extensions, the existing rectangular shape (when looking down at the vehicle from above) was retained and the 5.79m body length simply increased incrementally until the turning requirements could no longer be satisfied. The axle and king-pin positions were not changed so in effect the length was added to the front of the cab, as in the "bolt-on" nosecone described above. The test considers wall to wall turning circles, not kerb to kerb: changing the front axle position (e.g. to simulate the integrated nosecone designs) was not found to have any significant effect on the results and so was not modelled further.

Tapering the front of the cab would obviously help longer vehicles to meet the test requirement, because the outermost edge of the truck is effectively moved backwards. This effect was modelled in various ways, mostly by assuming that the tapering started from the original front edge of the cab and extended up to the length of the nosecone so as to give a nose-tip width equal to one half the width of the original cab (see Figure 5-4, the "Tapered" profile). Other options, e.g. to make the nose less pointed or to only taper the nose at its tip were also assessed (also shown in Figure 5-4).



Figure 5-4. Modelled nose profiles

5.2.3 Modelling Results

Figure 5-5 presents the results for the flat-fronted and strongly tapered vehicles, both without a self-steering rear trailer axle (as in the base vehicle configuration), and with this option deployed. The figure shows the maximum nosecone length/cab length increase (to the nearest 50mm) that when modelled still allowed the turning requirements to be met, up to the maximum modelled length of 2250mm (corresponding to a cab length of 8.04m and an overall vehicle length of 18.75m).

- The flat fronted vehicle, with the conventional, un-steered, trailer axles, could only keep within the boundaries prescribed by Directive 97/27/EC if the length increase was limited to 250mm or less.
- Adding a self-steered trailer axle increased this by 1m to 1250mm.
- Strongly tapering the front had a more significant effect, with a length increase of 1600mm just possible without a self-steered trailer axle.
- With the self-steered trailer, even the full 2250mm increase could be accommodated with the strongly tapered front.



Figure 5-5. At-limit nosecone lengths to meet 97/27/EC standard

To explore in more detail the effect of tapering, this configuration (2250mm tapered nosecone with self-steered trailer axle) was further modified to represent the "weak taper" and "composite" options described above, to find the limit conditions.

For the weakly tapered configuration, it was found that the nose-tip width could be increased from one half of the width of the standard truck (i.e. 1.25m) to 1.7m, which is about two-thirds of the cab width. Any wider and the vehicle could no longer stay within the boundaries prescribed by EC Directive 97/27.

For the composite profile, it was found that the nose could remain the same width as the rest of the cab (2.5m) for no more than 1.25m, with the remaining 1m of the 2250mm nosecone tapering down to half that width.

6 Aerodynamics, fuel consumption and emissions

This section describes the research undertaken to estimate the potential effects of nosecone frontal profiles on aerodynamic drag, fuel consumption and emissions. CFD (Computational Fluid Dynamics) modelling work by MIRA has been used to assess the likely effects of adding increasing lengths of an aerodynamically efficient nosecone shape to the front of an existing tractor unit design, coupled to an existing standard semi-trailer. A literature review has also identified some work by Scania that modelled an aerodynamically highly efficient articulated vehicle combination and assessed the additional improvements from increasing nosecone lengths. The PHEM (Passenger car and Heavy-duty Emission Model), created by the EU ARTEMIS project, has then been used to translate the aerodynamic drag coefficients into in-use projections of fuel consumption and emissions performance.



Figure 6-1. Standard Lawrence David trailer model

6.1 Modelling Aerodynamic drag

6.1.1 MIRA model

For the purposes of this project, an existing CAD articulated vehicle model was used as the baseline (developed originally for Lawrence David Trailers and further developed here with their permission), Figure 6-2. It should be noted that the only significant aerodynamic aids fitted to this vehicle are a hood mounted on top of the tractor roof (to allow air to flow smoothly over the top of the tractor and along the roof of the semitrailer) and flat panels covering the sideguards and part of the area between the rearmost trailer axle and the rear underrun guard. In many ways the airflow is far from optimised, with large gaps, for example, between the front and rear tractor axles and around the front and top of the sideguards area. These gaps are where air can flow, vortices can form and drag can result. The baseline vehicle is, therefore, likely to be representative of many current vehicle configurations in use today, but would also be likely to benefit, from an aerodynamic perspective, from a range of improvement measures, on both the tractor and semi-trailer, and not just an improved frontal (nosecone) profile.



Figure 6-2. Baseline vehicle

As well as the baseline vehicle, three nosecone extension lengths were modelled, using profiles chosen by experts from MIRA as being likely to offer significant aerodynamic benefits. The project budget and timescale did not allow for any model development, refinement or optimisation, so the results should be considered as being close to what can be achieved but are unlikely to be the optimum.

MIRA's brief was to choose nosecone profiles that would give good aerodynamics only; they were asked not to try to consider other issues such as driver's visibility, engine cooling, impact structures, etc. This further supports the view that the results should be considered as a guide to what may be possible, rather than a precise evaluation.

The three nosecone lengths modelled were 400mm, 900mm and 2250mm, using the profiles shown in Figure 6-3. The frontal area for all vehicles modelled was assumed to be $10m^2$ and all modelling was based on a 0 degrees yaw angle (i.e no crosswind).

The results are shown in Table 6-1. While the nosecones had their desired effect in that they significantly reduced the aerodynamic drag of the tractor unit (from 0.538 down to 0.459), the importance of considering the whole vehicle in combination is highlighted by the fact that the overall drag of the vehicle was actually higher with the longer nosecones than with the standard vehicle. The results clearly show that there is a very strong interaction between cab and trailer. This is considered to be a likely consequence of the nosecones causing higher pressures in the wake of the cab, which is where the semi-trailer is and which thus causes a higher semi-trailer drag component. With the semi-trailer modelled, this higher pressure and drag is sufficient to negate all of the benefit of the nosecone.

