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Technical Report

Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses

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REVIEW OF AERODYNAMIC DRAG REDUCTION DEVICES FOR HEAVY TRUCKS AND BUSES

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EXECUTIVE SUMMARY

The purpose of this study is to better understand what technologies or practices can be applied to highway tractor and trailer combinations and highway motor coach buses to reduce aerodynamic drag without negatively affecting the usefulness or profitability of the vehicles. Additionally, it is of interest to determine how these devices may affect other vehicles and vulnerable road users in close proximity to the tractor trailers or buses.

Pertinent information relating to drag reduction was extracted from sources and summarized in this report. In general, the authors attempted to explain each technology or product and present or calculate the expected potential reduction in drag coefficient for a typical highway vehicle. Where applicable, any barriers to entry within the Canadian trucking community were explained to separate those technologies which could likely be used to those that would likely never gain widespread acceptance due to operational barriers

General

For heavy vehicles such as tractor-trailer combinations and buses, pressure drag is the dominant component due to the large surfaces facing the main flow direction and due to the large wake resulting from the bluntness of the back end of such vehicles.

Although friction drag occurs along the external surfaces of heavy vehicles, particularly along the sides and top of buses and trailers, its contribution to overall drag is small (10% or less) and is not a strong candidate for drag-reduction technologies.

For heavy-duty vehicles, such as tractor-trailer combinations, the drag coefficient increases significantly with yaw angle.

In cold Canadian climates, the aerodynamic drag in winter can be nearly 20% greater than at standard conditions, due to the ambient air density. For highway tractor-trailers and intercity buses, this results in about a 10% increase in fuel consumption from drag when compared to the reference temperature, further emphasizing the importance of aerodynamic drag reduction strategies for the Canadian climate.

Long Combination Vehicles

The results of one study indicated that an LCV's drag coefficient while pulling two trailers can be as little as 0.05 higher than a conventional vehicle pulling one trailer at 0 deg wind yaw angle. This number increases to 0.13 higher at a yaw angle of 5 degrees. Therefore, adding a second trailer to form an LCV, and thus doubling the freight capacity, results in a very modest increase in drag coefficient of approximately 10% at zero yaw angles and 22% at five degree yaw angles when compared to the single trailer vehicle. Or put in other terms, the drag coefficient on an LCV is only marginally more than half of the sum of the drag on the two vehicles it replaces when wind angles are at zero degrees.

As vehicle length increases, the percentage contribution to overall drag from friction drag rises slightly since there is so much more planar surface aligned with the wind, yet the blunt front face of the vehicle remains unchanged. A study concluded that the percentage contribution of pressure drag on the baseline vehicle was 93.3% whereas the contribution of pressure drag on the LCV was 91.7%. The significance of this is that as vehicle length increases, strategies to

reduce friction drag become more effective in reducing fuel consumption. However, it is clearly still more beneficial to reduce pressure drag, regardless of vehicle configuration. The authors of one study concluded that some vehicle combinations can show an increase of 40% in friction drag with only a corresponding increase of 8% in pressure drag. However, this is still 40% of a very small number, and 8% of a very large number but the fact remains that increasing vehicle length increases the relevance of frictional drag reduction strategies and has much less effect on pressure drag.

The size of the gap between the lead and trailing trailer plays a significant role in the amount of drag experienced by the combination vehicle, particularly at higher yaw angles.

It is estimated that one LCV would burn approximately 23,200 fewer litres of fuel when compared to two conventional vehicles, assuming an annual distance of 100,000 km at highway cruising speeds.

Large reductions in pressure drag can be achieved by using LCVs and these reductions are well documented and understood using European vehicles with fixed yaw angles. However, there are very little data pertaining to North American LCVs experiencing variable wind yaw angles corresponding to a yearly wind averaged drag. Wind tunnel testing could be used to quantify the drag reduction of a North American type LCV taking wind averaged drag into consideration.

There are still opportunities for incremental decreases on LCV drag. Further study could be performed on Canadian LCVs to better understand the relationship between gap size and drag to demonstrate if devices that are currently designed to be installed in the gap between conventional tractors and trailers could also be used between the two trailers of an LCV. And if so, what configuration would be best suited to optimize drag reduction between the two trailers of an LCV. This study could be performed at both gaps to quantify the incremental effect of add on devices, compared to the large reductions that are achieved via the removal of one of the tractors. Ideally, a study could be conducted whereby a variety of gap fillers, side skirts and boat tails are sequentially added to the LCV in order to determine if the effects of these devices on LCVs is similar to their effect on conventional vehicles.

Camera Mirrors

Canadian Motor Vehicule Safety Standards (CMVSS) compliant mirrors are responsible for approximately 2% of the overall drag on a conventional tractor and trailer. A study concluded that if a tractor’s two side mirrors were removed, the tractor would burn 938 fewer litres of fuel annually based on current fleet wide average fuel consumption values. Some manufacturers are currently designing prototype vehicles that use rear facing cameras and in-cab video screens that replace the side view mirrors. However, these systems cannot be used independently without mirrors, under the current CMVSS regulations.

A cursory review of in service tractors in Ontario confirmed that drivers are currently accustomed to using mirrors that are nearly three times larger than what is required under CMVSS regulations. Therefore, it is not likely that reducing the minimum amount of glass required under CMVSS would result in any drag savings since most drivers would be reluctant to reduce their field of vision from what they are currently using.

Side view mirrors are considered ‘fail-safe’ devices. Replacing side view mirrors with rear view cameras will most certainly reduce the mean time between failure (MTBF) of the tractors and could fail when a driver must quickly assess the traffic situation in the left hand lane. However, further work would be required to compare the MTBF of conventional mirrors versus the MTBF of a camera system.

Some drivers may require more time to adjust to the concept of looking to the right into a video screen, rather than looking left and right into mirrors, particularly when required to do so in the event of an emergency lane change.

The drag reduction potential of removing the side view mirrors is understood, quantified and well documented by lab testing therefore there would likely be little benefit to reproducing those tests. However, there seems to be little documented testing with regards to the performance and reliability of rear cameras and driver acceptance of their use. If this is an area Transport Canada wishes to pursue, NRC recommends developing a study to determine the benefits and drawbacks of side view mirror replacement for aspects other than the well known aerodynamic benefits. These would include, reliability and maintainability, the weight of the added devices, the need for redundancy, the speed at which the drivers can view objects in the left lane, and driver acceptance, particularly for those drivers who have been using mirrors for many years. If it was determined that side view mirrors could be removed without any negative safety side effects, it would be worthwhile to investigate a pilot project to better understand the potential fuel savings as well as any unforeseen logistical issues under actual revenue driving conditions.

The benefits of infrared cameras could also be studied to determine if they could be combined with camera mirrors to enhance the vision of the drivers during inclement weather or if they would be more of a distraction than a useful device.

Platooning

Several research studies have demonstrated that platoons can be effective at reducing the drag on all of the vehicles in the platoon, even the lead vehicles. However, the largest reduction in drag occurs for the vehicles between the first and last vehicle. It is estimated that vehicles in a platoon could experience between a 9% and 25% reduction in fuel consumption, depending on spacing, vehicle speed, vehicle position and vehicle mass.

It is clear that platooning requires significant changes to the road infrastructure and would also require a significant change in driving behaviour for drivers in other vehicles who are surrounding the platoon but not actually in the platoon.

Although platooning appears to have a great potential to reduce aerodynamic drag it does not appear to be a practical solution to Canadian trucking in the near future due to the size of Canada's road network and the immature status of the technology. There are too many logistical and infrastructure barriers that must be overcome to make this a viable concept for the near future. Even if technology could allow two or more heavy vehicles to be electronically connected, the logistics of integrating these vehicles into existing traffic flows would prove to be extremely difficult. Further testing and understanding of the recently adopted LCVs would be a more practical approach to multi vehicle aerodynamic reductions until platooning has been perfected in smaller countries in Europe.

It would appear that many of the research studies focused on vehicles that were lighter than typical heavy vehicles found in Canada. The results of platooning can be more favourable when using lighter vehicles since a higher percentage of fuel consumption can be attributed to aerodynamic effects. The effects of platooning with vehicles loaded to the maximum Canadian legal weight would provide more useful information about the potential for platooning on Canadian roads.

Given the complexity of platooning and the relative simplicity of LCVs, it would be useful to quantify the differences in fuel consumption reduction from vehicles in a platoon versus an LCV. The study could begin by comparing an LCV against a two vehicle platoon and then against platoons with increasingly higher numbers of vehicles.

Tractor and Trailer add-on Devices

Trailers and tractors are not always owned by the same operators therefore there may be reluctance on the part of trailer owners to pay for devices that will benefit the tractor owners.

The results of aerodynamic testing on heavy duty front bumpers have been scattered with some results showing modest reductions and some showing modest increases in fuel consumption. Similarly, modest aerodynamic improvements may be achieved with the use of wheel covers and slotted mudflaps.

Superhydrophobic coatings could be used to reduce the likelihood that water and ice could build up on a trailer. However, this technology remains largely un-tested on road vehicles.

Base bleeding has been shown to reduce drag in laboratory settings, however, the need for electrical devices (which then become an electrical drain on the charging system and thus a parasitic loss to the engine) to provide airflow and the need to tune the ducting of passive systems makes base bleeding a much less practical alternative to drag reduction.

Cab underbody treatments have been shown to decrease the aerodynamic drag of tractors, however, testing should be performed using a rolling road type wind tunnel to quantity these effects.

It has been shown that the tractor-trailer gap begins to have a significant impact on vehicle drag once it is greater than about 0.45m, with the drag increasing by about 2% for every 0.25 m of increased gap beyond approximately 0.75 m. Research has suggested that by completely addressing the tractor-trailer gap issue, drag savings on the order of about 6% could be achieved for a typical tractor-trailer. This would amount to an approximate 3% improvement in fuel consumption at 98 km/h (60 mph). At least one manufacturer is developing a tractor fifth wheel that would move longitudinally to effectively reduce the tractor-trailer gap at high speed.

Several manufacturers have commercial products for the gap regions on the market today that claim fuel savings on the order of 2%. The percentage savings are, however, highly dependent of the test procedure chosen, including initial tractor-trailer gap size, and test speed.

Numerous academic studies have investigated the potential fuel saving effects of tractor-trailer gap devices. It is, however, appropriate to first investigate the theoretical maximum benefit of completely closing the gap. Studies have suggested that the upper limit of aerodynamic improvement expected was in the range of a 7% drag reduction. At a typical speed of 55 mph, this would translate to an approximate 3.5% fuel saving.

Recently, Mercedes introduced a concept trailer that is reported to provide an 18% reduction in drag for a full European tractor-trailer combination (consist of a cab-over tractor).

Side skirts are used to prevent air flow from entering the under-trailer region. In recent years, these have been widely adopted and are commonly observed on many trailers. Fuel consumption reductions on the order of 3-7% have been reported.

Side underbody boxes have also been shown to reduce drag by as much as 10% to 15% and can be used to store equipment that would normally be strapped to the outside of the tractor or the underside of the trailer. Side underbody boxes could also be used in place of traditional side guards. However, they add weight to the trailer and could also affect the breakover angle as trailers pass over railroad tracks and other obstacles.

Wind-tunnel and road tests have demonstrated that a boat tail with a length of 24 to 32 inches is optimal for drag reduction purposes and typical length restrictions. As with side skirts, the interaction of boat tails with other devices is important for optimization.

Currently, limited evidence exists in peer-reviewed scientific sources to indicate that vortex generators have a significant impact on fuel savings for heavy vehicles.

Retractable trailers (i.e. trailers whose height reduces by a wide margin) are being prototyped in Canada but testing has yet to be performed to quantify the potential for drag reduction.

Aero-tractor models provide a reduction in aerodynamic drag, over the classic style, on the order of 30%. This is accomplished primarily through rounding of the front surfaces, the use of roof air deflectors, and the use of fairings over the fuel tanks between the steering axle and the drive axles.

It is suggested that all the tractor and trailer add on devices described in this report could be worthy candidates for further study with the exception of the base bleed devices and active flow control technologies. Furthermore, an integrated study of all the devices could be made to ensure that the aerodynamic gains of one device does not reduce the aerodynamic performance of another device installed downstream on the vehicle.

The suggested process would involve scaled wind tunnel tests involving the sequential addition of each device until the vehicle was equipped with all of the above mentioned devices. Following that preliminary stage, full scale prototypes could be developed and tested in real world driving situations, or controlled track testing. Application to different trailer types (dry van, tanker, flatbed with and without representative cargo) should also be evaluated to identify the benefits to the overall transportation industry.

In order to best serve the trucking community, and meet overall fuel consumption improvement goals, it is suggested that effort be focused more on developing tractor-based drag-reduction solutions. That said, there is still a strong benefit to trailer based devices such as side skirts and boat tails due to their demonstrated drag-reduction potentials.

In any of these future studies, the approach should first be to understand the operational concerns and barriers to commercial entry, prior to undertaking any aerodynamic experimentation or simulation.

Aerodynamic Devices for Buses

The applicability of aerodynamic add-on devices for use on long haul intercity motor coach buses has been less well studied than those of class 8 tractor trailers. The North-American bus fleet is much smaller than the tractor-fleet and consequently, the annual fuel consumption and GHG emissions by intercity buses are significantly lower.

A typical highway coach exhibits a number of aerodynamic advantages over a class 8 tractor-trailer: there is no tractor-trailer gap; the body comes lower to the ground effectively incorporating side skirts; and a flat front end eliminates the multiple aerodynamic discontinuities typically caused by radiator-hood, hood-windscreen and windscreen-fairing locations. Consequently, a stock long haul highway coach may have a C_D as low as 0.384.

By virtue of its lower ratio of rolling-to-aerodynamic resistance (the drag density parameter), the aerodynamic losses of an intercity bus outweigh the mechanical losses at a significantly lower vehicle speed than for a tractor-trailer. For a given percent-reduction in drag coefficient, the net percent-reduction in fuel consumption is larger for a bus than it is for a tractor-trailer.

The dominant contribution to the aerodynamic drag of an intercity bus is the pressure differential between the forward- and rearward-facing surfaces of the body, with a minimal contribution from skin friction.

About 60 to 70 percent of the total wind-averaged drag of a bus is attributed to pressure loads acting on the vehicle forebody, making it the principal area for drag reduction strategies. By far the most efficient method of reducing forebody drag is to minimize flow separation by combining the rounding of the forward corners (sides and top) with the tapering of the forebody.

Underbody aerodynamics is becoming increasingly important, in the quest to reduce fuel consumption of surface vehicles. Wind tunnel tests showed a drag reduction reaching about $\Delta C_D \approx -0.012$, as a result of the underbody panels. In addition, it was found that streamlining the wheels with hub covers further reduced C_D by 0.022. Although the undersides of buses are already quite aerodynamically ‘clean’, research could be conducted to investigate channeling the underbody flow towards the vehicle rear end. Air must be diverted into the engine for cooling purposes and this can be a significant Bus undersides with minimal obstruction could provide the opportunity to utilise the kinetic energy of the flow to enhance the efficiency of engine cooling (partial RAM effect), and/or direct this channeled flow into the wake region.

Finally, an area of possible aerodynamic benefit is by re-profiling the roofline. As coach buses do not have the same cargo capacity constraints, it is believed that the rear roofline could be modified with minimal impact to passenger comfort. Operational issues should not be a concern.

Given the secrecy characterizing the bus industry, it is clear that the optimization process taking into consideration aerodynamic performance objectives and operational constraints would remain the responsibility of the Canadian bus manufacturers. In this respect, and outside the scope of this program, the NRC and Transport Canada could contribute, upon client request, to this process as an advisor providing aerodynamic expertise and guidance to the industry.

An area that could require further investigation within the context of the ecoTECHNOLOGY for Vehicles II program, is a *recommendations document* to Canadian bus manufacturers and operators that can help guide their development and selection efforts, respectively, towards reducing the fuel consumption and emissions from intercity buses. Such a document can be based on information contained within this report.

Snow and Ice Accumulation and Shedding

Very little information could be found regarding test or modeling results of how ice and snow can accumulate on aerodynamic devices.

Boat tails can significantly affect the flow field directly behind a van semi-trailer and it is also expected that snow could accumulate on top of the bottom boat tail panel. However, very little relevant work could be located to quantify how this change in flow field would affect vehicles following behind a trailer equipped with a boat tail or the way in which snow and ice accumulates and sheds from truck aerodynamic devices.
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NRC-CSTT recommends performing a similar study to the NRC-IAR study in which many aerodynamic devices were sequentially added to a tractor and trailer combination. However, for this study, the emphasis would be on ice and snow accumulation and shedding, rather than aerodynamic drag. Ideally, a scale model vehicle would be placed in a high speed wind tunnel at sub zero temperatures and snow and ice would be blown against the model vehicle. The amount of snow accumulation and shedding could be measured against a baseline vehicle that was placed beside the test vehicle. Downstream effects on a scale model passenger car following the trailer could also be monitored to determine if the snow and ice would be more likely to accumulate on a trailing vehicle and also to determine if the forward vision of drivers in trailing vehicles is affected in any way.

Ultimately, track testing or road testing on actual highway tractor trailers could be performed to determine if devices such as boat tails were likely to accumulate amounts of snow that could eventually become ejected onto the road surface or other vehicles in the surrounding area.

Scale Model Testing

Aerodynamic drag is a dissipative, non-recoverable loss of energy and is one of the most important factors for reducing fuel consumption and emissions of heavy vehicles. Significant drag reduction can be obtained with current and emerging technologies, but the uptake is generally slow due to the requirements from operators for a timely return on their investment. Typical evaluation strategies by device developers and manufacturers can be skewed and not very representative of real-world conditions, which is one of the reasons operators can be hesitant towards new technologies. The industry therefore needs guidance in selecting appropriate technologies that will provide a net benefit to the reduction of fuel consumption and emissions in Canada. Similar to the EPA Smartway program in the US, certification of technologies is a good approach to providing the industry with such guidance.

Based on the information described in this report, the NRC recommends a systematic evaluation of the drag reduction potential for standard and proposed drag-reduction technologies for tractor-trailer combinations. This plan would provide Transport Canada with recommendations for the most effective combinations of drag reduction technologies for reducing the fuel consumption in the transport industry. Combined with consideration of operational requirements, recommendations for best-use technologies can then be provided to the transportation industry. The plan, summarized below, will be similar to the test program performed at NRC in collaboration with NRCan, the Canadian Trucking Alliance, and the US Department of Energy, for which reliable estimates of fuel savings can be made. This new plan, based on scale-model wind-tunnel testing rather than full-scale testing, encompasses additional drag reduction technologies and will provide much improved simulation of the environment in which heavy vehicles operate in Canada. The benefit of scale-model testing over full-scale testing is the ability to provide a more representative environment (relative vehicle/ground/wind motions and terrestrial winds) as well as the ability to test equivalent full-length vehicles and long-combination vehicles. This scale-model testing provides much improved accuracy over past wind-tunnel campaigns. Another strong benefit of wind tunnel testing is the precision with which comparisons between technologies and configurations can be compared, by means of a systematically-controlled test environment.

Collaboration with operators, original equipment manufacturers (OEMs) and device manufacturers can provide a thorough evaluation of such technologies. The NRC already has partners in the transportation industry that would be open to collaboration through the provision of specifications of tractor-trailer and device geometry for model manufacturing.

An overview of a proposed plan for the aerodynamic evaluation of drag-reduction technologies is as follows:

- Using aerodynamic measurements from wind-tunnel and track-test programs undertaken with various collaborators and partners (with permission), the potential impact of performing tests at lower than full-scale Reynolds numbers will be assessed. An optimized model scale (between ¼ and ½) for tractor-trailer combinations will be selected to best provide accurate results from an evaluation of drag reduction technology.