Vehicle	C _D – cab only	C _D – whole vehicle	Delta-C _D	
Baseline	0.538	0.463	0	
400mm nosecone	0.506	0.449	-0.014	
900mm nosecone	0.478	0.464	+0.001	
2250mm nosecone	0.459	0.499	+0.036	

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Figure 6-3. 400mm, 900mm and 2250mm nosecone lengths

The MIRA study highlighted two important conclusions; first, that well designed nosecone profiles could significantly reduce the aerodynamic drag of the tractor units they were fitted to, but that, second, adding a nosecone in isolation from other aerodynamic changes might actually make the aerodynamic drag of an articulated vehicle combination worse. This was found to be the case for the maximum nosecone length considered of 2250mm. For a 400mm nosecone, the whole vehicle drag was reduced by 0.014 (reduction in cab only drag of 0.032), and for the 900mm profile, the overall vehicle drag was almost unchanged from the baseline case (up just 0.001). This left open the question of whether more aerodynamically optimised tractor/semi-trailer designs could allow the cab-only benefits of nosecones to translate into significant whole vehicle improvements, even with the longer nosecone lengths. Some recent work by Scania was identified that helps to answer that question.

6.1.2 Scania model

A recent study by Scania (Commercial Motor, 2009) involved a similar CFD analysis as performed by MIRA but used a much more aerodynamically efficient baseline vehicle.

Most notably, the baseline design includes full side-skirts on tractor and semi-trailer. The absolute drag coefficients are not reported, but are considered likely to be well below the 0.463 baseline used by MIRA (but representing more typical existing vehicle designs).

Nosecone lengths of 500mm, 1000mmm and 1500mm were modelled. The 1500mm nosecone design is shown as an example in Figure 6-4.



Figure 6-4. Scania 1500mm nosecone design (source: Scania)

The results (wind averaged for 0 and 5 degree yaw angles) are shown in Table 6-2. It can be seen that the overall aerodynamic drag was reduced for each nosecone length modelled, and the reductions were found to get larger as nosecone length increased.

Vehicle	Delta-C _D
Baseline	0
500mm nosecone	-0.018
1000mm nosecone	-0.022
1500mm nosecone	-0.029

Table 6-2. Scania CFD results summary

6.1.3 Results

Combining the MIRA and Scania findings reveals a range of similarities and differences.

- For modest nosecone lengths, up to about 500mm, both approaches indicate very similar drag reductions; of 0.014 and 0.018 from the 400mm and 500mm nosecone lengths modelled by MIRA and Scania respectively;
- Both studies show clearly that nosecones are able to substantially reduce the aerodynamic drag of the tractor unit to which they are fitted, and the scale of that reduction increases with nosecone length. This is true for all the nosecones studied, up to 2250mm in length;
- For intermediate and longer nosecone lengths (from 900mm to 2250mm) the two studies show diverging results for the drag of the whole vehicle in combination;

- The indication from the MIRA work is that if a standard tractor unit is simply modified to include a nosecone (designed to give very good aerodynamic performance for the tractor), but it is then coupled to a standard semi-trailer, the overall vehicle drag (and, therefore, fuel consumption and emissions) may actually increase. The effect seems to get worse as nosecone length increases, with the "break-even" point being around 900mm (giving an overall increase in drag of just 0.001). At 2250mm, the increase in overall drag was 0.036.
- Conversely, the Scania work indicates that if an articulated vehicle combination is designed as a single package, with optimised and matched aerodynamic features on both the tractor and semi-trailer, then longer nosecone lengths can produce increasing reductions in whole vehicle aerodynamic drag, and not just in the drag of the tractor unit. Such a vehicle combination when designed with a 1500mm nosecone produced overall reductions in vehicle drag of 0.029.

6.2 Fuel consumption and emissions

6.2.1 Analytical method

The emissions modelling followed the same procedure as used in the main longer semitrailers project (Knight et al, 2010). Emission and fuel consumption estimates were derived using PHEM (Passenger car and Heavy duty Emissions Model) over 120 typical driving cycles, for each of the vehicle configurations (all assumed to comply with Euro 5 standards). This included simulations of these vehicles operating part laden and fullyladen. The baseline vehicle was chosen to match that used in the aerodynamic modelling work, i.e. a 2+3 articulated combination, with properties consistent with those used for the analysis in the main longer semi-trailer analysis (Knight *et al.*, 2010). For fully laden conditions, the GVW (40 tonnes) was taken as the total weight. For part laden, a typical load for the baseline vehicle was used for all the vehicles (the total weight of the vehicle increased slightly with the addition of the nosecones and, where applicable, the trailer aerodynamic aids). These vehicle weights are summarised in Table 6-4.

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.

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 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.

6.2.2 Input parameter selection

The aerodynamic drag modelling work produced a wide range of effects for the longest nosecone lengths considered, from a 0.036 increase in overall vehicle drag (2250mm nosecone modelled by MIRA) through to a 0.029 reduction in drag (1500mm Scania model). Based on these data and the other analyses performed for this project, the

following general statements can be made about the concept of a very long (1500mm and above) nosecone length:

- Most of the potential casualty savings from nosecones arise for nosecone lengths up to about 1000mm. Very few additional savings are likely for nosecones over that length;
- Nosecone lengths of more than 1000mm would be likely to present difficulties with regard to manoeuvrability (when coupled to standard 13.6m semi-trailers) and approach/ramp angles;
- If regulatory changes to permit a nosecone at the front of the tractor were to be implemented alongside changes to allow longer semi-trailers then requiring the front of the tractor unit cab to be increased by more than 1500mm would mean that very little, if any, extra length could be added to the semi-trailer within the constraints of an overall maximum length of 18.75m;
- The potential aerodynamic effects for nosecone lengths of 1000mm or more are unclear, and likely to be heavily dependent on the specific vehicle combination characteristics, e.g. the aerodynamic performance of the semi-trailer. The potential exists for overall vehicle drag to increase if tractors and semi-trailers are poorly matched.