- Design the infrastructure to test scale models of North-American tractors and standard trailers (40 ft and 53 ft equivalent dry van, flatbed, tanker, long-combination vehicles). These models would be designed to accommodate a multitude of body shapes and drag-reduction devices/concepts to be evaluated. The models would be designed to be used with the ground-effect simulation system of the NRC 9 m x 9 m Wind Tunnel. This system provides a correct and important simulation of the relative motion between the vehicle, the terrestrial winds, and the ground.

- Design, development and fabrication of a turbulence-generation system to provide representative conditions that are encountered by tractor trailers under real road conditions. Turbulence has been demonstrated to be an important factor, generally neglected, when evaluating the drag-reduction potential of new technologies. Section 11.3 describes the requirements for this development project.

- Wind tunnel test program in the NRC 9 m x 9 m Wind Tunnel to evaluate the aerodynamic, and possibly the aero-acoustic (see Section 11.4) performance of drag reduction devices and vehicle combinations using the scale-model heavy vehicles. This program would consist of evaluating the performance of the drag-reduction technologies under smooth and turbulent-flow conditions, with and without ground simulation, to provide a correlation with other wind tunnel test programs that have already demonstrated some of the technologies under conditions with smooth flow and minimal or no ground-effect simulation.

- Dissemination of results and recommendations for optimum drag reduction combinations in the Canadian context, through reports and through presentations to the heavy truck industries at appropriate conferences and meetings. These results will be more representative in regards to fuel-reduction-potential than even the standard recommended methods to evaluate heavy-vehicle aerodynamic performance now required by the US EPA.

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ACKNOWLEDGEMENTS

The authors would like to thank the members of the NRC Library, CISTI, who searched for the relevant documents that ultimately formed the reference set for this report.

1 INTRODUCTION

1.1 Purpose

The Canadian Government is currently studying ways in which greenhouse gas emissions (GHG) may be reduced from all sectors, including the transportation sector and is committed to developing GHG reducing strategies that are aligned with those of the United States. The purpose of this study is to better understand what technologies or practices can be applied to highway tractor and trailer combinations and highway motor coach buses to reduce aerodynamic drag, and hence GHGs, without negatively affecting the usefulness or profitability of the vehicles. Additionally, it is of interest to determine how these devices may affect other vehicles and vulnerable road users in close proximity to the tractor trailers or buses.

Not all of the research presented in this report stems from work performed at the National Research Council of Canada. Rather, it is a compendium of current, relevant work from around the world and described here to better understand what technologies could legitimately be used within the current Canadian trucking industry, Canadian climates and network of roads and vehicular regulatory framework.

1.2 Limitations

Many bodies of work report drag reduction in terms of the amount of fuel that could potentially be saved annually. However, many assumptions regarding vehicle speed, distance driven per year and baseline engine fuel consumption must be made in order to estimate the relationship between drag coefficient (C_D) and fuel consumption for any particular vehicle. For this reason, most of the data in this report are presented in terms of drag reduction, which can be measured directly as an absolute figure, without the need for any duty cycle information or assumptions. The potential fuel consumption reductions stemming from reductions in C_D may then be calculated for individual vehicles if the parameters surrounding that vehicle's operating environment are well understood

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2 METHODOLOGY

The authors reviewed the list of current and previous projects undertaken at the NRC and summarized the methods and results from those projects, where relevant. The authors then devised and forwarded search criteria for the NRC-CISTI librarians to retrieve data for projects that had not been performed at the NRC. The librarians then performed searches for technical journals, presentations, academic papers and theses and retrieved electronic copies of all relevant documents. These documents were then forwarded to NRC-CSTT to be reviewed by the authors. Pertinent information was then extracted from the sources and summarized in this report. In general, the authors attempted to explain each technology or product and present or calculate the expected potential reduction in drag coefficient for a typical highway vehicle. Where applicable, any barriers to entry within the Canadian trucking community were explained to separate those technologies which could likely be used to those that would likely never gain widespread acceptance due to operational barriers.

The facts from the research were then amalgamated and conclusions were formulated and presented. Finally, recommendations were written to describe what further study, if any, could be performed in order to refute or validate some of the claims found in the literature search or to identify any un-published negative operational side effects from the device(s) or technology. Where possible, the recommendations were written to assist Transport Canada in assessing which products would have the greatest potential to reduce drag and what testing would be required to quantify those savings for vehicles that are relevant to Canada. Products that showed no appreciable potential to reduce drag or that were deemed impractical for use in Canada were excluded from the list of recommended products.

3 THEORY OF HEAVY VEHICLE AERODYNAMICS

3.1 Aerodynamics of road vehicles

The aerodynamics of road vehicles is a complicated discipline and many specific topics are outside the scope of this project. However, some of the facts relevant to the transportation industry, particularly pertaining to heavy trucks and buses, are presented in this chapter to familiarize the reader with the terminology and concepts.

The discipline of aerodynamics deals with the motion of air around and through a body and the interactions associated with this relative motion between the air and the vehicle system. The aerodynamic properties of a road vehicle include effects on its performance, handling, safety, and comfort [1]. In the context of this report, performance is the critical issue, and in particular the effect of aerodynamic drag (loads in line with the vehicle motion) and its effect on fuel consumption.

3.2 How fuel is consumed in a heavy truck

Fuel is consumed by a vehicle's engine as it travels on the road, with engine power output contributing to five primary factors, as listed in Table 1. Depending on the duty cycle of the vehicle (e.g. urban driving with low-speed stop-and-go traffic, or highway driving at constant high-speed), the contributions to fuel burn of these five factors change in proportion to one another as identified in Table 1. For example, in an urban environment the power dissipated through acceleration and braking of the vehicle is the dominant loss, whereas on the highway the aerodynamic losses are dominant. Lightweight hybrid vehicles with energy-recovery braking systems are potentially a good solution for reducing fuel consumption under urban environments, as proposed for urban-specific vehicles such as transit buses [2]. For the highway environment, in which most commercial goods are shipped, aerodynamic losses which are dissipative and cannot be recovered are the dominant source for power and fuel consumption. Motor coaches, which predominantly travel between major city centres, show a similar power loss-breakdown to the highway conditions on Table 1, but with a greater proportion dissipated through aerodynamic losses due to the lower rolling resistance associated with lower vehicle weight. The reduction of aerodynamic losses is a significant area in which fuel consumption improvements can be made.

Table 1 – Engine Power Balance for Fully-Loaded Class 8 Tractor Trailer (adapted from [2])

Source	Urban	Highway
Drivetrain	10-15%	5-10%
Inertia/braking/grade	35-50%	0-5%
Rolling Resistance	20-30%	30-40%
Auxilliary Loads	15-20%	2-10%
Aerodynamic Losses	10-25%	35-55%

The percentage contribution to fuel burn for each of the five categories varies from vehicle to vehicle, and varies with vehicle speed since the effects of aerodynamics are not linear, as is described in the next section. The contribution to fuel burn from internal losses is generally modeled as a constant, and acceleration/braking/grade portion can be modeled through a duty cycle.

3.3 Aerodynamic Drag

Aerodynamic drag is the force that resists the movement of a body through a fluid medium. Aerodynamic drag varies with the square of the relative speed U_∞ between the vehicle and the surrounding air. When a vehicle travels through still air, doubling the vehicle speed approximately quadruples the aerodynamic drag. In the presence of terrestrial winds that are not in-line with the vehicle motion, cross winds generate a non-zero yaw angle of the wind relative to the vehicle travel direction. For heavy-duty vehicles, such as tractor-trailer combinations, the drag coefficient increases significantly with yaw angle.
The drag force on a vehicle may be calculated as follows:

$$F_D = \tfrac{1}{2}\rho U_\infty^2 C_D(\psi_\infty)A \qquad [1]$$

where:

- F_D is the drag force;
- ρ is the density of the air;
- U_∞ is the speed of the object, relative to the surrounding air;
- ψ_∞ is the effective yaw-angle of the surrounding air relative to the vehicle motion;
- $C_d(\psi_\infty)$ is the drag coefficient, which varies with yaw-angle; and
- A is the projected frontal area of the vehicle.

To account for typical cross winds, a wind-average-drag coefficient can be defined that represents an average drag coefficient based on the predominant winds for a given region (typically an 11 km/hr (7 mph) wind speed in North America). The mathematical details are not presented here for conciseness but they can be found elsewhere [1], [3].

The non-linearity of drag with wind-speed is what accounts for the disparity in the aerodynamic contributions to power consumption between urban and highway environments shown Table 1. In general, the mechanical losses in the system vary linearly with vehicle speed. At 53 km/h the power required to overcome mechanical resistance is approximately double that required to overcome aerodynamic drag. At 80 km/h, the power necessary to overcome aerodynamic drag is roughly equal to the mechanical losses, and for higher vehicle speeds the aerodynamic losses dominate. Table 2 illustrates the contributions to fuel consumption at various constant speeds (i.e. no acceleration), assuming a zero grade and properly inflated tires etc and assuming that the internal power train losses can be modeled as a linear function of vehicle speed.

Table 2 – Example of the distribution of power consumption at various speeds (adapted from [2])

Vehicle Speed	Aerodynamic	Rolling & Accessories
32 km/h (20 mph)	28%	72%
53 km/h (33 mph)	33%	66%
64 km (40 mph)	36%	64%
80 km/h (50 mph)	50%	50%
96 km/h (60 mph)	62%	38%
105 km/h (65 mph)	67%	33%
113 km/h (70 mph)	70%	30%

Since aerodynamic drag is but one source of fuel consumption, it is important to understand its effects on overall fuel consumption. At 80 km/hr, a 20% reduction in drag will contribute to about a 10% reduction in fuel consumption. These fuel savings would rise as speed increased to a value of approximately 15% at 120 km/h. Examples like these are over-simplifications of higher-order engine specific calculations; however, they do provide a way to estimate the contribution to fuel burn from aerodynamics at various vehicle speeds.

In equation 1 above, the drag coefficient is represented in a simple manner as a function of wind angle alone, shown as the function $C_D(\psi_\infty)$. In reality, the drag coefficient is a function of a number of factors related to the vehicle and the environment in which it operates, as follows:

Major vehicle-specific influences on drag coefficient:

- Tractor design (classic or aero-style, day-cab or sleeper, etc.);
- Trailer configuration (dry box, flatbed, tanker, etc.);
- Gap region between tractor and trailer; and
- Appendages (mirrors, deflectors, external air filters, lights, skirts, etc.).

Major environmental influences on drag coefficient:

- Air properties (barometric pressure, temperature, humidity);
- Terrestrial winds (which change with height)
  - o Speed;
  - o Direction; and
  - o Turbulence (intensity, length scales, spectra).

The intent of this report is to document and recommend devices and techniques that can provide a reduction in the wind-averaged drag for heavy vehicles. The wind-averaged drag is the most important metric for evaluating vehicle drag because some drag-reduction technologies improve aerodynamic performance only for a subset of wind angles (typically centered on zero yaw) and therefore an averaged measure of the effects from representative wind conditions is more accurate and relevant.

There are two components of drag that affect a moving object:

- Pressure drag is the component of drag that acts in the direction of motion as a result of the pressure forces acting on the body.

- Friction drag is the component of drag that acts parallel to a surface as a result of shear and viscous effects in the flow adjacent to the body surface.

For heavy vehicles such as tractor-trailer combinations and buses, pressure drag is the dominant component due to the large surfaces perpendicular to the main flow direction and due to the large wake resulting from the bluntness of the back end of such vehicles. The pressure forces acting on the front and back face of the vehicle, as well as in the gap region between a tractor and trailer, are dominant. The large empty spaces in underbody regions of tractor-trailer combinations also contribute to the pressure drag. The cooling flows through a vehicle engine compartment are also dominated by pressure-drag effects.

Although friction drag occurs along the external surfaces of heavy vehicles, particularly along the sides and top of buses and trailers, its contribution to overall drag is small (10% or less [4]) and is not a strong candidate for drag-reduction technologies. Unlike flight vehicles that have streamlined bodies for which friction drag is the dominant contribution, road-vehicle aerodynamics is predominantly concerned with pressure drag and therefore the large body of knowledge concerning drag-reduction for flight vehicles is not strictly applicable to the road-vehicle and ground-transportation industries.

All combination vehicles are different, but in general terms, at zero yaw, the drag on the tractor accounts for approximately 70% of the total drag and the trailer accounts for the remaining 30% of the drag. However, at yaw angles in excess of 5 deg the tractor drag component increases very little but the trailer drag increases substantially such that it can exceed that of the tractor [1].

Aside from saving fuel, there are other potential benefits to reducing drag such as improved aerodynamic stability and reduced splash and spray.

3.4 The Effect of the Canadian Climate on Drag

Air density is another factor that can affect drag, as was shown in Equation 1. As temperature drops, the density of the air increases which increases the drag on a vehicle. This can cause significant changes in drag on a vehicle in climates such as Canada where temperature differences of 60 degrees Celsius can occur in the same location when comparing July conditions to, say, February conditions. Table 3 illustrates the approximate increase in drag at various temperatures when compared to the reference temperature of +15 °C.

Table 3 – Percent increase in drag at various temperatures

Temperature (°C)	% increase in drag
+15	0
0	5.5
-15	11.6
-30	18.5

In cold Canadian climates, the aerodynamic drag in winter can be nearly 20% greater than at standard conditions, due to the ambient air density. For highway tractor-trailers and intercity buses, this results in about a 10% increase in fuel consumption from drag when compared to the reference temperature, further emphasizing the importance of aerodynamic drag reduction strategies for the Canadian climate.

3.5 A Brief history of aerodynamics for heavy vehicles

The focus of recent drag-reduction-technology evaluation for tractor-trailer combinations has been concerned with second-generation drag-reduction devices. First generation drag-reduction devices, developed in the 1970s and 1980s consisted primarily of aerodynamic shaping devices for the tractor. Faired hoods and bumpers, air fairings/deflectors, and tractor skirts were the primary technologies that have led to the current "Aero Tractors" that have become the dominant models from the tractor manufacturers. These technologies provided a reduction in aerodynamic drag on the order of 30%, relative to the "Classic Tractor" designs [5]. These first-generation techniques have also been applied to some extent for motor coaches to minimize the pressure drag at the front end of the buses.

The second generation of drag-reduction technologies for tractors-trailers is primarily directed at lowering the drag associated with the trailer as well as the aerodynamic interactions between the tractor and trailer. In 2005 and 2006, as part of a collaboration with the NCRCan and the US Department of Energy (DOE), the NRC evaluated several commercially-available second-generation aerodynamic drag-reduction devices to demonstrate their effectiveness at reducing fuel consumption and to evaluate typical investment return periods for such devices [6], [7]. The tests were conducted on a full-scale tractor-trailer combination in the NRC 9m x 9m Wind Tunnel with 28 ft and 40 ft trailers. They focused on the three main areas of concerns for second-generation drag-reduction technologies:

- Tractor-trailer gap;
- Trailer underbody and bogie; and
- Trailer base.

Since those studies were reported, some of the technologies have been introduced and are in use in the North-American transportation industry. Trailer side skirts are commonly observed on highway tractors-trailer combinations, and boat-tail technologies are coming to market and are being evaluated by trucking fleets. Details of these technologies will be discussed in later chapters of this report. A multitude of other proposed technologies are discussed in later sections as well, along with an evaluation of their potential impact to the transportation industry.

The advancement of aerodynamic drag reduction for buses is less mature and has been developed mainly through proprietary means by the manufacturers themselves. Many of the lessons learned through tractor-trailer drag reduction can be applied to bus aerodynamics.

3.6 Recent programs, findings, and recommendations

There is a wide range of technology currently available or under development that could provide significant drag reduction of tractor trailers. In recent years, several programs in Canada, the Unites States, and Europe, have been looking at evaluating drag-reduction devices for the transportation industry. Those programs that have provided the most input in preparing this document are:

- The US Department of Energy (DOE) has been funding heavy-vehicle drag reduction technologies for nearly a decade through various programs. The DOE Consortium for Heavy Vehicle Aerodynamic Drag Reduction released many of its findings in 2006, funded by the DOE Energy Efficiency and Renewable Energy – FreedomCAR and Vehicle Technologies Program. NRC was a collaborator on this program. A recent full-scale wind-tunnel test program at the National Full-Scale Aerodynamics Complex (NFAC) Ames Research Center was part of the DOE Energy Efficiency and Renewable Energy – Vehicle Technologies Program. These programs consist of partnerships between the US government, manufacturers and operators [8], [9].

- NRC's collaborative contribution to the DOE Consortium program above was part of a Canadian partnership between NRC, Natural Resources Canada (NRCan), and the Canadian Trucking Alliance (CTA). This program, called "Truck Fuel and Emissions Reduction Program" involved small-scale wind-tunnel testing, full-scale wind-tunnel testing, and track testing of second-generation drag reduction devices available at the time [6], [7].

- The US Environmental Protection Agency (EPA) Smartway program certifies low fuel-efficiency and emission vehicles for use in the transportation industry. This program brands vehicles and devices that are demonstrated to promote such efforts [10].

- Under the US Clean Air Act and the Energy Independence Security Act of 2007, the US EPA and the National Highway Traffic Safety Administration (NHTSA) have been mandated to develop a national program to reduce greenhouse gas emissions and fuel consumption from medium and heavy-duty trucks. Environment Canada has been a close observer and collaborator of the EPA in this program, and NRC-IAR has been commissioned to investigate the aerodynamic aspects of heavy-duty trucks within the collaboration [11], [12], [13].

- The Platform for Aerodynamic Road Transport (PART) is an academic/manufacturer/operator partnership in the Netherlands aimed at developing technology to reduce fuel consumption and emissions of the road transport sector by 20% before 2020 [14].

A recent report by the US National Academy of Sciences (NAS) has documented current and emerging technologies for reducing fuel consumption of medium- and heavy-duty vehicles [2]. This report has provided, in part, a basis for new US EPA and NHTSA rules governing the fuel consumption and emissions of such vehicles, under the US Clean Air Act and the Energy Independence and Security Act of 2007 [15]. The final rules governing this program became effective in November 2011 and provide the regulatory framework in which medium- and heavy-duty engine and vehicle manufacturers must comply with the Clean Air Act beginning with the 2014 model year, with full compliance by model year 2016. In regards to the effect of aerodynamics on fuel consumption, manufacturers will be required to report the aerodynamic drag of their vehicles based on a standard method.

The NAS report provided four main findings with regards to aerodynamic technologies for the reduction of fuel consumption of medium- and heavy-duty vehicles, summarized in the following:

- Aerodynamic loads are dominant at highway speeds and drag-reduction technologies have little value for low-speed operation;
- The four main areas of a tractor-trailer identified as critical for aerodynamic improvements are:
  - Tractor streamlining;
  - Management of airflow around the tractor-trailer gap;
  - Management of airflow under the trailer;
  - Management of airflow at the rear of the trailer.

- By the 2015 to 2020 timeframe, drag-reduction technologies can improve fuel consumption of tractor-van trailer vehicles by 15% for vehicles operating at highway speeds of 65 mph (104 km/hr), with significantly less benefits for other classes of vehicles; and
- A significant barrier to implementation of drag-reduction technologies is their damage tolerance in operation and the costs of repair.

The primary recommendation of the NAS report in regards to aerodynamic drag reduction is a requirement for such technologies to be evaluated on a wind-averaged drag basis to take into account the effect of typical terrestrial winds. It also recommends certification of drag coefficient results by a standard assessment method. The new US EPA and NHTSA rules have adopted the latter recommendation by standardizing on a common aerodynamic evaluation method (coast-down testing, see Section 11.2) on which manufacturers must base their drag-coefficient reporting. The rules allow the manufacturers to use other evaluation methods, those on which they have built their development programs, as long as they can correlate back to the standard methods that can be used for auditing purposes. The primary recommendation for reporting based on wind-averaged drag has not been fully implemented in the new rules. Only zero-yaw drag-coefficient results are required for reporting. However, original equipment manufacturers (OEMs) are allowed to determine the drag-coefficient based on different yaw angles (i.e., a yaw sweep adjustment) to improve their GHG performance. Also, OEMs can generate additional credits for innovative technologies that reduce drag in cross-wind conditions that cannot be measured using the prescribed test procedures

3.7 Assessment criteria for drag-reduction technologies

The results of the current literature survey have corroborated knowledge gained by NRC through various research programs directed at road-vehicle aerodynamics and from consultation with collaborators and partners representing truck and bus manufacturers and operators. In general, the implementation of any drag-reduction technology must be tempered with the need to maintain the practicality, legality and usability of the vehicle. In order for an aerodynamic technology to gain acceptance in the industry, it must meet the following criteria:

- Reduce fuel consumption by a measurable amount;
- Be cost effective and have a reasonable return on investment (the definition of “reasonable” varies from operator to operator);
- Be relatively easy to install and maintain;
- Have little to no detrimental effects on operations on the road and around loading docks; and
- Not contravene existing federal, provincial or local regulations.

Sections 4 through 8 discuss a variety of technologies and devices that may be used to reduce aerodynamic drag on heavy transport vehicles and buses. The relative advantages and drawbacks of each technology are presented as well as their relevance to the Canadian trucking industry. Where possible, the reduction in drag coefficient has been quantitatively stated as well as any factors that must be maintained in order to achieve those stated or tested results. Sections 10 and 11 outline testing methodologies for evaluating the aerodynamic performance of heavy vehicles.

4 LONG COMBINATION VEHICLES

4.1 Current State

Long combination vehicles (LCV) are vehicles that consist of a single tractor pulling two full length trailers in either an A train drawbar configuration or a B train fifth wheel configuration. They differ from conventional Canadian B trains in that the total length of the combination vehicle may be as long as 40 metres, with a maximum length of 11.5 metres for each trailer. This is in contrast to conventional vehicles consisting of a tractor pulling a 14.65 m (53 ft) trailer or a B-train consisting of a tractor pulling a lead trailer and a 'pup' trailer for a total maximum length of 25 m (82 feet). An addition difference is the number of axles: an LCV typically has one steer axle, one set of drive axles and three trailer axles for a total of 11 axles and five axle groups whereas the two vehicles it replaces have two steer axles, two sets of drive axles and two trailer axles for a total of 12 axles (assuming tridem trailer axles) and six axle groups. There are numerous operational restrictions and conditions applied to the use of LCVs in the province of Ontario, most of which are outside the scope of this document, but may be viewed at the Ministry of Transportation of Ontario's (MTO) website [16].

An example of an A-train LCV is shown in Figure 1 and the two vehicles it replaces are shown in Figure 2.

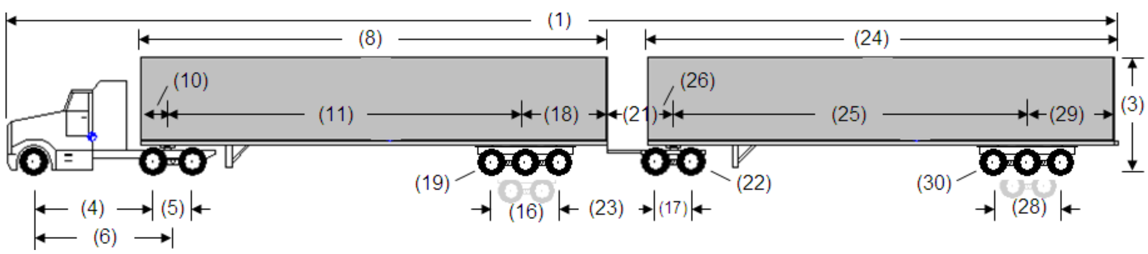

Figure 1 – Illustration of a long combination vehicle (LCV) [16]

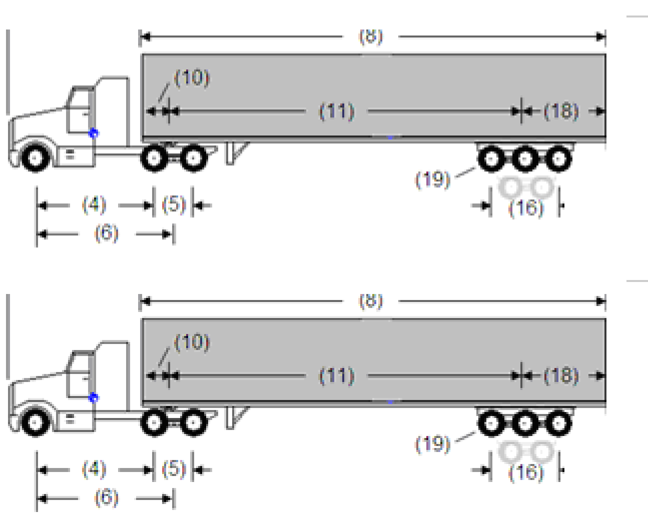

Figure 2 – Illustration of the two vehicles replaced by one LCV [16]

LCVs were initially developed and permitted to travel on provincial roads to allow operators to pull more freight using one tractor, and therefore one driver. This also reduces traffic congestion somewhat since every LCV is shorter than the equivalent two combination vehicles by the length of the second tractor and the distance between the two vehicles in Figure 2. However, one of the other benefits of LCVs is a reduction in greenhouse gas emissions and fuel consumption since only one tractor (albeit with a more powerful engine) is required to pull two trailers instead of two tractors.

When considering LCVs, a distinction must be made between the two types of drag on a heavy trailer: pressure drag and friction drag (see Section 3.3). Since both trailers are present in an LCV it stands to reason that the friction drag will be approximately the same between one LCV and the two vehicles it replaces. It also stands to reason that the gap drag between the first and second trailers will be similar to the gap drag between the tractor and trailer of conventional vehicles. However, the LCV has only one blunt front face and only one blunt rear end exposed to the free stream of air, whereas the two vehicles it replaces have two front blunt faces and two rear blunt faces. Therefore the blunt body component of drag (pressure drag) is reduced to approximately half of what it would be for the two vehicles. Since 90% of the total drag is the pressure drag component, reducing the amount of pressure drag by any amount has a significant effect on the overall drag for the combination vehicle.

LCVs are currently allowed in Ontario and Quebec under a pilot program that is meant to assess their effectiveness and safety under ideal and more conservative conditions than those of conventional vehicles. In order to make fair comparisons between LCVs and conventional vehicles, it is important to note some of the current restrictions placed on LCVs.

- LCVs are restricted to a gross vehicle weight of 63,500 kg and therefore cannot carry the same weight as the combination of the two trailers they replace. For this reason, LCVs tend to be more useful to freight carriers who fill their trailers to their maximum volumetric capacity with lower density freight (i.e. “cube out”) rather than by maximum mass; and

- In Ontario, LCVs are restricted to a maximum speed of 90 km/h whereas most conventional heavy vehicles are speed governed to between 95 and 103 km/h.

Therefore, since LCVs are lighter and drive more slowly than a typical single trailer vehicle, a direct comparison of current operating expenses and fuel consumption would artificially favour the LCV. Therefore, some assumptions should be made when making direct comparisons in order to properly assess the aerodynamic performance of the two types of vehicles since it is likely that the restrictions placed on LCVs may eventually be lifted, thus slightly reducing their potential to reduce fuel consumption.

Terrain and grade are also another discrepancy that must be considered. In Ontario, nearly all LCV movement occurs on divided highways that are nominally level and flat. The relatively low grades means that tractor engines can be sized smaller than LCV tractors that are destined to operate in, say, hilly areas of British Columbia. The percentage fuel savings of LCVs compared to two conventional vehicles could therefore be reduced when travelling in hilly areas where high horsepower tractors are required and speeds are lowered. An LCV will still burn less fuel than two vehicles, but the percentage decrease will be smaller.

Natural Resources Canada quotes possible fuel savings [17] up to 39% with the use of long combination vehicles compared to two conventional tractor trailers.

Many government websites indicate the range of potential fuel savings via the use of LCVs as compared to conventional tractor trailer combinations. However, the websites do not delineate the savings in terms of rolling resistance, aerodynamics or the need for higher horsepower LCV engines to pull the second trailer.

4.2 Academic Studies

A study performed in Sweden by Martini et al [18] attempted to quantify the aerodynamic drag at specific locations of European combination vehicles compared to that of a conventional tractor trailer. They developed six model vehicles for the study where model #1 was a reference vehicle and the others were variations of straight trucks, converter dollies, full trailers and semi-trailers. Many of the models were specific to the European market and are not discussed here, but models #1 and #6 were very similar to North American vehicles and are relevant to the study of LCVs with the exception of the single drive axle on the tractor which, in North America, would typically be a tandem drive axle for vehicles of this size.

The two vehicle models are described in Table 4 and shown in Figure 3 and Figure 4.

Table 4 – Specifications of vehicles in Martini et al study

	Model 1	Model 6
Overall length	16.50 m	25.25 m
Number of trailers	1	2
Number of axles	5	7
Gap #1 length	0.650 m	0.955 m
Gap #2 length	NA	0.650 m

Since aerodynamic drag is affected by yaw angle, that is the angle that the wind makes with the vehicle, the team produced simulations at 0 degrees yaw and 5 degrees yaw as well as results that were an average of the two yaw conditions. The results of the study indicated that model #6 had a C_D that was only 0.05 higher than the conventional vehicle at 0 deg yaw and 0.13 higher at a yaw angle of 5 degrees. Most tractor trailer combinations have C_D between 0.5 and 0.6 therefore the LCV's additional 0.05 C_D at zero yaw is only 10% of what the second tractor trailer combination would have whereas at 5 degrees of yaw the increase would be approximately 22%. As expected, the team detected a relationship between vehicle length and sensitivity to yaw angles, in other words, the longer the vehicle, the greater the increase in drag when subjected to cross winds.

Another interesting result of the study was the percentage contribution of friction and pressure drag. As discussed in Section 3.3, 90% to 95% of the drag on a tractor trailer is as a result of pressure drag. However, as vehicle length increases, the percentage contribution to overall drag from friction drag rises slightly since there is so much more planar surface aligned with the airstream, yet the blunt front face of the vehicle remains unchanged. The study concluded that the percentage contribution of pressure drag on the baseline vehicle was 93.3% whereas the contribution of pressure drag on the LCV was 91.7%. The significance of this is that as vehicle length increase, strategies to reduce friction drag become more effective in reducing fuel consumption. However, it is clearly still more beneficial to reduce pressure drag, regardless of vehicle configuration. The authors concluded that some long vehicle combinations can show an increase of 40% in friction drag with only a corresponding increase of 8% in pressure drag.

However, this is still 40% of a very small number, and 8% of a very large number but the point remains that increasing vehicle length increases the relevance of frictional drag reduction strategies.

After studying overall drag, the team analysed the drag at various locations on the combination vehicles, particularly around gaps between trailers. The team concluded that the size of the gap between the lead and trailing trailer played a significant role in the amount of drag experienced by the combination vehicle, particularly at higher yaw angles.

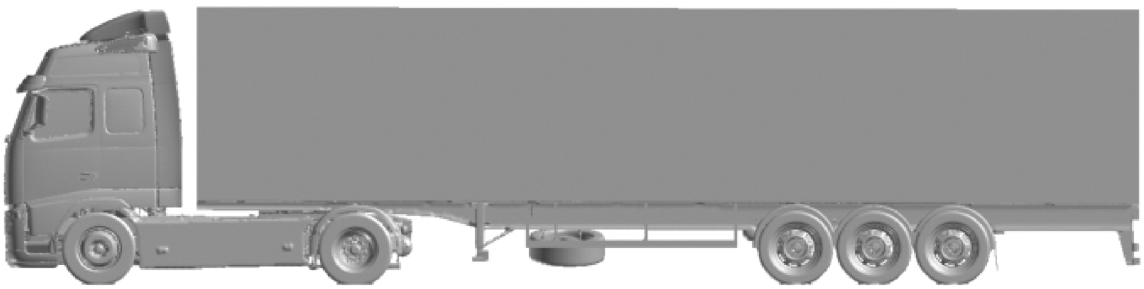

Figure 3 – Model #1, conventional tractor semi-trailer

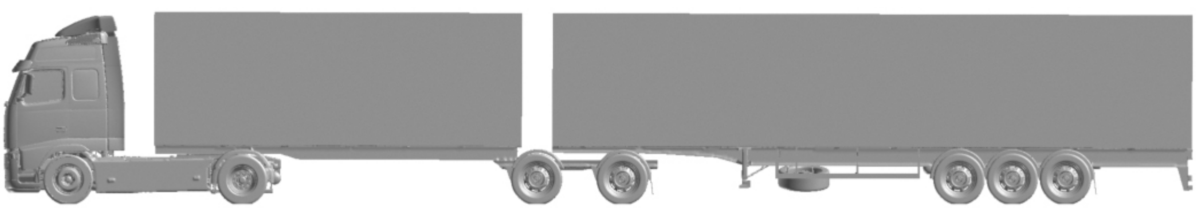

Figure 4 – Model #6, LCV

Most operators are not directly concerned with drag, however. To them it is the effect of drag reduction that impacts their operations, via an associated fuel consumption reduction. The following case study describes the effects of drag on LCVs with respect to fuel consumption and thus, fuel costs.

The calculations are based on an assumption that two tractor trailers are each travelling 100,000 km per year at a steady speed of 100 km/h, each pulling 53 foot van semi-trailers. The average fuel consumption of the two vehicles, taken from NRCan's website [17], is assumed to be 40 L/100 km. A third vehicle is used for comparison: an LCV, consisting of one tractor and two full trailers, connected in a B-train arrangement. The calculations are based on assumptions that at 100 km/h, aerodynamic effects are responsible for 50% of fuel burned in a highway tractor-trailer. Using the Martini study [18], it is assumed that the coefficient of drag of the LCV is only 10% higher than the coefficient of drag for each conventional tractor and trailer at zero yaw angles and 22% higher at 5 degrees of yaw. Also, using data from the BC Department of Transport, it is assumed that the LCV will burn 39% less fuel than the two conventional tractor trailers combined. It is assumed that engine efficiency and all parasitic drains such as air conditioning and electrical accessories would be relatively similar between the LCV and the conventional vehicles.

Table 5 illustrates the estimated distribution of fuel consumption for the two types of vehicles at five degree yaw wind angles given that a tractor and trailer over an entire year will have a non-zero average wind yaw.

Table 5 – Fuel consumption comparison between LCV and conventional vehicle at 5° yaw angle

	Conventional Tractor and Trailers			LCV
	Tractor #1	Tractor #2	Tractor #1 + #2	
Distance driven	100,000 km	100,000 km	200,000 km	100,000 km
Fuel burned	40,000 L	40,000 L	80,000 L	56,800 L
Fuel for aero	20,000 L	20,000 L	40,000 L	24,400 L
Fuel for rolling	20,000 L	20,000 L	40,000 L	32,400 L

4.3 Manufacturer Claims

LCVs are not a product, per se, therefore there are no relevant claims from manufacturers. However, user groups such as the Ontario Trucking Association (OTA) have endorsed the use of LCVs for a variety of reasons, including the potential for fuel savings as a result of aerodynamic reductions.

4.4 Operational Concerns

By far the greatest operational concern for an operator wishing to use an LCV remains unloading the front trailer. Unlike a tanker trailer, which can be unloaded via a variety of ports along the side of the trailer, a van trailer of an LCV must still be unloaded via the rear doors, However, the rear doors of the LCV's lead trailer are blocked by the front face of the second trailer, thus requiring the driver to unhook the second trailer while the lead trailer is being unloaded, or loaded. Therefore, operators wishing to benefit from the use of LCVs must take this into consideration when planning their delivery and pick up times. These issues can be lessened by the use of special switching yards near depots where pup trailers can be dropped off or by using trailers that have side curtains for loading and un-loading. Although not common, combinations with a tanker trailer in the lead position and a van trailer in the trailing position can also minimize loading and unloading delays.

Other concerns involve the perceptions of the driving public as they must negotiate their vehicles around LCVs which are significantly longer than the vehicles they replace, and 15 metres longer than B-trains which most drivers have accepted as the norm on Canadian highways, and even in city centres while delivering fuel.

4.5 Conclusions

The results of one study indicated that an LCV's drag coefficient while pulling two trailers can be as little as 0.05 higher than a conventional vehicle pulling one trailer at 0 deg wind yaw angle. This number increases to 0.13 higher at a yaw angle of 5 degrees. Therefore, adding a second trailer to form an LCV, and thus doubling the freight capacity, results in a very modest increase in drag coefficient of approximately 10% at zero yaw angles and 22% at five degree yaw angles when compared to the single trailer vehicle. Or put in other terms, the drag coefficient on an LCV is only marginally more than half of the sum of the drag on the two vehicles it replaces when wind angles are at zero degrees.

As vehicle length increases, the percentage contribution to overall drag from friction drag rises slightly since there is so much more planar surface aligned with the wind, yet the blunt front face of the vehicle remains unchanged. A study concluded that the percentage contribution of pressure drag on the baseline vehicle was 93.3% whereas the contribution of pressure drag on the LCV was 91.7%. The significance of this is that as vehicle length increases, strategies to reduce friction drag become more effective in reducing fuel consumption. However, it is clearly still more beneficial to reduce pressure drag, regardless of vehicle configuration. The authors of one study [18] concluded that some vehicle combinations can show an increase of 40% in friction drag with only a corresponding increase of 8% in pressure drag. However, this is still 40% of a very small number, and 8% of a very large number but the fact remains that increasing vehicle length increases the relevance of frictional drag reduction strategies and has much less effect on pressure drag.

The size of the gap between the lead and trailing trailer plays a significant role in the amount of drag experienced by the combination vehicle, particularly at higher yaw angles.

It is estimated that one LCV would burn approximately 23,200 fewer litres of fuel when compared to two conventional vehicles, assuming a yearly distance of 100,000 km at highway cruising speeds.

4.6 Areas Recommended for Further Work

Large reductions in pressure drag can be achieved by using LCVs and these reductions are well documented and understood using European vehicles with fixed yaw angles. However, there are very little data pertaining to North American LCVs experiencing variable wind yaw angles corresponding to a yearly wind average drag. The economic and operational benefits and drawbacks of LCVs are well understood as a result of the MTO pilot project.

There are still opportunities for incremental decreases on LCV drag. Further study could be performed on Canadian LCVs to better understand the relationship between gap size and drag to demonstrate if devices that are currently designed to be installed in the gap between conventional tractors and trailers could also be used between the two trailers of an LCV. And if so, what configuration would be best suited to optimize drag reduction between the two trailers of an LCV. This study could be performed at both gaps to quantify the incremental effect of add on devices, compared to the large reductions that are achieved via the removal of one of the tractors. A study such as Cooper and Leuschen [6] could be conducted whereby a variety of gap fillers, side skirts and boat tails are sequentially added to the LCV in order to determine if the effects of these devices on LCVs is similar to their effect on conventional vehicles.