For these reasons, further consideration of the most extreme nosecone lengths was considered unlikely to yield meaningful or useful results. The fuel consumption and emissions modelling has thus been based on nosecone lengths of up to 1000mm.

Four vehicle configurations were modelled, at three different nosecone lengths, as shown in Table 6-3. The baseline vehicle was chosen to match that used in the main longer semi-trailers project, and the delta- C_D values were chosen to represent the MIRA and/or Scania results, as appropriate.

Vehicle	Overall length	Vehicle CD	Delta-CD
Baseline (Vehicle 1)	16.5m	0.500	0
500mm nosecone (V2)	17.0m	0.482	-0.018
1000mm nosecone, standard semi-trailer (V3)	17.5m	0.504	+0.004
1000mm nosecone, aerodynamic semi-trailer (V4)	17.5m	0.478	-0.022

 Table 6-3. Vehicle parameters for PHEM analysis

The addition of aerodynamic improvements would cause an increase in the weight of the vehicle. For the emissions analysis, it was assumed that the effects would be comparable to those of increasing the length of the semi-trailer reported by Knight et al (2010):

- Vehicle 2 a 500mm nosecone would increase the unladen weight by 125 kg;
- Vehicle 3 a 1000mm nosecone would increase the unladen weight by 250 kg;
- Vehicle 4 a 1000mm nosecone and trailer aerodynamic aids would increase the unladen weight by 375 kg.

The rationale above led to the selection of the input parameters defined in Table 6-4 below.

		Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
		(Baseline)	(500mm nosecone)	(1000mm nosecone)	(1000mm nosecone + aerodynamic trailer)
		Fully-laden			
Unladen weight	kg	13,543	13,668	13,793	13,918
Maximum payload	kg	26,457	26,332	26,207	26,082
Gross weight	kg	40,000	40,000	40,000	40,000
		Typical load			
Unladen weight	kg	13,543	13,668	13,793	13,918
Typical payload	kg	10,730	10,730	10,730	10,730
Gross weight	kg	24,273	24,398	24,523	24,648

Table 6-4. Vehicle specifications used in the PHEM analysis

6.2.3 Modelling results

Table 6-5 and Table 6-6 show the estimated emissions for each of the 4 vehicle types, expressed in terms of g/km of pollutant, and in terms of per tonne 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).

Table 6-5. Emission rates	for Euro 5	vehicles with	typical laden	weight
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	Emission rates						
	CO (g/km)	HC (g/km)	NO _x (g/km)	PM (g/km)	CO₂ (g/km)	FC (g/km)	Payload (kg)
Veh 1	0.094	0.012	2.41	0.021	729.1	230.0	10,730
Veh 2	0.094	0.012	2.38	0.021	723.5	227.3	10,730
Veh 3	0.094	0.012	2.42	0.021	734.0	231.6	10,730
Veh 4	0.094	0.012	2.38	0.021	727.3	228.4	10,730

Emission rates per tonne of payload

	CO (g/km/t)	HC (g/km/t)	NO _x (g/km/t)	PM (g/km/t)	CO₂ (g/km/t)	FC (g/km/t)
Veh 1	0.009	0.001	0.224	0.002	67.95	21.44
Veh 2	0.009	0.001	0.222	0.002	67.43	21.18
Veh 3	0.009	0.001	0.226	0.002	68.41	21.58
Veh 4	0.009	0.001	0.222	0.002	67.78	21.29

	Emission rates									
	CO (g/km)	HC (g/km)	NO _x (g/km)	PM (g/km)	CO₂ (g/km)	FC (g/km)	Payload (kg)			
Veh 1	0.101	0.012	3.12	0.022	1014.2	320.0	26,457			
Veh 2	0.101	0.012	3.10	0.022	1006.2	317.5	26,332			
Veh 3	0.102	0.013	3.12	0.022	1018.7	321.4	26,207			
Veh 4	0.101	0.012	3.10	0.022	1006.2	317.5	26,082			

Table 6-6. Emission rates for Euro 5 vehicles with maximum laden weight

Emission rates per tonne of payload

	CO (g/km/t)	HC (g/km/t)	NO _x (g/km/t)	PM (g/km/t)	CO₂ (g/km/t)	FC (g/km/t)
Veh 1	0.004	0.000	0.118	0.001	38.33	12.09
Veh 2	0.004	0.000	0.118	0.001	38.21	12.06
Veh 3	0.004	0.000	0.119	0.001	38.87	12.26
Veh 4	0.004	0.000	0.119	0.001	38.58	12.17

The analyses have estimated the emission rates for the vehicles with different aerodynamic packages (i.e. nosecone lengths and, for Vehicle 4 only, extra aerodynamic improvements to the semi-trailer) – 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 effects are very small. CO, HC and PM emissions are hardly affected by the changes. For NO_x , CO_2 and fuel consumption, there is a very small effect. Vehicles 2 (500mm nosecone) and 4 (1000mm nosecone plus aerodynamic trailer) both reduce NO_x , CO_2 and fuel consumption. However, Vehicle 3 produces a small increase. The best performing option overall was Vehicle 2 (500mm nosecone) with a 1.2% reduction in fuel consumption (per vehicle km and per tonne km) at a typical laden weight. However, this is reduced to an improvement of only 0.8% per vehicle km and just 0.25% per tonne km at maximum laden weight. This is because aerodynamic resistance is responsible for a smaller proportion of total power consumption at heavier weights and also because the additional unladen weight of the vehicle reduces the available payload.

These results may at first sight appear to run counter to other studies that have suggested much larger fuel consumption and emissions benefits from aerodynamic improvements, e.g. the 5% to 10% reported by the APROSYS project. It is important to note, however, that these generally refer to rigid vehicles. In this respect, the "cab only" drag coefficients modelled by MIRA may be a better indication of the potential effects of nosecones on rigid HGVs – with the substantial reductions in drag likely to lead to much larger reductions in fuel consumption and emissions than was the case with the articulated combinations. Other studies also tend to measure the fuel consumption only at steady cruising velocities, rather than the more realistic duty-cycle assessments used by PHEM for this project. Thus, the fuel used to accelerate the mass of the vehicle is ignored and this can actually be greater where the aerodynamic aid adds mass to the vehicle and this is not compensated by reducing the mass of goods carried (which also has implications for emissions through the number of journeys required.). There is, however, very good agreement between the PHEM analysis for this project and the Scania work, which suggests a 1% reduction in fuel consumption for the 1000mm nosecone at full GVW (40 tonnes).