5 CAMERA MIRRORS

5.1 Current State

CMVSS 111 stipulates that all highway tractors must be fitted with side view mirrors, on both sides of the vehicle, with no less than 325 cm^2 (50 in^2) of reflective surface. There are many other physical requirements involving reflectivity and mirror curvature, all of which are outside the scope of this document as they do not affect the overall aerodynamics of the mirrors.

However, there is a significant and measurable increase in vehicle aerodynamic drag caused by the addition of the mandatory side view mirrors stipulated in CMVSS 111. The placement in the airstream and the blunt body area of the mirrors remain the principal factors when considering aerodynamic losses.

Technological advances have made it possible to replace the rear view mirrors with cameras, thus drastically reducing aerodynamic drag. However, at the time of writing it is still illegal to remove the side view mirrors on a highway tractor in Canada therefore cameras can, at best, be used as a supplemental vision system.

5.2 Academic Studies

A 2006 study [7] by the Institute for Aerospace Research at the National Research Council (NRC-IAR) tested the individual contributions to aerodynamic losses from a variety of devices that are, or could be, attached to a highway tractor and trailer combination. The study used a Volvo class 8 highway tractor and a 28 foot van semi-trailer. The coefficient of drag of the tractor and trailer combination without devices was measured and then devices were added back to the combination vehicle, one at a time, to determine the individual contribution to increasing or decreasing aerodynamic drag for the combination vehicle. The drag coefficient (C_D) of the baseline vehicle was measured to be 0.659 at 100 km/h. The addition of the two CMVSS compliant side view mirrors (similar to those shown in Figure 7, which are approximately three times larger than the minimum stipulated in CMVSS 111) increased the vehicle C_D by 0.0156, which is 2% higher than the baseline vehicle. This increase in drag could typically increase fuel consumption by approximately 1% at 100 km/h. The NRC-IAR authors assumed a yearly cruising distance of 130,000 km for each tractor. They concluded that if a tractor's two side mirrors were removed, the tractor would burn 938 fewer litres of fuel annually based on current fleet wide average fuel consumption values. This would result in an estimated Canadian fleet wide savings of approximately 212,926,000 litres of fuel every year, or 562,124,640 kg of CO_2 if the side view mirrors were removed from all 227,000 highway tractors. More fuel could be saved with the removal of mirrors from straight trucks, however, this would be less effective than removal on highway tractors since straight trucks tend to drive at considerably slower speeds than highway tractor. Similar testing was performed on the fender mounted convex mirrors. The results indicated that approximately 588 litres of fuel are burned, per tractor, annually to overcome the drag from fender mirrors on a single tractor.

5.3 Manufacturer Claims

The projected savings from the removal of mirrors must be tempered by the fact that rear view cameras that could replace mirrors will undoubtedly also project into the airstream and thus create some drag, albeit much less than full CMVSS 111 mirrors. Figure 6 illustrates one company's prototype of side view cameras and the cantilevered beams required to support the cameras.

One of the risk factors associated with side view cameras is reliability. With the exception of vandalism or damage from flying road debris, traditional mirrors have a mean time between failure that far exceeds the practical life of the tractor to which they are mounted. Conversely, rear view cameras and monitors introduce a variety of electronic components, each of which will carry a mean time between failure that is most certainly lower than that of a mirror (although the exact amount is not known at this time). It may be necessary for camera equipped vehicles to carry some form of redundancy in the event of camera failure. This redundancy, however, must be lightweight and stowed in such a manner to not affect the aerodynamic drag of the vehicle when not in use; otherwise the aerodynamic benefits of cameras would be lost.

The effect of adding weight to the tractor must be considered for rear facing cameras to ensure that aerodynamic savings are not negated by the addition of weight, above that of conventional mirrors which tend to add very little weight to the tractor. If the weight differential between the camera equipment and the typical mirrors was enough to cause the tractor to burn 1% more fuel every year then the aerodynamic savings would be lost. According to the EPA [19], every 10 percent decrease in a truck's weight reduces fuel use between 5 and 10%. At a gross weight of, say, 41,000 kg, the added weight of the camera equipment would, at most, represent a 0.05% to 0.1% increase in GVW. Therefore, the estimated fuel consumption increase would be between 0.025% and 0.05% which is still substantially less than the estimated 1% decrease in fuel consumption with the removal of side mirrors. Actual specifications of volume and weight of the camera equipment and full scale dynamometer and wind tunnel testing would be required to confirm these estimates.

One area of research worth noting is short wave infrared (SWIR) cameras. These cameras use infrared technology to penetrate through fog and darkness to capture images that would normally be difficult or impossible to see by a human operator. Combining rear vision cameras with SWIRs would not only reduce aerodynamic drag but would also increase the functionality of the vision system above what is normally provided by conventional mirrors. Figure 5 [20] illustrates how captains of sea vessels could use a SWIR camera to penetrate through fog to see other ships or land. Similar technologies could be used for drivers of heavy trucks to see other vehicles or obstacles in the road during fog or white-out conditions. Studies would have to be performed to determine if devices that were designed to be used on ships, in which the operators are typically looking kilometers ahead with a wide field of view, could be used in tractors where the operator's field of view is much closer and within a confined lane.

Figure 5 – Example of SWIR camera in fog [20]

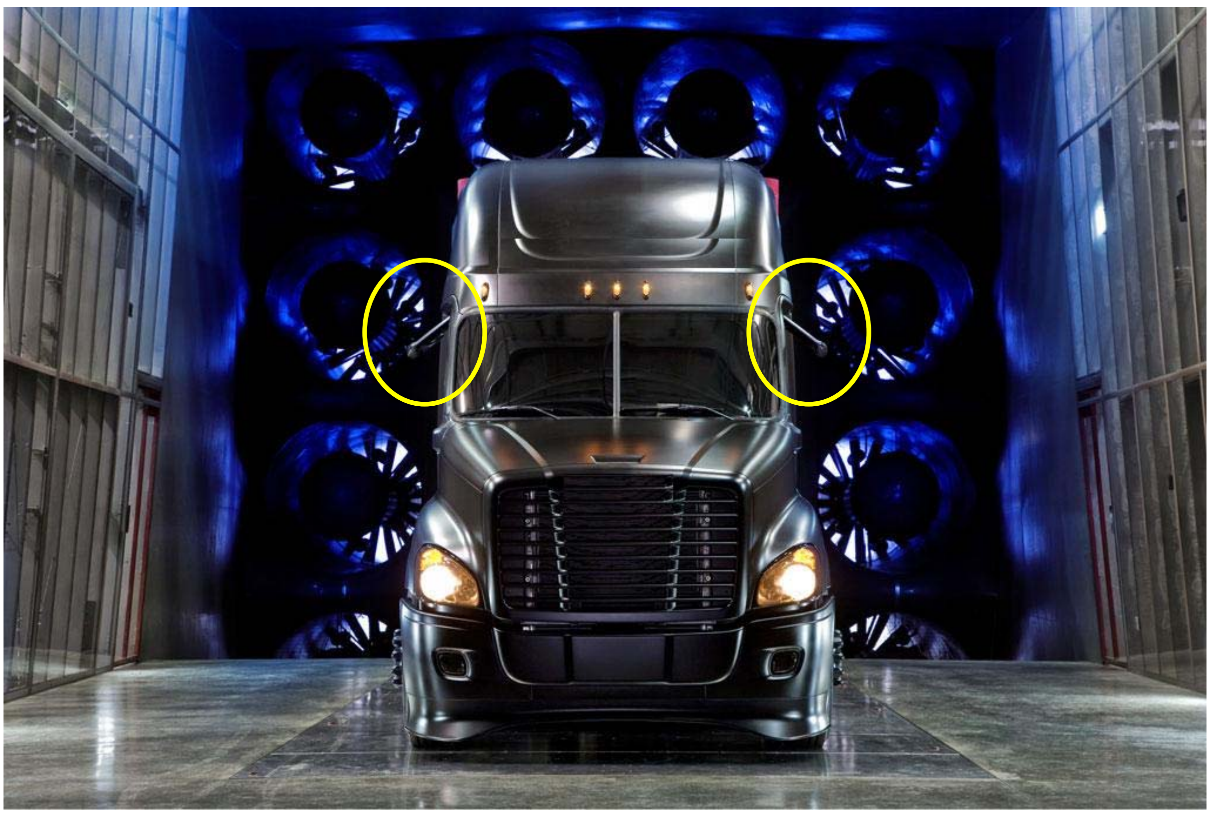

Figure 6 – Example of innovative truck with side view cameras in place of mirrors

NRC-CSTT reviewed the mirror requirements in the United States and in Australia. Canada and the United States have harmonized their requirements such that CMVSS 111 is identical to FMVSS 111 with respect to mirrors. The Australian requirement, Australian Design Rule (ADR) 14/02 "Rear Vision Mirrors" [21] is more complicated to decipher as it is divided into truck classes that are different than in North America, but appears to allow a much smaller area of reflective surface at 150 cm^2 rather than the 325 cm^2 required in North America. Therefore, some consideration could be given to reducing the amount of glass on a CMVSS compliant mirror and thus reducing its area and aerodynamic drag. However, NRC-CSTT measured the reflective surfaces of two in-service Canadian based tractors used for other testing in winter 2011 and found that these tractors were equipped with mirrors that were already two and a half to three times larger than what is required under CMVSS regulations, if both the plane and convex sections are considered. In fact, the plane sections alone of the mirrors were approximately twice the size required in the CMVSS regulation. The exact dimensions of the mirrors are shown in Table 6, expressed in area and percentage of the CMVSS 111 standard; and photos of mirrors #1 and #2 are shown in Figure 7 and Figure 8. Therefore, if manufacturers and operators are already accustomed to vehicles equipped with nearly three times the required minimum in order to drive safely, it is not likely that reducing the legal minimum will motivate manufacturers to provide smaller mirrors.

5.4 Operational Concerns

NRC-CSTT interviewed two experienced heavy truck drivers and each of them agreed that rather than alter the size of the mirrors, they would prefer a hybrid side view mirror that included an inboard plane section with an outboard convex section to increase the field of view. This increased field of view would allow them to see smaller and faster vehicles, such as motorcycles, as they pass in the left hand lane, possibly in the left hand portion of the left lane. Most mirror systems required the driver to look into the plane mirror and then lower their eyes to look into the convex mirror below the plane mirror for the expanded field of view. The hybrid construction would allow them to assess an emergency lane change much faster, without the need to lower their eyes or head. Additionally, one driver indicated that (in his opinion), newer drivers could easily be trained to use video camera systems whereas more experienced drivers may find the migration to viewing a video terminal to their right difficult after so many years of looking to their left. This, he felt, would be particularly difficult in an emergency situation where they react on instinct rather than on process or thought.

Table 6 – Sizes of two side view mirrors

Section	Mirror #1	Mirror #2
Upper Section (plane)	701.1 cm^2 (216%)	597.6 cm^2 (184%)
Lower Section (convex)	251.6 cm^2 (77%)	235.6 cm^2 (72%)
Total Area	953.2 cm^2 (293%)	833.2 cm^2 (256%)

The Canadian and Australian regulations are paraphrased below:

<u>Canada (and USA):</u>

27) Every multi-purpose passenger vehicle, truck and bus with a GVWR of more than 4 536 kg (10,000 pounds), other than a school bus, shall have on each side of the vehicle an outside rearview mirror of which not less than 325 cm^2 (50 square inches) of reflective surface area is located so as to provide the driver with a view to the rear along both sides of the vehicle.

<u>Australia [21]</u>

REQUIREMENTS FOR MD3; MD4; ME; NB; AND NC VEHICLES ONLY

4.1. There shall be affixed to every vehicle a mirror or mirrors so designed and fitted and of such dimensions as to be capable of reflecting to the driver as far as practicable a clear view of the road to the rear of him and of any following or overtaking vehicle.

4.2. At least one such mirror shall be affixed to each side of the vehicle and may project 150 mm beyond the point of 'Overall Width' of the vehicle or the 'Overall Width' of any trailer it may be drawing-

4.2.1. if the vehicle is a goods vehicle or an omnibus;

4.2.2. if the trailer be of greater width than the drawing vehicle; or

4.2.3. in any case where, because of the manner in which the vehicle is constructed or equipped, or the fact that it is drawing a trailer or for any other reason, the driver could not, by means of a mirror affixed to the inside of the vehicle, have reflected to him as far as practicable a clear view of the road to the rear of him and of any following or overtaking vehicle.

4.3. The mirrors may project 230 mm on each side beyond the point of 'Overall Width' of the vehicle provided that the mirror is capable of collapsing to 150 mm.

4.4. All such mirrors fitted to vehicles shall be at least 150 square centimetres in area.

4.5. Mirrors on the driver's side shall be flat, and mirrors on the passenger's side may be flat or convex.

4.5.1. 'Convex mirrors', if fitted, shall meet the requirements of Clauses 2.4.2.1 and 2.4.2.2.

Figure 7 – Example of typical side view mirror

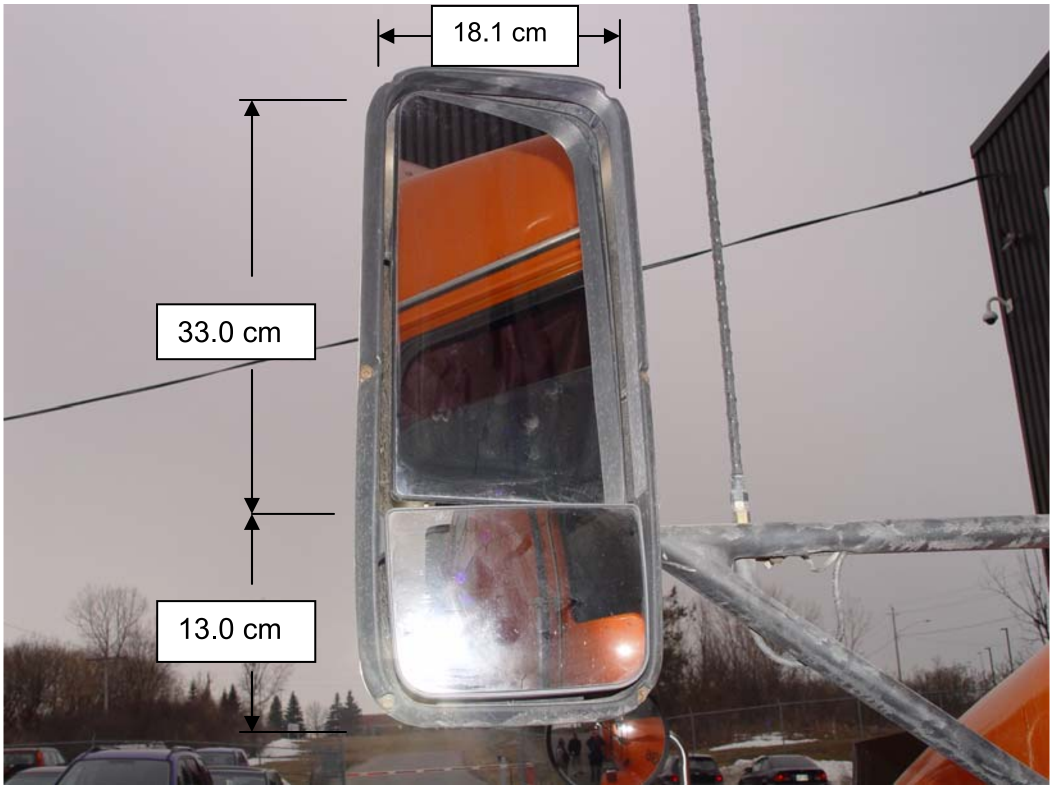

Figure 8 – View of typical driver's side mirror

5.5 Conclusions

CMVSS compliant mirrors are responsible for approximately 2% of the overall drag on a conventional tractor and trailer. A study concluded that if a tractor's two side mirrors were removed, the tractor would burn 938 fewer litres of fuel annually based on current fleet wide average fuel consumption values. Some manufacturers are currently designing prototype vehicles that use rear facing cameras and in-cab video screens that replace the side view mirrors. However, these systems cannot be used independently without mirrors, under the current CMVSS regulations.

A cursory review of in-service tractors in Ontario confirmed that drivers are currently accustomed to using mirrors that are nearly three times larger than what is required under CMVSS regulations. Therefore, it is not likely that reducing the minimum amount of glass required under CMVSS would result in any drag savings since most drivers would be reluctant to reduce their field of vision from what they are currently using.

Side view mirrors are considered 'fail-safe' devices. Replacing side view mirrors with rear view cameras will most certainly reduce the mean time between failure (MTBF) of the tractor. However, further work would be required to compare the MTBF of conventional mirrors versus the MTBF of a camera system.

Some drivers may require more time to adjust to the concept of looking to the right into a video screen, rather than looking left and right into mirrors, particularly when required to do so in the event of an emergency lane change.

5.6 Areas Recommended for Further Work

The drag reduction potential of removing the side view mirrors is understood, quantified and well documented by lab testing therefore there would likely be little benefit to reproducing those tests. However, there seems to be little documented testing with regards to the performance and reliability of rear cameras and driver acceptance of their use. NRC-CSTT recommends developing a study to determine the benefits and drawbacks of side view mirror replacement for aspects other than the well known aerodynamic benefits. These would include, reliability and maintainability, the weight of the added devices, the need for redundancy, the speed at which the drivers can view objects in the left lane, and driver acceptance, particularly for those drivers who have been using mirrors for many years. If it was determined that side view mirrors could be removed without any negative safety side effects it would be worthwhile to investigate a pilot project to better understand the potential fuel savings under actual revenue driving conditions.

The benefits of infrared cameras could also be studied to determine if they could be combined with camera mirrors to enhance the vision of the drivers during inclement weather.

6 PLATOONING

6.1 Definition

Platooning is the act of coupling two or more vehicles together while they are travelling on a highway. The intent of platooning is to improve safety, traffic flow and efficiency while also improving the efficiency of the individual vehicles within the platoon [22].

This coupling can be mechanical, electrical, magnetic or electronic. This allows vehicles to travel as a synchronized unit, reducing the distance between vehicles which reduces the lag time as successive vehicles accelerate in the same direction. It also allows vehicles to brake as one unit, rather than as separate entities, thus reducing the risk of rear end collisions.

Although platooning is generally aimed at reducing traffic congestion, one of the greatest side-benefits of platooning is the reduction in aerodynamic drag on all of the vehicles in the platoon, even the lead vehicle. Although aerodynamic drag is a factor that affects all vehicles, the fuel consumption of Class 8 tractor trailer combinations is significantly affected by aerodynamic effects owing to their large size and blunt front faces. For this reason, the concept of platooning makes sense when applied to very large, blunt face, vehicles.

Advanced platooning would allow intelligent vehicles to join or leave the platoon at any time, however, there are many challenges involved with platooning, principally the interaction between the platoon vehicles and non-platoon vehicles as well as strategies to optimize the vehicles spacing.

Although there are many aspects of platooning, the concepts relating to drag reduction of heavy vehicles have been presented in Sections 6.2 through 6.6

6.2 Current State

Platooning remains a concept that is being studied, researched and tested in many developed countries, however, there are no examples of platoons that can currently be found on active public roadways.

6.3 Academic Studies

The concept of platooning dates back to a pilot study conducted in 1962 by Dr. Robert Fenton at the University of Ohio [23]. Although computers were used, they filled nearly the entire free space inside the vehicle making the project impractical for everyday use. This research continued until funding was cut in the early 1980s. However, computing and sensor development and evolution has allowed the concept of platooning to be considered again, as a viable project for the future.

Globally, there are several significant projects underway, each attempting to define how a platooning system could be integrated into a smart highway. These projects are as follows:

6.3.1 KONVOI

KONVOI was a German study aimed at defining how platooning could be implemented exclusively on heavy trucks. Although much of the research tended to focus on the effects of platooning on traffic flow, there were also theoretical modules that dealt with the aerodynamic effects. One KONVOI model, using ANSYS, was set up with the lead truck pulling the following truck at a distance of 32 feet, at a speed of 80 km/h (50 mph). The simulation illustrated that a savings of between 11% and 12% was possible, depending on the weight of the trucks. However, the publication [101] was not clear if that was a fuel consumption savings or a drag savings. The model was validated using track testing and the results indicated a potential saving of greater than 9%, however, once again it was not clear if this was a drag or fuel savings.

6.3.2 PATH

Partners for Advanced Transit and Highways (PATH) is a collaboration between the California Department of transportation, UC Berkeley and other private and public institutions that has evolved over the past 20 years. The mission on PATH is to reduce traffic congestion, increase traffic flow and safety and decrease energy consumption.

Some of the aerodynamic results that have been demonstrated via the PATH project include:

- Simulated results showed a potential fuel savings up to 25% whereas actual field testing demonstrated fuel savings closer to 15%;

- All of the vehicles in a platoon benefit from the platoon, even the lead vehicle;

- The greatest aerodynamic benefits are achieved by the vehicles in the middle of the platoon, then by the last vehicle, and then the lead vehicle;

- Although smaller gap distances are preferable, the difference in fuel savings between a 2 m to 10 m gap are relatively low;

- Optimal performance could be gained in a group of vehicles by having the aerodynamically ‘clean’ vehicle at the lead position and the aerodynamically ‘dirty’ vehicle in the last position. “Dirty’ refers to vehicles with many protrusions, disturbances and edges.

- Studies would be required to determine if platooning could cause a lack of airflow to the engines of the non-lead vehicle, thus increasing the risk of engine overheating or necessitating the use of accessory cooling fans that could create a parasitic drag on the engine, increasing fuel consumption slightly.

6.3.3 SARTRE

Safe Road Trains for the Environment (SARTRE) is a European consortium project aimed at studying the possibility of a multi vehicle type platoon system that could include passenger vehicles, heavy trucks and buses driving on un-altered conventional roads. The main focus of the project is the environment, traffic safety and traffic congestion.

The system comprises one lead vehicle, driven by a professional driver who leads the platoon, and a series of autonomous following vehicles, operated by conventional drivers. The following drivers are then free to engage in activities that would normally be prohibited, such as reading or using a cell phone. One of the principal goals of the project is to determine how a platoon can be successfully integrated with other non-platoon traffic, for such things as lane changes and departing the highway.

One of the principal goals of the SARTRE project [27] is to determine the optimum spacing for vehicles such that aerodynamic gains are maximized while still respecting the needs to maintain a safe distance. Even sophisticated control systems require some feedback time to brake the trailing vehicle fast enough to prevent a collision, therefore a limit on the minimum distance between vehicles will be required, regardless of aerodynamic effects.

6.3.4 PROMOTE CHAUFFEUR

Other researchers have partnered with the PROMOTE-CHAUFFEUR project to gain insight into a variety of other factors. One such study, performed by Bonnet and Fritz [26] studied the aerodynamic effects of having one heavy truck following a similar heavy truck by as little as 5 m. The principal difference between this study and many others was the focus on fuel consumption rather than drag coefficient.

They developed what was known as an 'electronic towbar' which essentially joined the two vehicles together without any form of mechanical linkage. The purpose of the study was to determine the relationship between following distance and potential drag reduction, assuming all other factors such as grade, wind speed, vehicle speed and rolling resistance remained constant. The lead vehicle was driven by a human driver at steady speeds of 60 km/h and 80 km/h whereas the trailing vehicle was operated by the electronic vehicle controller. Infra-red lights mounted on the rear of the lead vehicle were used to send information to the towed vehicle controller (TVC) which controls the lateral and longitudinal position of the trailing vehicle by accelerating, steering and braking as necessary. However, the driver of the trailing vehicle always maintains the option of overriding the system and driving the vehicle manually if required for emergency or operational reasons.

The vehicles were driven at trailing distances between 6 and 16 metres and the fuel consumption of both vehicles was calculated using a moving average taken every 10 seconds and by calculating the total amount of fuel consumed for each test leg. These two methods were then averaged to obtain an overall fuel consumption difference at various following distances for each of the vehicles compared to when the vehicles were being driven at a typical following distance.

Some of the important findings of the report were as follows:

- As expected, fuel consumption differences were higher at 80 km/h than at 60 km/h;

- Relative to the baseline condition, the fuel consumption of the trailing vehicle decreased linearly from a trailing distance of about 16 m up to 10 m and then leveled off from 10 m down to 6 m. The highest percentage reduction in fuel consumption was 21% and appeared at a vehicle spacing of 8 m;
- Platooning with a following distance of 16 m at 80 km/h still resulted in a fuel consumption reduction of more than 15%;

- Similar trends were found at speeds of 60 km/h, however, the reduction ranged from 10% to 16%;

- Fuel consumption reduction was also achieved in the lead vehicle, however, they were less than that of the trailing vehicle;

- At 80 km/h the lead vehicle experienced a range of fuel consumption reduction from 4% at a trailing distance of 14 m to 10% at 10 m;

- At 60 km/h the lead vehicle experienced a range of fuel consumption reduction from 4% at a trailing distance of 8 m to 7% at 5 m;

The test team concluded that a trailing distance of 10 m was optimum when considering a variety of speeds as well as the fuel consumption reduction for both the lead and trailing vehicles. Trailing distances of less than 10 m did not produce increased benefits.

The test team also investigated the effects of vehicle weight on the potential fuel savings. The lead and trailing test vehicles had masses of 14.5 tonnes and 28 tonnes respectively. Since rolling resistance is greatly affected by vehicle weight, it stands to reason that the relative aerodynamic benefit of platooning decreases as vehicle weight increases as more and more fuel is being used to overcome rolling resistance. Using extrapolation methods, the team calculated that a lightly loaded trailing vehicle at 14.5 tonnes could potentially achieve fuel savings of 28% at a 10 m following distance whereas a heavily loaded 40 tonne truck would likely only achieve a savings of 17% at 10 meters.

6.4 Operational Concerns

Platooning remains a largely theoretical study, with no known current practical applications. Therefore it is difficult to itemize all the areas that may be of concern to an operator. Certainly the biggest operational concern relates to how non-platoon vehicles will interact with long platoons of heavy vehicles. Even if long platoons could be arranged in a safe and efficient manner, there will be many challenges regarding how other vehicles will negotiate around the platoons, particularly when trying to exit a highway via the rightmost lane. Of all the items described in this report, platooning remains the furthest from actual deployment due not only to the large technical challenges, but also to the monumental task of determining how other vehicles would interact with the platoon.

6.5 Conclusions

Several research studies have demonstrated that platoons can be effective at reducing the drag on all of the vehicles in the platoon, even the lead vehicles. However, the largest reduction in drag occurs for the vehicles between the first and last vehicle. It is estimated that vehicles in a platoon could experience between a 9% and 25% reduction in fuel consumption, depending on spacing, vehicle speed, vehicle position and vehicle mass.

It is clear that platooning requires significant changes to the road infrastructure and would also require a significant change in driving behaviour for drivers in other vehicles who are surrounding the platoon but not actually in the platoon.

6.6 Areas Recommended for Further Work

Although platooning appears to have a great potential to reduce aerodynamic drag it does not appear to be a practical solution to Canadian trucking in the near future due to the size of Canada's road network and the immature status of the technology. There are too many logistical and infrastructure barriers that must be overcome to make this a viable concept for the near future. Even if technology could allow two or more heavy vehicles to be electronically connected, the logistics of integrating these vehicles into existing traffic flows will prove to be extremely difficult. Further testing and understanding of LCVs would be a more practical approach to multi vehicle aerodynamic reductions until platooning has been perfected in smaller countries in Europe.

It would appear that many of the research studies focused on vehicles that were lighter than typical heavy vehicles found in Canada. The results of platooning can be more favourable when using lighter vehicles since a higher percentage of fuel consumption can be attributed to aerodynamic effects. The effects of platooning with vehicles loaded to the maximum Canadian legal weight would provide more useful information about the potential for platooning on Canadian roads.

Given the complexity of platooning and the relative simplicity of LCVs, it would be useful to quantify the differences in fuel consumption reduction from vehicles in a platoon versus an LCV. The study could begin by comparing an LCV against a two vehicle platoon and then against platoons with increasingly higher numbers of vehicles.

7 TRACTOR-TRAILER DRAG REDUCTION DEVICES

7.1 Definition

Today, there are a large number of Class 8 tractor-trailer drag-reducing devices and technologies both in-use and under development. Many of these have been extensively studied, with the performance benefits well documented in the research press. These include roof deflectors, cab side extensions, trailer “boat tails” and trailer side skirts. The section will also describe some of the less well studied, and less commercially-adopted technologies for improving aerodynamic efficiencies of tractor-trailor combinations.

In a report by the US National Academy of Sciences that documented current and emerging technologies for fuel reduction of medium- and heavy-duty vehicles [2], they identified the four following critical areas for aerodynamic improvement of tractor trailers under highway conditions:

- Tractor streamlining;
- Management of airflow around the tractor-trailer gap;
- Management of airflow under the trailer;
- Management of airflow at the rear of the trailer.

With the status of some current and emerging technologies, it is predicted that aerodynamic treatment to these key areas can lead to a reduction in fuel consumption under highway conditions on the order of 15% within the 2015 to 2020 timeframe [2].

The drag-reduction technologies described in this section can be separated into two major categories; those mounted to the tractor and those mounted to the trailer. As is pointed out by Leuschen and Cooper [29] and others, there exist as many as three to four times as many trailers in service as there are tractors. As a large majority of add-on drag-reduction devices tend to be trailer mounted, there has been reluctance in the industry to adopt these devices, as there is a clear distinction between tractor owners/operators and trailer owners. Since trailer manufacturers are typically not also operators, and the cost of gap devices increases overall trailer acquisition costs, there is little motivation on the part of the trailer manufacturers to adopt these devices. The payback period for tractor-mounted devices will be much shorter than that for trailer-mounted devices, which will affect the rate of adoption of such technologies to the transportation industry. As such, the tractor devices and technologies will likely be adopted earlier.

When evaluating the potential fuel savings of tractor-trailer devices, it is important to understand the context under which any measurements or evaluations have been performed. Results, especially those based on road testing, can be biased depending on the conditions of the vehicle and the environmental under which they were tested. For example, favourable drag-reduction claims based on fuel-economy tests can be biased if a device is tested on a lightly-loaded vehicle in low-wind conditions. Also, although manufacturers’ and researchers’ claims may be valid at 60 to 65 mph, one researcher [30] reports the average speed of a highway tractor is approximately 48 mph therefore the actual fuel consumption reduction would be less than the published data at 60 mph. This provides difficulty in evaluating various technologies based on separate studies or claims. A systematic and consistent manner in which the devices can be tested would be required to provide a set of recommendation to policy makers, manufacturers, and operators.

Much of the previous research has been conducted on very specific, or a small set of tractor-trailer combinations. Since many of today's tractors may pull loads consisting of a variety of trailer types, that themselves have significantly varying aerodynamic properties, it is well worth studying the effects of the most common commercially available drag reduction devices on various tractor-trailer combinations. Specifically, there has been little study of the possible negative effects that could arise from cab roof fairings and side extensions, when used with certain combinations of trailers. [31] Most recent studies aimed at the second-generation technologies generally perform evaluation of drag reduction or fuel economy using a streamlined newer-generation tractor shape. Lifestyle truckers often prefer older boxier-style tractors with many appendages, lights, and no air deflectors. It is also worthwhile to evaluate the effects of some newer technologies, those that may not significantly affect the appearance of the vehicle, on these classic-style tractors.

As noted above, four critical areas are identified for application of drag reduction technologies. In the following, drag-reduction devices and technologies for each of these four areas are described. Initially a general list of concepts was devised based on several references [2], [5], [6], [7], [8], [14], [23], [32], [33], [34], [35] that identify technologies and devices that can be evaluated for drag-reduction potential of tractor-trailer combinations. Further references are provided within specific section below.

7.2 Tractor Streamlining

7.2.1 Current state

Tractor streamlining has been a driving factor in tractor development by manufacturers for the last three decades. The fuel crisis of the 1970s promoted the development and subsequent adoption of aero-tractors to the market in the 1980s and through the 1990s. Despite the demand by older-generation drivers for the classic style tractors with square hoods, flat bumpers, and large external appendages such as air filters and exhaust pipes, all manufacturers have aero-tractor models that have been developed with fuel economy in mind. Aero-tractor models provide a reduction in aerodynamic drag, over the classic style, on the order of 30% [5]. This is accomplished primarily through rounding of the front surfaces, the use of roof air deflectors, and the use of fairings over the fuel tanks between the steering axle and the drive axles. Examples of a classic tractor model and a modern aero tractor model are shown in Figure 9.

Figure 9 –Tractor styles: Classic (left – Peterbuilt 389), Aero (right – International ProStar)

Current efforts towards incremental drag reduction of tractors are directed at the bumper areas, the underbody, and the gap region between tractor and trailer.

A summary of many of the most current and popular tractor “add ons” can be found in Leuschen and Cooper [29], and repeated, in part, below. The values below have been calculated on an assumed distance of 130,000km (81,000 mi) covered at a nominal wind averaged cruising speed of 107 km/hr (65 mph). The specific details of the calculations are well presented by Leuschen and Cooper. Of note is that the addition of some common devices, such as OEM Mirrors, bug deflectors and fender mirrors negatively impact fuel burn.

Table 7 – Tractor Add-ons potential Fuel Savings [29]

	Potential Fuel savings/yr (L)
OEM Side Mirrors	-938
OEM Bug deflector	-903
OEM fender mirrors	-588
Blocked Engine Inlets	6
Sun Visor/windshield brow	54
Truck and trailer hubcaps	120
“Deer” Bumper	120
Wrap-around splash guards	292
Prototype roof deflector filler	825
Gap reduction of 10 inches	982
OEM cab tank skirts	1596
OEM Side extenders	2499
OEM Roof Deflector	4318

Many other significant areas of possible aerodynamic drag reduction for tractors have been identified or proposed, as described below.

7.2.2 Technologies

7.2.2.1 Mirrors

Generally, truck manufacturers aerodynamically optimize their standard mirror design. However, as noted in Section 5, these standard mirrors are larger than required by law. Proposed camera systems instead of side mirrors, as described in Section 5, or combinations of both, may require aerodynamic optimization for shape, size and location.

7.2.2.2 Bumpers

The shape of a tractor in its bumper region provides a strong influence on the flow underneath the tractor. Lowering of the tractor bumper using air dams or spoilers can redirect flow to the sides of the vehicle rather than underneath it, which may provide a reduction in drag by reducing the momentum of fluid directed to the underbody.

In the study by Leuschen and Cooper [29] described above, the "Deer Bumper" provided a slight decrease in drag, however its magnitude was on the order of the experimental uncertainty. This indicates that such bumpers may not necessarily reduce fuel consumption, but their proximity to the stagnation region on the front face of a vehicle may make be them aerodynamically neutral.

Many transport companies are choosing heavy-duty bumpers because of the combined effect of very high insurance premiums and the fragility of the lightweight materials used for front-end components. Having a heavy-duty bumper makes it possible to avoid claiming minor collisions but comes with a fuel consumption penalty. The impact on fuel consumption of this approach was also evaluated by FPInnovations during Energotest™ campaigns [37]. Testing resulted in a 2% increase in fuel consumption for the vehicle equipped with the heavy-duty bumper, which can be partly explained by increased weight. Aerodynamic optimization of such bumpers may be possible to limit any fuel-consumption solely to weight increases.

Figure 10 – Heavy duty bumper mounted to a tractor

The bumper is located in close proximity to the ground, and the relative motion of the ground with respect to the vehicle creates complex aerodynamic flow characteristics that are not intuitive. Any aerodynamic evaluation of bumper shapes and technologies would require proper accounting of this relative motion. Work done at the NRC in a wind tunnel using a rolling-road system to simulate properly the vehicle-air-ground motions has shown for some lower-vehicle modifications significantly different aerodynamic behavior depending on whether the ground-plane was fixed or moving. Some configurations that provided in a decrease in drag with a fixed floor provided an increase in drag for a moving floor, indicating this strong dependence of lower vehicle aerodynamics on these relative motions. In a wind tunnel simulation, the moving floor represents most accurately the on-road case.

7.2.2.3 Accessories

A potential exists for accessories such as hub-caps and mud-flaps to provide some aerodynamic benefit to reducing fuel consumption of vehicles.

Leuschen and Cooper [29] note a small decrease in the drag of a tractor trailer with smooth hub caps, based on wind-tunnel tests with stationary wheels. The decrease in drag was within the experimental uncertainty of the tests, however with rotating wheels there may be an advantage to covering the wheels. If a net benefit can be gained by using hub caps or wheel covers, it will also be necessary to evaluate their effect on brake cooling to ensure they do not restrict air flow to the brakes.

Mud flaps inhibit the lifting of soil, rocks and mud into the air by blocking the motion of air in the direct downwind vicinity of the wheels. This provides restriction to the flow and therefore introduces drag to the overall vehicle. Some concepts for slotted mud-flaps have been proposed [14] that block the motion of solid particles while allowing some air to pass through. Using Computational Fluid Dynamics (CFD), Hyams et al. [38] indicate that a 9% reduction in drag can be attained by using slotted vertical slats behind the trailer bogie instead of full flaps.

7.2.2.4 Deturbulator Tapes and Surfaces

Sinha [33] describes a passive technology, called deturbulators, consisting of strips of material that claims to dampen the energy of large-scale vortex structures and provide improved flow conditions over a tractor-trailer that effectively reduces the drag (See Figure 11). Fuel economy tests showed a 4% reduction in fuel consumption. No uptake of this technology has been observed, and an independent evaluation of this approach is required to demonstrate/validate this technology fully.

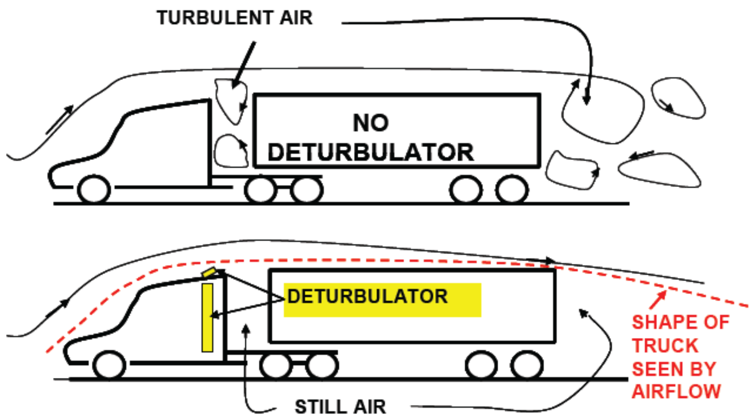

Figure 11 – Effect of deturbulator on a tractor trailer [95]

7.2.2.5 Superhydrophobic Coatings

In many aircraft studies using a “generic transport model” [39], [40], [41], the effect of ice buildup on aerodynamic drag has been studied. Depending on where ice accretes, an increase in drag may be observed for tractor trailers in icy conditions. Additionally, ice buildup on a tractor-trailer also leads to weight increases which lead to higher fuel consumption. Finally, there is an increased risk to other road users should large chunks of attached ice and snow dislodge at highway speeds.