7 Cost-benefit analysis

7.1 Analytical method

In order to provide consistency of analysis, the costs and benefits of safer aerodynamic fronts were based on the use of the same parametric cost benefit model used by Knight *et al* (2008) when assessing the likely effects of longer and/or longer and heavier vehicles and by Knight (2010) when comparing the results of that model to the results from the analysis of the likely effects of longer semi-trailers. This model is described in detail by Knight *et al.* (2008) but can be summarised as an aggregate model of predicted freight volumes in the UK from 2006-2020 including the following variables:

- Vehicle mass, payload and capacity
- Fuel consumption and emissions
- Operating costs
- Safety performance and accident rates
- Mode shift
- Infrastructure wear
- Route restriction

This analysis will consider the effect that safer aerodynamic front structures will have on the first four variables, the likely effects being very small on infrastructure wear, even smaller on mode shift (no change in capacity, marginal change in operating cost) and no additional route restrictions envisaged if such structures were to be implemented. The outputs are expressed in terms of:

- Effect on traffic (vehicle kms)
- Effect on emissions (tonnes of CO₂, societal cost of gaseous emissions from freight)
- Effect on safety (fatalities, monetary values for the prevention of casualties)
- Effect on total transport costs (total road/rail operating costs plus "external costs")

7.2 Input parameter selection

7.2.1 Possible policy options to be assessed

A wide range of possible policy options could be conceived based on the results of this work. However, the cost benefit model to be used and some of the outcomes described earlier in this report were not fully developed for rigid vehicles. Therefore, only application to articulated vehicles was considered in this cost benefit analysis. The intention is to isolate the effects of this measure from those of increasing trailer capacity and thus the baseline articulated vehicle will be assumed to be 16.5m long and the semi-trailer length will remain as 13.6m in all options.

Preceding sections of this report found that:

- almost all of the potential casualty benefits could be obtained at nosecone lengths of 0.9m or less
- The aerodynamic benefits were uncertain at lengths greater than 1m, being highly dependent on tractor trailer interaction

• Increases in length of more than 1m could potentially create significant manoeuvrability difficulties, depending on exactly how the change was implemented in the vehicle design

For this reason, the maximum length assessed in the cost benefit analysis was selected to be 1m. An interim length of 500mm will also be considered on the basis of the results of the aerodynamics and a further length of 200mm will be considered because it is the maximum that could be added to a combination using a 15.65m semi-trailer, if permitted, without exceeding the maximum length of existing drawbar trucks and articulated buses.

This leads to matrix of assessments shown in Table 7-1.

Additional length for nosecone	Standard semi-trailer aerodynamics	Optimised trailer aerodynamics
0.2 metres	\checkmark	×
0.5 metres	\checkmark	\mathbf{x}
1.0 metres	\checkmark	\checkmark

Table 7-	1:	Matrix	of	options	for	cost	benefit	assessment
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7.2.2 Vehicle mass, capacity, and average load

Little information exists to estimate exactly how much mass would be added by altering the front of vehicles as considered in this report. However, the manufacturing industry provided evidence (Knight *et al*, 2010) to suggest that increasing the length of a semi-trailer would add approximately 192kg to 250kg per metre on average. The mass implications of the safer aerodynamic front with standard semi-trailer have, therefore, been based on the upper figure in this range. It has also been assumed that the addition of an optimised package of aerodynamic aids for the semi-trailer would add a further 125kg.

In reality, nominally similar tractors and trailers from different manufacturers will have different masses. However, Knight et al (2010) found that the mass of a standard triaxle semi-trailer was typically approximately 6,350kg. Similar analyses for a two-axle tractor unit suggest a typical unladen mass of approximately 7,200kg for a baseline combination mass of 13,550kg such that the payload of a 5 axle combination would be 26,450kg.

When considering the effect that adding a safer aerodynamic front to a truck will have, it is important to understand what is constraining the loads carried. Load constraints can be defined as follows:

- 1. Full by mass (i.e. vehicle has reached GVW or will exceed GVW if one more load unit is put on the vehicle). CSRGT analysis suggests approximately 8% of articulated vehicle tonne kms are constrained by mass capacity.
- 2. Full by volume (no more space available within the truck even though GVW limits have not yet been reached). CSRGT analysis suggests approximately 36% of articulated vehicle tonne kms are constrained by volume capacity.
- 3. Full by both mass and volume. CSRGT analysis suggests approximately 31% of articulated vehicle tonne kms are constrained by both mass and volume capacity.
- 4. Loaded but not full. CSRGT data suggests that for approximately 25% of articulated tonne kms the vehicle carrying the goods is not full.

5. Empty. CSRGT data suggests approximately 27% of articulated vehicle kms involve vehicles that are not loaded.

On journeys where the vehicle is full by mass (1 and 3 above) then the additional unladen mass will mean that the quantity of goods carried will be reduced by the same amount in order to avoid exceeding the maximum authorised mass. Thus, the total loaded mass will not change. In theory this would mean all journeys in this condition will be at GVW but in practice the average will be slightly below GVW because most goods are divided into units of significant mass. For example if a 44 tonne vehicle was carrying 25 pallets of 1.15 tonnes each then the GVW would be approximately 43.3 tonnes, 0.7 tonnes below GVW. However, adding one more pallet to reach volume capacity would cause GVW to be exceeded by 0.415 tonnes and is therefore not possible. In order to transport the same quantity of goods additional journeys would be required.

On journeys where the vehicle is full by volume or not full (3, 4 or 5 above), then the additional unladen mass will not add any additional constraints on the load. However, the total loaded mass would increase by the amount of the increase in unladen weight, with consequent increases in fuel consumption and emissions.

Analysis undertaken to generate the model used by Knight (2010) showed that for all standard articulated vehicles the loading and constraints were as shown in Table 7-2, below.

Load		Percentage by		Laden vehicle	Empty running	Unladen	Average load when laden	Average load including empty running
constraint	Tonne kms	constraint	Vehicle kms	kms	(%)	vehicle kms	(tonnes)	(tonnes)
Weight	9,667,528,235	8.41%	369,642,044	369,642,044		0	26.154	26.154
Volume	41,316,957,528	35.93%	2,915,468,363	2,915,468,363		0	14.172	14.172
Both	35,608,202,359	30.96%	1,369,551,641	1,369,551,641		0	26.000	26.000
None	28,411,643,541	24.70%	5,995,662,827	3,406,704,002		2,588,958,826	4.739	4.739
All	115,004,331,663	100.00%	10,650,324,875	8,061,366,049	24.31%	2,588,958,826	14.266	10.798

Table 7-2: Load constraints and average	loads for existing articulated vehicles
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Altering the average load when laden for weight constrained trips, recalculating the vehicle kms required to transport the same tonne kms, increasing the empty kms in line with the increased laden kms allows the average load including empty running to be estimated for all trips once the changes to the weight constrained trips are accounted for. Adding this new average load to the new unladen mass allows the total mass to be calculated when the average load is being carried.

Table 7-3: Mass capacities and average loads for vehicles with safer fronts

		Maximum	Maximum	Average load	Total mass
	Unladen	Authorised	payload	including empty	at average
Description	mass (kg)	Mass (kg)	(kg)	running (kg)	load
Baseline 44 tonne 16.5m artic	14,533	44,000	29,467	10,798	25,331
Safer front 0.2m	14,588	44,000	29,412	10,790	25,378
Safer front 0.5m	14,658	44,000	29,342	10,777	25,435
Safer front 1.0m standard aerodynamics	14,783	44,000	29,217	10,756	25,539
Safer front 1.0m optimised aerodynamics	14,908	44,000	29,092	10,734	25,642

7.2.3 Fuel consumption and emissions

The changes to the mass of the vehicle and the aerodynamic drag each have an effect on the fuel consumed per vehicle km and the tailpipe emissions. These effects were modelled at full load and at a typical load as described in section 6.2. Knight et al (2008) showed that it was reasonable to use linear interpolation to assess the fuel consumption and emissions at masses between values modelled using this method. In this way the results shown in Table 7-4, below, were produced for use in the cost benefit model.

			Total							
	Unladen	Load	running							
	mass	mass	mass	CO	нс	NOX	PM	CO2	FC	
Description	(kg)	(kg)	(kg)	(g/km)	(g/km)	(g/km)	(g/km)	(g/km)	(g/km)	FC Index
Baseline 44 tonne 16.5m artic	14,533	10,798	25,331	0.094	0.012	2.413	0.021	730.138	230.328	1.000
Safer front 0.2m	14,588	10,790	25,378	0.094	0.012	2.399	0.021	727.483	229.073	0.995
Safer front 0.5m	14,658	10,777	25,435	0.094	0.012	2.382	0.021	724.215	227.528	0.988
Safer front 1.0m standard aerodynamics	14,783	10,756	25,539	0.094	0.012	2.421	0.021	734.398	231.725	1.006
Safer front 1.0m optimised aerodynamics	14,908	10,734	25,642	0.094	0.012	2.380	0.021	727.367	228.422	0.992

Table 7-4: Fuel consumption and emissions based on average load includingempty running

It should be noted that the fuel consumption and emissions were not modelled for a 0.2m extension to the front so the figures for this vehicle option are based on linear interpolation between the baseline vehicle and the 0.5m extension.

7.2.4 Operating costs

It is reasonable to assume that the addition of additional frontal structures would add to the capital cost required to purchase a tractor unit for an articulated vehicle. Knight et al (2010) estimated that increasing the length of a semi-trailer would cost in the region of \pounds 515/metre to \pounds 590/metre. This could be used as a guide to the possible cost of changes to the front of a tractor unit. However, this would be likely to represent a lower estimate because a semi-trailer is a relatively simple structure and the front of a tractor unit is more complex with potentially conflicting requirements for packaging space for components (e.g. lights) ventilation and cooling for the engine, and various different structural properties for safety. It is therefore considered reasonable to assume that the actual cost increase associated with a safer aerodynamic front would be 50% more per metre than for increasing the length of a semi-trailer, resulting in an estimate of approximately \pounds 830 per metre.

Hatfield (2010) developed cost models for a range of standard articulated vehicles. These models have been modified to incorporate the capital costs and fuel consumption estimates above to predict the operating costs for the vehicles equipped with safer aerodynamic fronts. The results are shown in Table 7-5, below.

		Fuel	Total	
	Purchase	consumption	costs per	Indexed
Description	price (£)	(g/km)	km (£)	costs/km
Baseline 44 tonne 16.5m artic	£63,000	230.328	£0.961	1.000
Safer front 0.2m	£63,166	229.073	£0.960	0.999
Safer front 0.5m	£63,415	227.528	£0.959	0.998
Safer front 1.0m standard aerodynamics	£63,830	231.725	£0.964	1.003
Safer front 1.0m optimised aerodynamics	£64,330	228.422	£0.961	1.001

Table 7-5: Estimated operating costs

7.2.5 Safety

A number of potential areas for casualty savings were identified:

- Car occupants in head on collisions
- Truck occupants involved in collisions with fixed objects and other heavy vehicles
- Vulnerable road users hit by the front of a truck

Casualty statistics show that between 2006 and 2008 inclusive there were on average approximately 188 fatalities from accidents involving articulated HGVs each year. Table 7-6 summarises the expected effect on fatalities and the fatality rate (number of fatalities per billion vehicle kms).