One proposal to alleviate the build-up of ice and snow on tractor-trailer and van bodies is the adoption of superhydrophobic coatings. Superhydrophobic surfaces, such as the leaves of the lotus plant, are highly hydrophobic which makes them extremely difficult to wet. The contact angle of a water droplet exceeds 150° and the roll-off angle is less than 10°. This is referred to as the Lotus effect, as seen in Figure 12, and consequently water does not remain on treated surfaces, and by extension ice should not accumulate.

There have been significant advances in the development of these superhydrophobic coatings, whose applicability to reducing snow and ice accumulation could be investigated. Additionally, the water droplet interaction at the surface of a treated surface could be investigated to see if there are benefits in the reduction of road spray. It is possible, though as yet unstudied, that superhydrophobic surfaces may cause water shedding that reduces the effects of road spray on other road users.

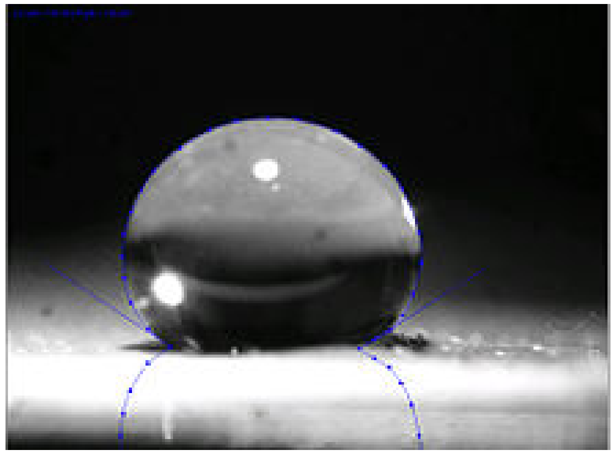

Figure 12 – Water droplet on a lotus leaf

Note the large included angle at the interface of the droplet and leaf surface. If this angle is large, contact forces between the droplet and the leaf are small, resulting in low droplet adhesion.

7.2.2.6 Base Bleeding

Some of the most significant sources of drag on a tractor-trailer result from the large pressure differences between the front of the cab and the rear of the trailer and from the rear of the cab and the front of the trailer, previously discussed as the "gap" drag. A large pressure on the surface facing the flow, coupled with a negative pressure on the surfaces facing away from the flow result in significant aerodynamic drag.

One proposed technique to minimize this source of drag is called base bleeding. Essentially, high pressure air is introduced into these low/negative pressure zones. The result is that the differential pressure between the two surfaces is reduced, and consequently drag is reduced. Two methods for achieving this pressure equalization have been studied. [42], [43]. These methods comprise so-called active base bleeding and passive base bleeding.

In active base bleeding, a mechanical source (compressor) is used to generate volumes of air which are introduced into the low pressure regions. These techniques are claimed to be aerodynamically effective under research conditions (wind tunnel testing and computational analysis) but in practice, can be very difficult to implement. These systems add weight, electrical drag on the engines (i.e. require power) and can be quite complex. As well, active base bleeding techniques would most likely suffer similar reliability issues due to sleet, snow and dirt accumulation.

Passive base bleeding involves the careful manipulation and ducting of naturally occurring high pressure air to areas of low pressure. Though the electrical system load drag is eliminated, there are still weight and space penalties and the systems need to be carefully tuned in order to operate most effectively. This fine tuning is often speed dependent, and reliant on maintaining exacting geometries. In practice, this might be difficult to maintain during normal trucking operations on roads where snow, sleet and debris are often present, resulting in the possible obstruction of the base bleeding structures.

Several university teams are looking at active suction and/or blowing technologies to increase the base pressure of trailers. ATDynamics has road tested two such configurations (from Tel

Aviv University and Georgia Tech Research Institute) and found that when the energy expenditure of the fans/blowers are accounted for, there is a *net loss* in system efficiency [44]. Improvement in the air supply/suction systems can be made, but the same study showed passive panels and boat tails provide at least as much drag reduction as the active devices, without any energy expenditure.

Operationally, active systems will be much more difficult to maintain, especially those that require air exchange through thin slots and holes such as those studies by ATDynamics.

Given the expected reliability issues of active and passive base bleeding systems when operating under normal weather conditions, further study in this area is not recommended.

7.2.2.7 Cooling airflow exhaust

Engine cooling is accomplished by airflow through the engine compartment, either driven by fans at low driving speeds or by ram effects at higher speeds. As the cooling air passes through the engine compartment after passing through the radiator, condenser and other auxiliary components, it is then reintroduced into the main airstream.

The manner in which the cooling air flow exhausts from the engine compartment may have an effect on the drag characteristics, particularly for underbody effects. It is not expected that cooling flow can be used for the passive base bleeding applications described in the previous section due to the large loss in pressure/energy as it travels through the engine compartment. For exhausting below the vehicle, the relative motions between the vehicle, the road, and the main airflow will be important, and one could conceive of scenarios to create either a drag reduction or a drag penalty.

7.2.2.8 Cab Underbody Treatments

Many aerodynamic treatments exist that have been proposed for the tractor-trailer industry. Some, like side skirts, were adopted long ago for tractors and are beginning to be adopted for trailers, but many more remain at the research phase. One area where possible gains exist with the addition of aerodynamic treatments is the underbody of the tractor. As reported in research [45], there were measurable improvements in aerodynamic performance when smoothing plates were added to the underside of the tractor. These benefits were measured to be in the range of a 0.015 to 0.018 reduction in drag coefficient. Using the methods found in Leuschen and Cooper [29], these reductions would equate to an annual possible fuel saving of up to 1080 litres of fuel per tractor. This is an area of the vehicle for which the relative motion between the vehicle, the ground and the main airflow is critical. As yet unpublished experiments at NRC have shown diverging results for techniques applied to the lower body depending on the motion, or lack there-of, of the wind-tunnel floor.

Implementation of such devices could pose operational issues with regards to maintenance, and increased weight, however, some benefits may be observed in that critical under cab components would be better protected, and fewer locations may exist for the accumulation of dirt, snow and ice.

7.3 Management of airflow around the tractor-trailer gap

7.3.1 Current state

The area immediately behind a Class 8 tractor and in front of the attached trailer is defined as the tractor-trailer gap (See Figure 13). The flow behaviour in this gap region affects directly the pressures on the back-face of the cab and the front face of the trailer, both of which are large surfaces perpendicular to the vehicle motion and therefore strong contributors to the overall drag on the vehicle. When prevailing winds impinge on the tractor-trailer at even moderate oblique angles, the cross flow through the gap modifies the pressures on the cab and trailer faces resulting in an increase in overall vehicle drag [46]. This is a dominant region for which a wind-averaged-drag evaluation is required to ascertain the benefits of drag reduction devices.

Figure 13 – Typical tractor-trailer gap

To minimize the effect of the gap flow on drag, completely sealing the gap would eliminate its drag contribution under cross-wind conditions. However, due to operational requirements, a minimum gap distance is required to allow the tractor to articulate relative to the trailer to facilitate manoeuvring at loading facilities and vehicle depots. Typical tractor-trailer gaps are in the range of about 1.0 meter (40 inches).

It has been shown that the gap begins to have a significant impact on vehicle drag once it is greater than about 0.45m, with the drag increasing by about 2% for every 0.25 m of increased gap beyond approximately 0.75 m. Research by Landman et al. [47] has suggested that by completely addressing the gap issue, drag savings on the order of about 6% could be achieved for a typical tractor-trailer. This would amount to an approximate 3% improvement in fuel consumption at 98 km/h (60 mph), as illustrated in Figure 14.

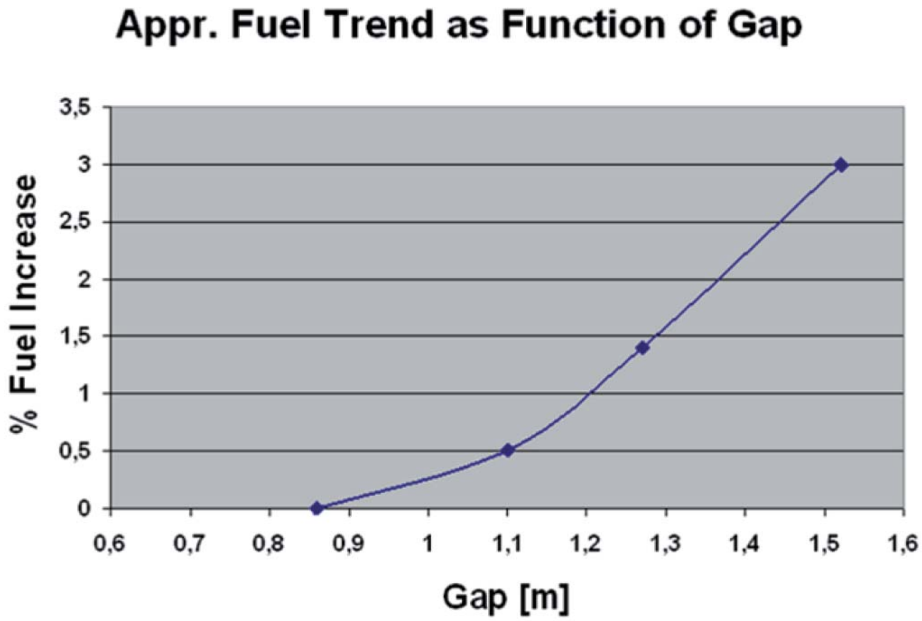

Figure 14 – Fuel burn increase vs. gap [99]

There are two primary types of devices aimed at reducing aerodynamic drag in the tractor-trailer gap. These are tractor side extensions and devices in the gaps.

7.3.2 Technologies

7.3.2.1 Tractor-Mounted

Side extenders (shown in Figure 15) act to extend the rear-edge of the cab to inhibit the flow of air into the gap region. Most OEMs offer side extenders as standard options for tractors.

Figure 15 – Cab side extensions

Additionally, the gap area is also often used to store ancillary tractor equipment. It is envisioned that a stowage solution could be designed that would not only allow the secure and efficient stowage of the ancillary equipment, but could also serve as a cab mounted gap filler device.

It has been reported in the research [43], [45] that significant opportunity exists for aerodynamic improvements in the treatment of the surfaces immediately behind the tractor cab. By covering the area in a horizontal fairing and blending it into the wheel fairings, it has been observed that significant aerodynamic benefits are possible.

A gap splitter (large vertical plate) is a technique often promoted for trailers (see next section). Cooper demonstrated [16] this as viable technique for cross-wind conditions. A tractor-mounted gap splitter would behave similarly while minimizing the cost of implementation.

A final tractor-mounted technique to reduce the drag associated with the gap is to reduce the distance between the rear of the tractor and the front of the trailer. This method is limited by the need of the operator to retain sufficient turning radius to enable loading and unloading at constrained dock areas or to negotiate tight right turns. Navistar/International Trucks is developing an active fifth-wheel system that will provide actuated gap reductions at highway speeds to reduce aerodynamic drag [48], thus eliminating the articulation problems of small gaps at low speeds. This concept would likely require low energy consumption that would be more than outweighed by the benefit of a smaller gap in highway conditions. Additionally, for tractors without roof fairings, or those with fairing not optimized for the trailer being pulled, gap reduction may not provide any significant benefit.

7.3.2.2 Trailer-Mounted

Many of the proposed devices intended to reduce the aerodynamic losses in the gap region are trailer-mounted devices. Consequently, there has not been a high level of adoption of the current gap-seal devices, with the exception of the tractor mounted side extensions discussed below. Gap splitters, trailer fairings and gap fillers are the here main techniques applied to the trailer (Figure 15). Further, gap splitters typically come in two varieties: center plane boards, and devices that attempt to fill the actual gap.

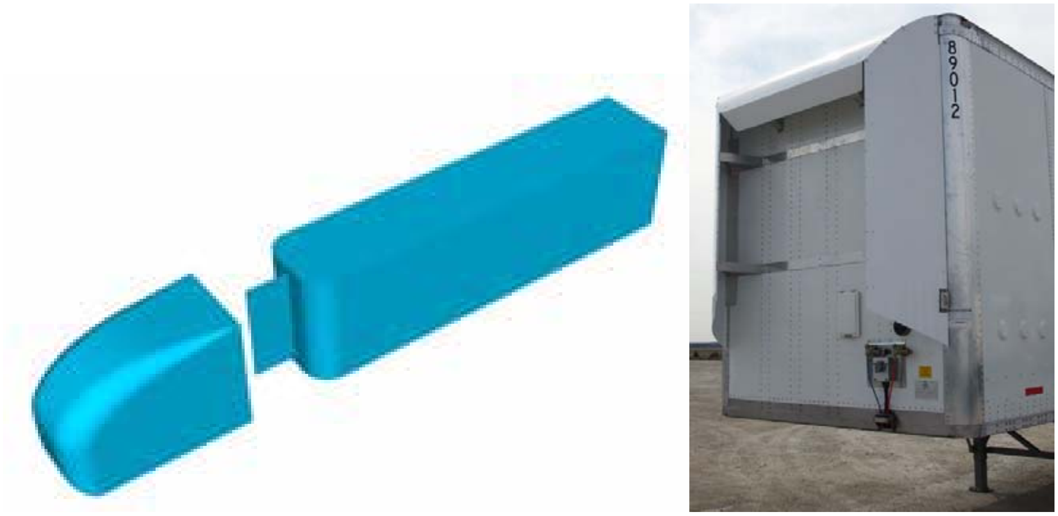

Figure 16 – Devices for the gap region: gap splitter (left), trailer fairing

Several manufacturers have commercial products for the gap regions on the market today that claim fuel savings on the order of 2%. The percentage savings are, however, highly dependent of the test procedure chosen, including initial gap size, and test speed.

Some of the gap-filling devices look similar to refrigeration units. It may be possible to optimize the shape of such refrigeration units to take advantage of the gap reduction effect.

7.3.3 General studies

Numerous academic studies have investigated the potential fuel saving effects of tractor-trailer gap devices. It is however appropriate to investigate first the theoretical maximum benefit of completely closing the gap. Such a study [47] suggested that the upper limit of aerodynamic improvement expected was in the range of a 7% drag reduction. At a typical speed of 55 mph, this would translate to an approximate 3.5% fuel saving.

Other studies, including [29], [37], [49] have reported fuel savings of between 1% and 3% for typical gap closure devices. These are important findings, as they are in line with quoted manufacturers numbers. There does exist, however, a significant opportunity to refine and optimize the traditional gap treatment devices to attain the maximum possible fuel savings. Additionally, little has been done to study the effects of towing a variety of trailers behind an aerodynamically streamlined cab. There exists the possibility that some combinations of tractor-trailer may exhibit reduced aerodynamic performance with the addition of certain gap treatments.

7.4 Management of airflow under the trailer

7.4.1 Current state

In a similar manner to the gap between the tractor and trailer, the open area below the trailer provides a greater drag detriment under cross-wind conditions. The general approach to minimize drag associated with this region is to prevent air from entering. Recently, Mercedes introduced a concept trailer that is reported to provide an 18% reduction in drag for a full European tractor-trailer combination (consist of a cab-over tractor) [50]. The trailer makes use of air dams, trim panels, side skirts, wheel fairings, and a boat tail to reduce the overall vehicle drag. The concept is a complete package and does not consist of individual add-on components. A thoroughly evaluated combination of add-on devices may provide the same level of drag reduction.

7.4.2 Technologies

7.4.2.1 Side Skirts

Side skirts, shown in Figure 17, are used to prevent air flow from entering the under-trailer region. In recent years, these have been widely adopted and are commonly observed on many trailers. Fuel consumption reductions on the order of 3-7% have been reported [2]. Also, these devices have simple mechanical designs such that maintenance and reliability should not be a major concern.

Figure 17 – Example of typical side skirt

Some variants on side skirts have been proposed. Modified version of side skirts, wedge skirts and side wings [14] are claimed to be optimized to enhance further the under-body aerodynamics.

7.4.2.2 Trailer Underbody Boxing

In a similar manner to side skirts, one approach to minimize under-trailer aerodynamics drag might be the development of lightweight underbody boxes, similar to those seen on commercial moving vans (Figure 18). Drag reductions on the order of 10-15% have been shown for wind-tunnel tests using scaled models of such configurations [51].

Figure 18 – Commercial moving truck with underbody boxes

There are operational issues that would need to be resolved, as well as significant weight penalties that may arise as well as changes to the breakover angle of the trailer; however there are benefits as well. It is envisioned that these boxes could be developed for the stowage of binding straps, chains, spare tires and other accessories. Such boxes could offer side under-ride protection to vulnerable road users. Any such implementation would have to be well designed to ensure that no ground clearance operability issues arose.

7.4.2.3 Wheel/bogie fairings

Leuschen and Cooper [29] found a measurable drag reduction associated with fairings around either the trailer wheels or around the full bogie. However, basic side skirts provide a larger magnitude of drag reduction and are generally of simpler design and construction. Therefore it is not expected that fairings will be strong contenders for the transportation industry.

7.5 Management of airflow at the rear of the trailer

7.5.1 Current state

The trailer base is one of the largest sources of drag for tractor trailers. Low pressure on the trailer face due to the aerodynamic wake, combined with the high pressure on the front face of the vehicle, causes a net pressure differential that generates a force in the downwind direction. This front-to-back pressure differential is the primary source of drag for most heavy vehicles. Increasing the base pressure will reduce this differential and reduce the net drag on the vehicle. Therefore, many drag-reduction technologies for the trailer are aimed at increasing this back pressure.

7.5.2 Technologies

7.5.2.1 Boat tails/extension panels

Tapering the back end of a long vehicle will increase its base pressure by providing pressure-recovery of the surrounding flow before it leaves the sharp back edges and forms a wake. This increased base pressure provides a lowered overall pressure difference from front-to-back of the tractor-trailer combination. Boat-tails, otherwise known as extension panels, is another technology that has been demonstrated to be effective to reduce the drag of tractor-trailer combinations, although various configurations are available (see examples in Figure 19).

Figure 19 – Boat tail concepts

Wind-tunnel and road tests [23], [32] have demonstrated that a boat tail with a length of 24 to 32 inches is optimal for drag reduction purposes and typical length restrictions. As with side skirts, the interaction of boat tails with other devices is important for optimization. A collaboration between NRC and Transport Canada has identified some optimum configurations (aerodynamically and operationally) using a 1:10-scale wind tunnel model. Demonstration in representative road conditions would be beneficial to provide further recommendations.

7.5.2.2 Vortex generators

Vortex generators are devices that, when placed on a surface, generate a vortex or array of vortices in the flow along the surface that can influence the flow-separation behaviour further downwind. Several concepts for implementing such devices on the sides and tops of trailers have been proposed as a means to reduce the aerodynamic drag of heavy vehicles. A small-scale wind-tunnel study of a vortex-strake concept showed a small benefit [49].

In their 2006 study, Leuschen and Cooper [29] attempted but were unable to find a vendor or concept developer available to have their vortex generator devices systematically tested on a full-scale truck in a wind tunnel. Therefore, they developed their own prototype vortex generator for testing purposes, which was based on the vortex-strake concept studied in [29]. They found it provided a measurable increase in vehicle drag with an associated increase in fuel consumption greater than 1% for typical usage of long-haul vehicle.

Since the first publication of this report in 2012, a privately funded track test program has demonstrated limited potential of a vortex generator concept applied to the roof and back side edges of a 53 ft trailer [36]. Test results indicated a fuel savings smaller than 1%.

7.5.2.3 Lowered/retractable trailers

The frontal area of a tractor-trailer is dictated by the trailer and its cargo volume. To reduce the drag of a tractor-trailer combination when running with an empty trailer, Brad Bennett, a designer from British Columbia, has proposed a retractable trailer concept as shown in Figure 20 [52]. This technology also requires a retractable tractor fairing, in order to be effective.

Figure 20 – Retractable trailer concept

7.5.2.4 System Drag Reduction (SDR)

A Spanish company, System Drag Reduction, S.L. has developed a technology that increases the base pressure on the base of the trailer by redirecting flow around the upper rear edge the trailer [35]. SDR claims a 4-6% reduction in fuel consumption and also claim the device reduces turbulence in the wake.

7.6 Operational Concerns

The most significant barrier to the adoption of any of the aforementioned devices will not be from a technical point of view, but rather, from an operational stand point and industry acceptance. It is believed however, that with an appropriate balance between operational concerns and aerodynamic benefit, significant enhancements can be made without unduly affecting operation or greatly increasing overall tractor or trailer acquisition costs.

In any of these future studies, the approach should first be to understand the operational concerns and barriers to commercial entry, prior to undertaking any aerodynamic experimentation or simulation.

7.7 Conclusions

Trailers and tractors are not always owned by the same operators therefore there may be reluctance on the part of trailer owners to pay for devices that will benefit the tractor owners.

The results of aerodynamic testing on heavy duty front bumpers have been scattered, however other factors are driving operators to use such devices. The vehicle-road-wind relative motion is an important for evaluating bumper and lower-body technologies.

Modest aerodynamic improvements may be achieved with the use of wheel covers and slotted mudflaps.

Superhydrophobic coatings could be used to reduce the likelihood that water and ice could build up on a trailer. However, this technology remains largely un-tested on road vehicles.

Base bleeding has been shown to reduce drag in laboratory settings, however, the need for electrical devices (which then become an electrical drain on the charging system and thus a parasitic loss to the engine) to provide airflow and the need to tune the ducting of passive systems makes base bleeding a much less practical alternative to drag reduction.

Cab underbody treatments have been shown to decrease the aerodynamic drag of tractors, however, testing should be performed using a rolling-road type wind tunnel to quantity the important vehicle-road-wind relative motions and hence actual performance gains.

It has been shown that the gap begins to have a significant impact on vehicle drag once it is greater than about 0.45m, with the drag increasing by about 2% for every 0.25 m of increased gap beyond approximately 0.75 m. Research has suggested that by completely addressing the gap issue, drag savings on the order of about 6% could be achieved for a typical tractor-trailer. This would amount to an approximate 3% improvement in fuel consumption at 98 km/h (60 mph). At least one manufacturer is developing a tractor fifth wheel that would move longitudinally to effectively reduce the tractor-trailer gap at high speed.

Several manufacturers have commercial products for the gap regions on the market today that claim fuel savings on the order of 2%. The percentage savings are, however, highly dependent of the test procedure chosen, including initial gap size, and test speed.

Numerous academic studies have investigated the potential fuel saving effects of tractor-trailer gap devices. It is, however, appropriate to first investigate the theoretical maximum benefit of completely closing the gap. Studies have suggested that the upper limit of aerodynamic improvement expected was in the range of a 7% drag reduction. At a typical speed of 55 mph, this would translate to an approximate 3.5% fuel saving.

Recently, Mercedes introduced a concept trailer that is reported to provide an 18% reduction in drag for a full European tractor-trailer combination (consist of a cab-over tractor).

Side skirts are used to prevent air flow from entering the under-trailer region. In recent years, these have been widely adopted and are commonly observed on many trailers. Fuel consumption reductions on the order of 3-7% have been reported.

Side underbody boxes have also been shown to reduce drag by as much as 10% to 15% and can be used to store equipment that would normally be strapped to the outside of the tractor or the underside of the trailer. Side underbody boxes could also be used in place of traditional side guards. However, they add weight to the trailer and could also affect the breakover angle as trailers pass over railroad tracks and other obstacles.

Wind-tunnel and road tests have demonstrated that a boat tail with a length of 24 to 32 inches is optimal for drag reduction purposes and typical length restrictions. As with side skirts, the interaction of boat tails with other devices is important for optimization.

Currently, limited evidence exists in peer-reviewed scientific sources to indicate that vortex generators have a significant impact on fuel savings for heavy vehicles.

Retractable trailers (i.e. trailers whose height reduces by a wide margin) are being prototyped in Canada but testing has yet to be performed to quantify the potential for drag reduction.

Aero-tractor models provide a reduction in aerodynamic drag, over the classic style, on the order of 30%. This is accomplished primarily through rounding of the front surfaces, the use of roof air deflectors, and the use of fairings over the fuel tanks between the steering axle and the drive axles.

7.8 Areas Recommended for Further Work

It is suggested that all the devices described in this section could be worthy candidates for further study with the exception of the base bleed devices and active flow control technologies. Furthermore, an integrated study of all the devices could be made to ensure that the aerodynamic gains of one device do not reduce the aerodynamic performance of another device installed further downstream on the vehicle.

The suggested process could involve scaled wind tunnel tests involving the sequential addition of each device until the vehicle was equipped with all of the above mentioned devices. Following that preliminary stage, full scale prototypes could be developed or purchased and tested in controlled real world driving situations. Application to different trailer types (dry van, tanker, flatbed with and without representative cargo) should also be evaluated to identify the benefits to the overall transportation industry. The wind-averaged drag coefficient measurement, which was designed to account for angle variations in terrestrial winds, is the most effective evaluation criteria.

In order to best serve the trucking community, and meet overall fuel consumption improvement goals, it is suggested that effort be focused more on developing tractor-based drag-reduction solutions. That said, there is still a strong benefit to trailer based devices such as side skirts and boat tails due to their demonstrated drag-reduction potentials.

In any of these future studies, the approach could first be to understand the operational concerns and barriers to commercial entry, prior to undertaking any aerodynamic experimentation or simulation.

8 AERODYNAMIC DRAG REDUCTION FOR INTERCITY BUSES

8.1 Definition

Canada is a major player in the design and manufacturing of intercity coaches, with two manufacturers sharing approximately 75% of the North American market in 2009, and employing a total of approximately 2000 workers [53]. The Canadian production of intercity buses totalled approximately 1800 units, with both manufacturers exporting about 90% of their production to the United States. In 2009, approximately 35,000 intercity coaches were in operation in North America.

The body of available literature on aerodynamic drag-reduction techniques and add-on devices for intercity buses is less extensive than for class 8 tractor-trailers. Several factors may account for this difference. The North-American bus fleet is much smaller than the tractor-trailer fleet and consequently, the annual fuel consumption and GHG emissions by intercity buses are significantly lower. Unlike tractor manufacturers, bus producers have control over the aerodynamic design of the entire vehicle and notwithstanding operational and regulatory constraints, they benefit from considerable design freedom to minimize aerodynamic drag through shape optimisation, among other things, with a direct impact on vehicle efficiency. There are also few manufacturers of intercity buses and in this competitive industry, design secrecy is the rule and little information is made public.

The popular belief is that buses, due to their characteristic shape, are not burdened by the large aerodynamic losses that plague tractor-trailers. This assertion is inaccurate and must be confronted to physical arguments. Based on the analysis of the respective contributions of mechanical and aerodynamic losses to the energy consumption of road vehicles, it is possible to determine a 'cross-over' vehicle speed beyond which aerodynamic losses dominate. Figure 21 presents an adaptation of the analysis of Cooper [55] who derived cross-over speeds for various categories of vehicles. A loaded intercity bus (24 tonnes) has a cross-over speed of about 70 km/h, whereas for the empty, 17-tonne bus this speed reduces to approximately 60 km/h. In comparison, for a tractor-trailer with a gross weight of 36 tonnes, the cross-over speed reaches about 90 km/h. By virtue of its lower ratio of rolling-to-aerodynamic resistance (the drag density parameter), the aerodynamic losses of an intercity bus outweigh the mechanical losses at a significantly lower vehicle speed than for a tractor-trailer. At highway speeds, a significant fraction of the energy expended is dissipated into aerodynamic losses. The corollary is that for a given percent-reduction in drag coefficient, the net percent-reduction in fuel consumption is larger for a bus than it is for a tractor-trailer. For a conventional North American intercity bus traveling at highway speed, aerodynamic drag represents approximately 60% of the energy expended to maintain vehicle speed.

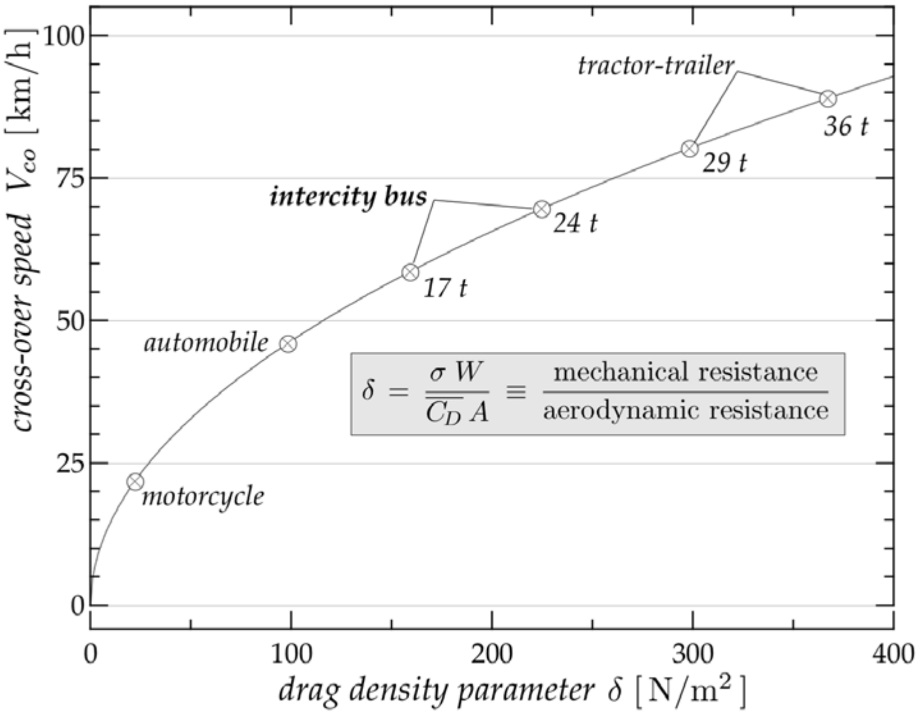

Figure 21 – Cross-over speed for which aerodynamic and mechanical resistances are equal, for several vehicle types. Adapted from Cooper [55]

A typical intercity bus is characterised by a refined and enclosed shape and the absence of pronounced discontinuities. This configuration has the potential to provide a high level of aerodynamic efficiency, provided that the design takes under serious consideration the physics that will govern the aerodynamic behaviour of the vehicle in its real operating environment. The aerodynamic losses can be broken down into four categories, each requiring a custom treatment:

A. External aerodynamics (body shape, texture);
B. Appendage aerodynamics (mirrors, antennae, etc.);
C. Underbody aerodynamics; and
D. Engine cooling aerodynamics.

A- The dominant contribution to the aerodynamic drag of an intercity bus is the pressure differential between the forward- and rearward-facing surfaces of the body, with a minimal contribution from skin friction. According to Cooper [56], about 60 to 70 percent of the total wind-averaged drag of a bus is attributed to pressure loads acting on the vehicle forebody, making it the principal area for drag reduction strategies. By far the most efficient method of reducing forebody drag is to minimize flow separation by combining the rounding of the forward corners (sides and top) with the tapering of the forebody. This was also confirmed by the experiments of McDonald and Palmer [57] who retrofitted existing bus models with forebody fairings, achieving drag reductions up to 27%. Camara and Girardi [58] reported a 40% drag reduction with optimal rounding, compared to a square front. This reduction was attributed to reduced static pressures on the corners, indicating flow attachment. Recent experiments by Newnham et al. [104] reveal that the flow field around such corners is strongly influenced by free-stream turbulence. Hence, a proper simulation aimed at minimizing the aerodynamic drag of buses must reproduce both the Reynolds number and the turbulence characteristics that will be experienced by the vehicle in real operating conditions. Of significant importance, as well, is the presence of obstacles in the vicinity of a corner, such as rubber mouldings or joints, which may trigger premature flow separation. Notwithstanding the critical importance of forebody flow, gains can also be made in the tail region, where it is desirable to energize the wake and reduce the spatial extent of the separation bubble. Experimental and numerical work has been done on generic bluff-body shapes where parametric variations of a tapered tail were studied [59]. By combining corner rounding and tapering with an innovative tail comprising a "vortex trap", Fletcher and Stewart's wind tunnel investigation [60] reported a reduction of the aerodynamic drag coefficient from 0.43 to 0.29, compared to a baseline commercial bus configuration. More recently, the CFD experiments of Raveendran et al. [61] revealed a C_D reduction from 0.53 to 0.29, resulting from a radical redesign incorporating features such as: reduced frontal area, windshield inclination, corner rounding, rear roof taper and the elimination of rear-view mirrors. Another wind tunnel investigation by Balakrishnan et al. [62] on scale models of commercial buses explored the combined effects of front edge rounding and tapering of the roofline in the tail area. These modifications allowed the coefficient of aerodynamic drag of the original box-like buses to be reduced from as high as 0.93, down to 0.42. The CFD experiment of Kim et al. [63] on a modified bus model revealed that the addition of a downwards-sloping rear roof spoiler reduced the aerodynamic drag coefficient by about 0.083, a reduction of more than 13%. In light of the large C_D-reduction potential afforded by a sound aerodynamic design of the body shape, a bus optimisation process aimed at reducing fuel consumption ought to assign a high priority to aerodynamic shaping, early in the design process.

As pointed out by Fletcher and Stewart [60], reducing aerodynamic drag by optimising body shape, besides diminishing fuel consumption, also provides substantial secondary benefits associated with a "cleaner flow", including:

- better handling in side-winds;
- safer passing and overtaking;
- lessened dirt accumulation (soiling, visibility);
- reduced aerodynamic noise (attached flow); and
- reduced driver fatigue.

B - It is paradoxical that bus appendages such as rear-view mirrors, when fastened to an aerodynamically-optimised bus body, may cause a non-negligible deterioration of the vehicle's aerodynamic performance. Consider a pair of mirrors, each with a surface area of 0.08 m^2, with a drag coefficient of unity. When installed on a typical intercity bus model (frontal area of 8 m^2), the incremental drag coefficient caused by the mirrors can be estimated to be $\Delta C_D \approx 2 \times 0.08 / 8 = 0.020$. This corresponds to more than 3% of the overall aerodynamic drag, for a bus with a drag coefficient of C_D=0.60. This is without considering that the presence of such mirrors in the vicinity of the forward lateral corners perturbs the local flow field and may induce detrimental flow separation coupled with a further drag increase. As the design trends move towards bus configurations with streamlined shapes and drag coefficients approaching 0.30, the drag penalty associated with rear-view mirrors and other drag-enhancing appendages will become less tolerable. In this context, regulations authorizing the use of standard rear-view cameras to replace mirrors would be a step in the right direction, to minimize aerodynamic disturbances, as was discussed in Section 5 in regards to tractor-trailers. This implementation could be coupled with the mandatory installation of standard mechanical pop-out mirrors that would deploy in the event of camera failure.

C - Underbody aerodynamics is becoming increasingly important, in the quest to reduce fuel consumption of surface vehicles. A recent experimental program conducted at BMW [64] and comprising wind tunnel and road tests, quantified the reduction of aerodynamic drag resulting from the installation of underbody panels covering approximately 60% of the underside. The correlation between the wind tunnel and track tests were based upon the measurement of 124 static pressures, distributed over the panels. The wind tunnel tests showed a drag reduction reaching about $\Delta C_D \approx -0.012$, as a result of the underbody panels. In addition, it was found that streamlining the wheels with hub covers further reduced C_D by 0.022. The study revealed the importance of proper ground simulation and wheel rotation, to ensure the realism of the wind tunnel measurements of the underbody flow. A recent CFD parametric study conducted by Ortega and Salari [65] focused on the effect of an underbody fairing installed on the underside of a trailer attached to a heavy-duty tractor. Each tapered fairing tested was located immediately downstream of the tractor wheels and extended as far as the trailer bogey. Its main purpose was to mitigate or eliminate the observed flow recirculation zone originating downwind of the tractor drive wheels and inducing negative pressures on downstream-facing elements. The best configuration tested (longest fairing) was found to reduce the drag coefficient by 0.042, a reduction of about 6.5%, a performance that was found to be superior to that of side-skirts. The objectives of underbody modifications can be summarised into three fundamental sub-objectives:

- to shield forward-facing surfaces from high-speed flow;
- to mitigate wakes behind underbody elements, in order to attenuate suction pressures on rearward-facing surfaces; and
- to maximize the air velocity exiting at the rear of the vehicle underside, in order to energize the vehicle wake, thereby reducing the magnitude of the negative base pressure.

The underside of an intercity bus is already quite "clean", when compared to other vehicle types. However, there are areas where fairings could reduce the exposure of underbody components to high-speed flows or attenuate wake-induced drag. In particular, the shielding of protruding suspension components in the forward, high-speed flow region, coupled with a wake-mitigating fairing, offers a potential for drag reduction. For tractor-trailers, side-skirts coupled with underbody fairings can provide a substantial reduction in aerodynamic drag [66]. Intercity buses effectively already incorporate a skirt-like configuration which could be further optimised. Channeling the underbody flow towards the vehicle rear end with minimal obstruction could provide the opportunity to utilise the kinetic energy of the flow to enhance the efficiency of engine cooling (partial RAM effect), and/or direct this channelled flow into the wake region.

D - Engine cooling requires ambient air to be channelled from an inlet towards a heat exchanger, and thereafter expelled into the surroundings through an outlet. Through this process, energetic losses are incurred, which contribute to an effective increase of the vehicle aerodynamic drag. For RAM cooling, where the cooling flow is driven passively by making use of favorable pressure differentials between the inlet and outlet (i.e. without a cooling fan), the cooling drag was defined as follows by Williams [67]: "the increase in vehicle drag from a closed front-end reference condition. It consists of two parts - the internal drag (internal momentum loss) of the cooling airflow and the external interference to vehicle pressure distribution, both at the inlet and at the exit". Much insight can be gained into the physics of cooling, via analytical means, by examining the momentum balance of a simplified cooling system. According to Ivanić and Gilliéron [68], for conventional automobile configurations, the cooling drag can represent as much as 10% of the aerodynamic drag of an automobile. Their analysis, coupled with wind tunnel experiments on a model incorporating a simplified passive cooling system, identifies the fundamental parameters defining the energetic efficiency of a cooling system: the inlet/outlet cross-section ratio and the inflow and outflow angles at the cooling inlet and outlet. Their analysis reveals that cooling efficiency is increased under the following conditions:

1. The cooling inlet is located in the region of stagnation, on the vehicle forebody
2. The cooling outlet is located in a low-pressure region, such as the vehicle rear end (wake)
3. An outlet angle of about 50° from the horizontal appeared most favourable
4. An inlet/outlet section ratio of unit is most favourable

These conditions are not necessarily trivial to implement for a long vehicle, such as an intercity bus. The fact that the engine is located at the rear facilitates the ejection of cooling air in the wake region. However, the vehicle stagnation zone is located some twelve metres forward of the engine. A design consisting of conveying RAM-air over this distance through a dedicated duct is likely to suffer from significant static pressure losses that will result in insufficient cooling flow. For this reason, a cooling fan is necessary. Notwithstanding, the configuration of the cooling system, in particular the location and orientation of the inlet and outlet, as well as the internal configuration, will determine the power required by the fan to achieve proper cooling. As mentioned above, the efficient channeling of underbody flow towards the rear, where the cooling intake would be located, may enhance cooling efficiency. Considering that the fan power is provided by the engine, the optimisation of the cooling system to minimize losses can lead to measurable reductions in fuel consumption. For development and optimisation purposes, as stated by Cooper [55], the wind tunnel remains the most efficient tool. However, as pointed out by Wickern et al. [69], for cooling system optimisation, proper ground simulation incorporating a moving ground plane and rotating wheels is critical to ensure the realism of the wind tunnel simulation. It was found that testing a vehicle without proper ground simulation resulted in a considerable underestimate of cooling drag.