	Predicted a	nnual avera	ge fatality re	duction	_	
	Car	Truck	Fatality	Index fatality		
Description	occupants	occupants	road users	Total	rate	rate
Baseline 44 tonne 16.5m artic	0.00	0.00	0.00	0.00	13.174	1.000
Safer front 0.2m	0.70	0.25	4.00	4.95	12.828	0.974
Safer front 0.5m	1.50	0.30	7.50	9.30	12.523	0.951
Safer front 1.0m standard aerodynamics	2.00	0.50	12.00	14.50	12.158	0.923
Safer front 1.0m optimised aerodynamics	2.00	0.50	12.00	14.50	12.158	0.923

Table 7-6: Predicted casualty effects

7.3 Results

The results of the parametric cost benefit model are shown in Table 7-7, below.

		Magnitude of changes with respect to baseline											
					CO2	CO2	HGV	HGV					
		Cost	Number of	Fatalitie	Emissions	emissions	traffic	traffic					
Description	Cost (£)	(%)	Fatalities	s (%)	(tonnes)	(%)	(BVKM)	(%)					
Baseline 44 tonne 16.5m artic	£0	0.00%	0.00	0.00%	0	0.00%	0.00	0.00%					
Safer front 0.2m	-£18,706,989	-0.11%	-4.70	-1.17%	-28,551	-0.26%	0.01	0.04%					
Safer front 0.5m	-£30,549,084	-0.17%	-8.84	-2.20%	-61,091	-0.57%	0.03	0.09%					
Safer front 1.0m standard aerodynamics	£64,952,042	0.37%	-13.80	-3.43%	96,986	0.90%	0.05	0.18%					
Safer front 1.0m optimised aerodynamics	£43,474,359	0.25%	-13.80	-3.43%	21,460	0.20%	0.08	0.28%					

Table 7-7: Cost benefit analysis results (annual averages)

It can be seen that all safer front options result in a very small increase in traffic. This is because of the assumption that the safer front would add significant mass to the vehicle and be used on all articulated vehicles, including those carrying mass constrained goods. The payload capacity would be reduced for the latter class of traffic, thus generating additional vehicle kms to transport the same tonne kms. This additional traffic generates additional internal and external costs. In the case of the 0.2m and 0.5m extensions these additional costs are not as great as the reduction in costs arising from the safety and environmental improvements resulting in a net benefit for emissions, casualties and total costs.

The options to extend by 1m clearly provide the biggest safety improvement but also require the biggest mass increases and thus generate the most additional traffic. In the case of the standard trailer the safety benefits are insufficient to offset the disadvantage in terms of fuel consumption, emissions, operating cost, and traffic generation. The optimised aerodynamic trailer option restores the environmental advantage on a per vehicle basis but this is still insufficient to reverse the environmental disadvantage of increased traffic. The assumptions regarding the additional unladen mass are critical to this outcome and if the desired structures and performance levels could be achieved with little additional mass then this would become the most effective option.

On the basis of the inputs modelled, the 0.5m extension clearly offers the most benefit. However, it should be noted that increased traffic could lead to increased congestion and the societal cost of congestion is not included in the model. These costs will at least offset the net cost reduction currently indicated.

8 Discussion

The foregoing sections of this report have described the results of analyses to assess the likely casualty reduction, aerodynamic and fuel consumption benefits of additional nosecone structures and quantify the potential disbenefits from reduced manoeuvrability and payload capacity.

In casualty reduction terms, the analyses show the biggest casualty savings are for pedestrians; a 1m pedestrian-friendly nosecone applied to all tractor units would be likely, for example, to save 10 pedestrian fatalities per year in GB and 2 pedal cyclists. Designing a 1m nosecone just for truck to car/car derived van impacts would probably save 2 car/car derived van occupants per year, and designing purely for HGV to HGV impacts would be likely to save around 1 HGV occupant death every other year (assuming all HGV drivers wear seat belts).

When modelled under real-world duty cycle conditions, the aerodynamic effects on fuel consumption were found to be small. For modest nosecone lengths, small reductions in fuel consumption and emissions were evident, e.g. a 1% reduction with a 500mm nosecone. For longer nosecones there was found to be a trade-off between aerodynamic improvements to the tractor unit and the characteristics of the semi-trailer. The indication is that if a standard tractor unit is simply modified to include a nosecone (designed to give very good aerodynamic performance for the tractor), but it is then coupled to a standard semi-trailer, the overall vehicle drag (and, therefore, fuel consumption and emissions) may actually increase slightly. The effect seems to get worse as nosecone length increases. Conversely, if an articulated vehicle combination is designed as a single package, with optimised and matched aerodynamic features on both the tractor and semi-trailer, then longer nosecone lengths can produce reductions in whole vehicle aerodynamic drag, and not just in the drag of the tractor unit.

A very modest increase in length of just 0.2m would be enough to provide additional benefits to vulnerable road users. Two approaches could be conceived:

- an add-on design, in a manner similar to, the APROSYS safety-bar concept, which would be unlikely to compromise manoeuvrability to any significant extent, even if retrofitted to an existing vehicle. However, this would be expected to have no significant effect on car or truck occupant casualties, fuel consumption or emissions;
- An integrated design, providing a mildly shaped front which could potentially provide very small additional benefits for car occupants, reduced aerodynamic drag, fuel consumption and emissions.

The cost benefit analysis suggests that an integrated design would have a net monetary benefit of approximately £18.7m per year with reductions of approximately 29,000 tonnes (0.26% of articulated vehicle and rail freight emissions) of CO_2 , and 5 fatalities per year (1.2% of all fatalities from HGVs>3.5 tonnes). However, a small (0.01 billion vehicle kms, 0.04%) increase in HGV (>3.5 tonnes) traffic would be expected as a result of reduced payload capacity requiring additional HGV trips in some sectors.

An increase in length of 0.5m offers further benefits, but would have to be designed carefully to provide optimum protection, with different parts of its structure having different stiffness characteristics depending on whether protecting pedestrians, car occupants or the occupants of the HGV itself. Such a nosecone would be an integrated design shaped like a smaller version of the APROSYS optimised geometry to deflect pedestrians and pedal cyclists away from the front of the truck in an impact. It would have an outer skin of foam to absorb energy in those vulnerable road user impacts, and would also have crumple zones behind the foam and in front of the existing cab structure to better protect car and truck occupants.

The cost benefit analysis also suggested that this would have larger net monetary benefits of approximately £30.5million per year, including a reduction of approximately

61,000 tonnes of CO_2 (0.6%) and 9 fatalities (2.2%) despite a slightly greater increase in traffic (0.3 billion vehicle kms, 0.09%).

An increase in length of approximately 1m would allow an optimised safety approach with greatly improved field of view, an outer skin of foam to absorb energy in vulnerable road user impacts, and 0.8m crumple zone behind the foam and ahead of the front underrun protection to protect car occupants as well as 0.6m of crumple zone in front of the existing cab structure to protect truck occupants. At this length, some manoeuvrability difficulties would be likely to arise, but could be overcome with relatively straightforward modifications such as making the rearmost trailer axle selfsteered. Approach and ramp angles also need not be seriously compromised by such a length increase. The effects of such a nosecone on fuel consumption and emissions would be likely to be very small, and whether or not those effects were positive or negative would depend on the degree of aerodynamic optimisation of the tractor unit and semi-trailer combination, which is difficult to achieve in practice.

If it is assumed that the trailer aerodynamics were not optimised, then the cost benefit analysis suggests that there would be a net monetary disbenefit of approximately $\pounds 65$ million/year, despite a fatality reduction potential of approximately 14 (3.4%) per year. This is because:

- The unladen mass would be further increased, resulting in an increase in truck traffic of approximately 0.05 bvkms (0.18%);
- Combined with an increased purchase price and slightly increased fuel consumption this would lead to increased operating costs (0.64%); and
- Increased fuel consumption and emissions combined with increased traffic would result in an increase of approximately 97,000 tonnes (0.9%) CO₂ emissions.

Assuming that optimising the aerodynamics for the tractor and trailer in combination means that the fuel consumption and emissions advantage is restored on a per-vehicle basis but would be likely to require yet more added mass and reduced payload on mass constrained trips. This means that, with a net disbenefit of approximately £43.5m/year, the "per vehicle" benefits are not sufficient to outweigh the disbenefits of increased HGV traffic (0.08bvkms, 0.28%) resulting in a predicted increase in CO₂ emissions of approximately 21,000 tonnes (0.2%).

A 2.25m length increase would take a standard articulated vehicle (13.6m semi-trailer) up to the existing maximum permitted length (for drawbar combinations) of 18.75m. If that increase were applied solely to the front of the cab, the additional safety benefits over the 1m nose length would be limited to 1 or 2 more HGV occupant fatalities saved per year, which would be contingent upon all HGV occupants wearing seat belts. Manoeuvrability difficulties would be significant, with chamfering and a self-steered trailer axle (or other more sophisticated axle/bogie technologies) needed to allow compliance with 97/27/EC, and with front bumper ground clearances of more than 0.6m being needed to retain acceptable approach angles (which would compromise the front underrun performance). Aerodynamically, the effects of such a nosecone are difficult to predict and likely to be highly dependent on the aerodynamic characteristics of the whole vehicle combination. Coupling such a tractor unit to a conventional semi-trailer (rather than one designed to be aerodynamically highly efficient) could actually lead to increased fuel consumption and emissions. For these reasons further cost benefit analysis was not undertaken.

Based on the analyses above, the optimum length increase would appear to be in the region of 0.5m. However, the analyses have been based on a relatively small set of policy options and assumptions. Variations to these could substantially affect the overall outcome, for example:

- The analysis is based on a mandatory fitment to all articulated vehicles;
 - If the policy were to be extended to all rigid vehicles then the potential scope of casualty benefits could be doubled. The effect on aerodynamic drag would be simpler for such vehicles (no trailer interaction to be considered) but overall the effect of aerodynamics on fuel consumption is likely to be less because of differing duty cycles (more time accelerating and deceleration and less time at constant maximum speed)
 - One of the main disbenefits of a safer aerodynamic front would be the additional mass resulting in additional fuel consumption on volume constrained or unconstrained trips and reduced payload (and increased traffic) in mass constrained markets. While mass constrained loads are carried on a wide variety of different vehicles, a core part of this market could be approximately identified as being carried either by tipping or tank bodied vehicles. Excluding such vehicles from the requirement would prevent most of the additional traffic generation but would also reduce the scope of safety and aerodynamic benefits. Depending on the balance of these effects this might improve the overall net benefits.
- The analysis is based on simplistic estimates of the mass implication
 - Advanced engineering and materials may be able to offer similar effectiveness at reduced mass, which would improve the net benefits and, in particular, may make the 1m extension the most effective approach.
 - Protection for car occupants and truck occupants represents only a small proportion of the casualty benefits (e.g. 17% for the 1m extension), which are dominated by the effect on vulnerable road users. However, to produce these benefits requires heavy duty, energy absorbing structures which are likely to be responsible for a significant proportion of any mass increase. Removing the need to protect these groups with this measure (perhaps preferring advanced, lightweight, active safety measures such as Automated Emergency Braking Systems (AEBS) instead) might enable the structures to be added with a much reduced mass penalty. If so, the safety benefit would be reduced by about 15% to 20% but the environmental benefit may possibly be increased by more, potentially improving the net benefits.

9 Conclusions

- 1. A range of nosecone geometries and lengths (up to 2.25m, which would take articulated vehicles up to the existing maximum permitted length for drawbar combinations of 18.75m) have been analysed and modelled in various ways (based on towing a 13.6m semi-trailer), to quantify:
 - a. The energy absorption and casualty reduction potential in collisions with light vehicles;
 - b. The energy absorption and casualty reduction potential in frontal HGV impacts with other large, heavy vehicles and objects;
 - c. The energy absorption, impact kinematics, forward field of view and casualty reduction effects in frontal HGV impacts with pedestrians and pedal cyclists;
 - d. The effects on approach angles, ramp angles and ability to comply with the turning requirements of 97/27/EC;
 - e. The effects on aerodynamic drag, fuel consumption and emissions;
 - f. The overall costs and benefits of the defined options.
- 2. A 0.2m length increase could allow two different approaches:
 - a. An "add-on" approach where the front-end would be designed to protect pedestrians and other vulnerable road users (VRUs) in frontal impacts with articulated HGVs in a manner similar to the steel and foam "safety-bar" concept developed by the APROSYS FP6 project. This would be expected to save around 4 lives per year in Great Britain, have no significant effects on manoeuvrability or aerodynamics and minimal effects on traffic generation through reduced payload mass capacity. The limited benefit of this approach for vehicle operators (i.e. no aerodynamic effect) meant that it was not considered in the full cost benefit analysis.
 - b. An "integrated" approach where a mildly shaped and styled front end would be expected to save around 5 lives per year but could also produce small aerodynamic benefits at the cost of a small increase in unladen mass and a consequent small increase in HGV traffic for the same loads transported. This would be expected to produce net benefits (excluding congestion costs) of around £18.7million/year
- 3. An increase of about 0.5m would allow a shaped front end that could offer substantially improved field of view, deflect VRUs away from the front of the truck in an impact and have an outer skin of foam to absorb energy in collisions with VRUs. In addition to this it could have short sections of crumple zone intended to protect car occupants and truck occupants. This would be expected to reduce fatalities by about 9 per year at the same time as reducing fuel consumption and emissions per vehicle km. If appropriately shaped this would be unlikely to cause significant manoeuvrability difficulties. However, unladen mass and, thus, HGV traffic would be increased further. The net benefit, excluding congestion costs, would be expected to be around £30.5million/year.
- 4. An increase of approximately 1m would allow a front end that was optimised for safety in terms of field of view, VRU kinematics and energy absorption, and car occupant protection. It would also allow an improved capacity for HGV occupant protection. Some manoeuvrability difficulties would be likely but could be overcome with relatively straightforward modifications such as making the rearmost trailer axle self-steered. This would be expected to reduce fatalities by about 14 per year. However, other effects would depend on how the aerodynamics were controlled:

- a. If the optimised tractor towed a standard trailer there would be an increase in unladen mass and, thus, in HGV traffic. There would be very little effect on aerodynamic drag. The increased mass would combine with the increased traffic to produce a significant increase in emissions (e.g. c.97k tonnes of CO2), resulting in net costs of about £65million/year
- b. If the tractor and trailer aerodynamics were optimised as a combination then the aerodynamic drag would be improved as would the fuel consumption and emissions. However, this would be expected to require additional aerodynamic aids, and hence unladen mass, on the trailer, further reducing payload and generating additional HGV traffic. The beneficial effect on aerodynamics would not be expected to outweigh the disbeneficial effect of the mass resulting in a net annual cost of about £43.5million/year.
- 5. If a 2.25m length increase were applied solely to the front of the cab, the additional safety benefits over the 1m nose length would be limited to 1 or 2 more HGV occupant fatality savings per year. Manoeuvrability problems would be significant making compliance with Directives 97/27/EC (turning requirements) and 2000/40/EC (front underrun protection) difficult. Aerodynamically, the effects of such a nosecone are difficult to predict and likely to be highly dependent on the aerodynamic characteristics of the whole vehicle combination. Coupling such a tractor unit to a conventional semi-trailer (rather than one designed to be aerodynamically highly efficient) could actually lead to increased fuel consumption and emissions. The mass implications of such a front end are likely to be significant. For all these reasons the cost benefit of such a change was not analysed in detail.
- 6. The analyses were based on a limited set of policy options and assumptions of how the industry would react. A range of subtle variations would be possible and could influence the results. In particular, investigating the following possibilities could identify further optimisation of the concept:
 - a. Extending application of the policy to rigid goods vehicles
 - b. Restricting application of the policy to vehicles carrying loads not constrained by mass, possibly approximated by excluding tipping and tank bodied vehicles.
 - c. Removing consideration of requirements for car and truck occupants, potentially allowing lower mass solutions which may (or may not) improve net benefits when both safety and environment are considered.
 - d. Investigating the potential for advanced engineering and materials to offer solutions with a mass lower than that assumed in this analysis.
- 7. The results described above would be equally valid if semi-trailers of up to 15.65m in length were to be permitted, except for manoeuvrability where further analysis may be required if the overall combination length exceeded 18.75m. They are also based on applying the principles of safer aerodynamic fronts to articulated vehicles only. Further casualty reductions, particularly for vulnerable road users, could be achieved if the measures were also applied to rigid vehicles. This has been quantified in the main body of the report.

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Approximately 1% of all GB road vehicles are HGVs but they account for approximately 6% of all motor vehicle traffic and are involved in accidents resulting in approximately 15% of all road traffic fatalities. In 2000, freight trucks were responsible for approximately 23% of global transport CO_2 emissions, which in turn represented 14% of ALL global CO_2 emissions. Thus, freight trucks were responsible for approximately 3% of ALL global CO_2 emissions.

Most trucks are currently designed to maximise the load space that can be achieved within the legally permitted maximum dimensions. This usually means that the front of the truck approximates a flat vertical surface where the cab is positioned above the engine. This has disadvantages for aerodynamics, field of view and collisions with other road users. Re-designing the front of a truck to minimise these disadvantages could potentially offer significant benefits in terms of casualty and emission reduction.

The DfT decided that, in parallel with its research into the feasibility and likely effects of permitting longer semi-trailers, research should also be undertaken into the merits of allowing additional length, irrespective of load space, for the purposes of improved safety and environmental performance. This final report describes the study in full.

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