It was convenient to break down the contributions to aerodynamic drag into four catagories (A-D), in order to direct the focus on independently coherent themes. However, it must be recognized that all four aerodynamic categories interplay with each other. The important objective is the end results, that is, a global reduction of the aerodynamic drag, which can only be reached via an all-encompassing, "holistic" approach, also including practical and operational considerations. For this purpose, three test methods are available: Wind tunnel testing, CFD and road testing. While the wind tunnel is a choice tool, CFD generates a wealth of information not available otherwise, and can provide much insight into flow physics and guidance for the design of wind tunnel experiments. The ultimate verification tool is road testing which provides real-life operating conditions to validate vehicle efficiency. These different testing methods are described in Section 11.

Finally, there is little research that has been done on sloping the rear roofline of intercity buses. As buses do not suffer the same constraints on cubic interior volume as highway trailers, there is room to investigate gains by sloping the rear portion of the bus roof.

8.2 Current State

Considering the design of present-day North American intercity buses, it is not unrealistic to expect their drag coefficient to be in excess of 0.50, at zero yaw angle. For comparison, the recent bus design shown in Figure 25, produced by a German manufacturer and currently in operation on European roads, is characterized by a drag coefficient of 0.35 [70], [71] Given the low drag levels that have been reported in the literature for optimised configurations with C_D as low as 0.28, it is clear that there exists a potential for substantial improvements of North American bus designs, in all four areas outlined above. For example, a reduction of the aerodynamic drag coefficient from 0.60 to 0.30 would lead to a decrease of fuel consumption of approximately 30%. A proposed direction for future work is provided in last section of this chapter.

Figure 22 – German-designed intercity bus with $C_D \approx 0.35$.

8.3 Operational Concerns

Aerodynamic optimisation would be easily achieved without operational and practical constraints: all vehicles would be teardrop-shaped. Intercity buses, which are meant to transport a number of passengers, have specific constraints that impose compromises to the aerodynamicist. These include:

1. maximising number of passengers
2. interior space and passenger comfort
3. heating/cooling/ventilation of bus interior
4. driver visibility - forward, lateral and rearward
5. need for rear-view mirrors (ideally cameras)
6. required appendages (antennae, etc.)
7. access and emergency doors, windows (potential surface discontinuities)
8. exterior dimensions and clearances (regulations)
9. need for cargo space (for luggage, etc.)
10. soiling must be minimised
11. snow and ice accumulation in wheel wells and underbody
12. windshield wipers (flow disturbance)

Finally, an area of possible aerodynamic benefit is by re-profiling the roofline. As coach buses do not have the same cargo capacity constraints, it is believed that the rear roofline could be modified with minimal impact to passenger comfort. Operational issues should not be a concern.

8.4 Conclusions

The applicability of aerodynamic add-on devices for use on long haul intercity motor coach buses has been less well studied than those of class 8 tractor trailers. The North-American bus fleet is much smaller than the tractor- fleet and consequently, the annual fuel consumption and GHG emissions by intercity buses are significantly lower.

A typical highway coach exhibits a number of aerodynamic advantages over a class 8 tractor-trailer: there is no gap; the body comes lower to the ground effectively incorporating side skirts; and a flat front end eliminates the multiple aerodynamic discontinuities typically caused by radiator-hood, hood-windscreen and windscreen-fairing locations. Consequently, a stock long haul highway coach may have a C_D as low as 0.384.

By virtue of its lower ratio of rolling-to-aerodynamic resistance (the drag density parameter), the aerodynamic losses of an intercity bus outweigh the mechanical losses at a significantly lower vehicle speed than for a tractor-trailer. For a given percent-reduction in drag coefficient, the net percent-reduction in fuel consumption is larger for a bus than it is for a tractor-trailer.

The dominant contribution to the aerodynamic drag of an intercity bus is the pressure differential between the forward- and rearward-facing surfaces of the body, with a minimal contribution from skin friction.

About 60 to 70 percent of the total wind-averaged drag of a bus is attributed to pressure loads acting on the vehicle forebody, making it the principal area for drag reduction strategies. By far the most efficient method of reducing forebody drag is to minimize flow separation by combining the rounding of the forward corners (sides and top) with the tapering of the forebody.

Underbody aerodynamics is becoming increasingly important, in the quest to reduce fuel consumption of surface vehicles. Wind tunnel tests showed a drag reduction reaching about $\Delta C_D \approx -0.012$, as a result of the underbody panels. In addition, it was found that streamlining the wheels with hub covers further reduced C_D by 0.022. Although the undersides of buses are already quite aerodynamically 'clean', research could be conducted to investigate channelling the underbody flow towards the vehicle rear end. Air must be diverted into the engine for cooling purposes and this can be a significant factor. Bus undersides with minimal obstruction could provide the opportunity to utilise the kinetic energy of the flow to enhance the efficiency of engine cooling (partial RAM effect), and/or direct this channelled flow into the wake region.

Finally, an area of possible aerodynamic benefit is by re-profiling the roofline. As coach buses do not have the same cargo capacity constraints, it is believed that the rear roofline could be modified with minimal impact to passenger comfort. Operational issues should not be a concern.

8.5 Areas Recommended for Future Work

Given the secrecy characterizing the bus industry, it is clear that the optimization process taking into consideration aerodynamic performance objectives and operational constraints would remain the responsibility of the Canadian bus manufacturers. In this respect, and outside the scope of this program, the NRC and Transport Canada could contribute, upon client request, to this process as an advisor providing aerodynamic expertise and guidance to the industry.

An area that could require further investigation within the context of the ecoTECHNOLOGY for Vehicles II program, is a *recommendations document* to Canadian bus manufacturers and operators that can help guide their development and selection efforts, respectively, towards reducing the fuel consumption and emissions from intercity buses. Such a document can be based on information contained within this report.

9 SHEDDING OF ICE AND SNOW

9.1 Definition

The idea of ice and snow shedding off highway tractors and trailers is not new. However, the addition of any of the aerodynamic devices described in this document provides more surface area onto which snow and ice may accumulate. The ice and snow not only adds weight to vehicles that may already be near, or at, their legal weight limit but the snow or ice may eventually become dislodged or ejected onto vehicles surrounding the tractor or trailer. For these reasons, it will be important to understand if aerodynamic devices that are designed for use in, say, Southern California could contribute to ice and snow accumulation and shedding when used in Canada. It will also be important to understand if snow and ice could accumulate on an aerodynamic device to the point that the device actually begins to increase the aerodynamic drag, compared to a vehicle without the device. Another effect worth considering is splash and spray and how aerodynamic devices could affect the flow of water and slush as it leaves the tractor and the trailer.

9.2 Current State

Currently, Canadian operators use side skirts, boat tails and other add on devices with little regard for ice and snow shedding other than to bang off the snow during their pre-trip inspection or at truck stops while re-fuelling. And this is likely done to remove excess weight, rather than to preserve any aerodynamic effects of the devices.

9.3 Manufacturer Claims

Many manufacturers of aerodynamic devices make claims that the addition of their devices alters the flow field downstream of the trailer. However, the do not specifically make mention of how snow and ice are shed from their devices. The claims of one boat tail manufacturer are listed as follows:

- Improved vehicle stability from streamlined flow;
- Improved driver visibility due to reduced spray from rear wheels; and
- Reduced tail-gating and fatal rear end collisions due to 4 ft collapsible extension.

9.4 Academic Studies

NRC-CSTT performed a study [32] to determine what effects boat tails would have on other vehicles on the road, particularly vehicles that were travelling directly behind a boat tail equipped trailer.

The term boat tail refers to a kit of extension panels or fairings that are mounted to the rear of a trailer for the purpose of reducing overall vehicle drag by reducing turbulence and pressure drop at the rear of the trailer. Although it would be possible to design rear fairings for nearly any type of trailer, boat tails are normally used on dry van semi-trailers as these trailers tend to have relatively high drag due to their large surface area (both frontal and side). Dry van trailers also lend themselves nicely to the addition of extension panels off the rear edges, provided care is taken to design them such that access to the doors is not impeded. Current commercially available boat tails are fully extended while in use and fold back against the trailer doors when the driver wishes to back the vehicle into a loading dock and/or open the rear doors.

The three major sections of a non-inflatable, straight panel boat tail are the side panels, the bottom panel and the top panel. The two side panels are attached to the right and left rear vertical edges of the trailer and must be angled inboard in order to be aerodynamically effective. The top and bottom panels are optional panels that help to further reduce drag beyond what could be achieved with the two side panels.

The boat tail works by streamlining the rear of the trailer. The air follows the panels off the boat tail around the rear corner, Instead of separating at the rear edge of the trailer. The suction drag on the rear of the trailer is reduced by deflecting the air inwards.

One section of the study used CFD to illustrate the flow field behind a 53 foot van semi trailer, with and without boat tails. The authors concluded that even a two foot long boat tail significantly altered the downstream flow field compared to a trailer without a boat tail. The effect of the boat tails on the downstream flow field can be seen in Figure 23. However, the CFD was not used to model how snow or ice would be shed from a trailer with a boat tail. Further study would be required to determine if the difference in flow fields, seen in Figure 23, would affect the ability of drivers to see clearly when following heavy trucks during a snow storm.

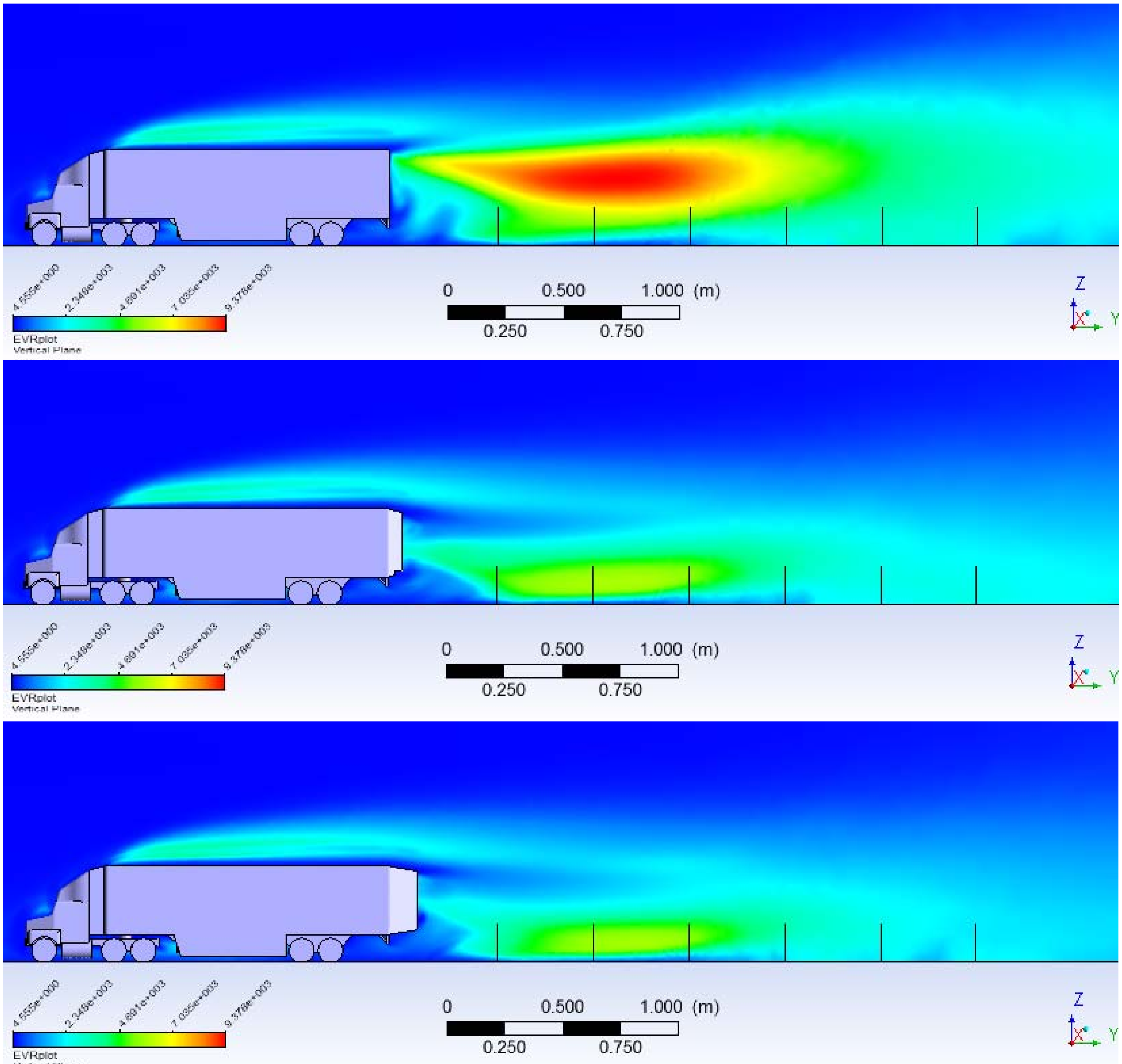

Figure 23 – Flow field behind three trailers with no boat tail, 2 ft boat tail and 4 ft boat tail

NRC-CSTT performed an extensive literature search for other international studies and could only find subject matter regarding ice and snow shedding from aeronautical equipment and devices such as aircraft, helicopters and rotors.

9.5 Operational Concerns

Operational concerns are presented throughout this section.

9.6 Conclusions

Very little information could be found regarding test or modeling results of how ice and snow can accumulate on aerodynamic devices.

Boat tails can significantly affect the flow field directly behind a van semi-trailer and it is also expected that snow could accumulate on top of the bottom boat tail panel. However, very little relevant work could be located to quantify how this change in flow field would affect vehicles following behind a trailer equipped with a boat tail or the way in which snow and ice accumulates and sheds from truck aerodynamic devices.

9.7 Areas Recommended for Further Work

NRC recommends performing a similar study to the NRC-IAR [6] study in which many aerodynamic devices were sequentially added to a tractor and trailer combination. However, for this study, the emphasis would be on ice and snow accumulation and shedding, rather than aerodynamic drag. Ideally, a scale model vehicle would be placed in a wind tunnel at sub zero temperatures and snow and ice would be blown against the model vehicle. However, the problem of adequate physical scaling will have to be undertaken before such a concept can be developed. If such a technique is adequate, the amount of snow accumulation and shedding could be measured against a baseline vehicle that was placed beside the test vehicle. Downstream effects on a scale model passenger car following the trailer could also be monitored to determine if the snow and ice would be more likely to accumulate on a trailing vehicle and also to determine if the forward vision of drivers in trailing vehicles is affected in any way.

Ultimately, track testing or road testing on actual highway tractor trailers could be performed to determine if devices such as boat tails were likely to accumulate amounts of snow that could eventually become ejected onto the road surface or other vehicles in the surrounding area.

10 SCALE MODEL TESTING

10.1 Introduction

Various methods are available to test drag reduction devices for tractor trailers: road/track testing, wind tunnel testing and CFD simulation. Full-scale testing of a production vehicle and accessories would appear the ideal scenario. The SAE has defined test procedures for fuel consumption based on road testing (SAE J1321 [72]) and rolling resistance and aerodynamic drag based on coast-down testing (SAE J1263 [73], J2263 [74]). However, the variability in atmospheric conditions cannot provide a consistent and comparable method to provide quantitative performance and reliable comparability between different configurations. Wind tunnel testing has become a medium for such comparisons. The NRC-IAR has been active in the field of surface-vehicle wind-tunnel simulation for more than three decades, and has contributed towards the SAE recommended practice for wind-tunnel testing of heavy vehicles (SAE J1252, [3]). The NRC-IAR has the capabilities to test model-scale as well as full-scale truck within two of its main facilities: the 2 m x 3 m Wind Tunnel and the 9 m x 9 m Wind Tunnel. Many of the standard drag reduction devices found in the transportation industry were first studied in research conducted at the NRC-IAR wind tunnels dating back to the 1970s [5].

In general, the aerodynamic performance of a tractor trailer combination is affected by many environmental factors. Those most pertinent to evaluating the aerodynamic performance and efficiency of such vehicles are:

- Vehicle geometry;
- Vehicle speed;
- Air properties (barometric pressure, temperature, density, humidity);
- Wind speed, which can vary with height;
- Wind direction, which can vary with height; and
- Wind turbulence intensity, length scales, spectra, which can all vary with height.

Section 11 describes the typical methods used for evaluating the aerodynamic performance. This Chapter emphasizes scale-model wind-tunnel testing for the evaluation of drag reduction technologies for tractor trailers.

10.2 Wind tunnel testing

10.2.1 Model scale factor

Scale model testing provides smaller wind loads on the vehicle than would be experienced by a real truck, but the aerodynamic drag can be scaled to full-size conditions through the drag coefficient, defined as:

$$C_D = \frac{D}{QA} \qquad [2]$$

where D is the drag force, A is the model reference area (typically frontal area), and Q is the dynamic pressure of the oncoming wind ($Q = \frac{1}{2}\rho V^2$). This aerodynamic scaling allows model-scale results to be directly applied to full-scale conditions [6].

A wind tunnel provides consistent conditions from which detailed analyses and quantification of drag reduction devices can be performed. Although consistent conditions can be maintained, wind-tunnel simulation has some drawbacks, primarily those associated with the scale of the models and the size of the models relative to the wind-tunnel cross section. There are various factors to consider when developing a wind tunnel test program, and NRC-IAR has considerable experience with wind tunnel tests of ground vehicles. Important considerations are:

a) Blockage and wall-interference: The confinement of the flow around the body combined with the interaction of the flow with the tunnel boundary (closed walls or open-jet) modifies the flow field that would be encountered on the open road. Techniques are available to correct the wind tunnel data for these effects. However, whenever possible, model scaling is done to have a blockage area ratio of 5% or less to minimize the uncertainty in the results. However, blockage corrections for area ratios up to 10% are well documented and perform well.

b) Reynolds number: Although small models are preferable to minimize blockage and boundary-interference effects, as well as to accommodate smaller wind tunnels, this can lead to inaccurate flow scaling. The aerodynamic loads on a surface vehicle can be strongly dependent on viscous effects (friction on the model surface and turbulence in the shear layers, wake and flow-separation regions over the vehicle) and a true simulation of on-road conditions would require matching of an aerodynamic parameter called the Reynolds number in order to accurately simulate these effects. The Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho L V}{\mu} \qquad [3]$$

where ρ is the density of air, L is a length scale representative of the body, V is the wind speed, and μ is the viscosity of the air. The air properties of road conditions (ρ and μ) can easily be matched in a wind tunnel, as can the wind speed. However, the length scale often cannot be matched. To match the Reynolds number, the combined parameters in Equation 3 must match to obtain a true representation of the aerodynamic performance of the vehicle. Typical wind tunnels operate under atmospheric conditions and therefore the air properties cannot be varied enough to offset the length-scale disparity. This leaves the wind speed. For example, a half-scale model ($L_{model} = 0.5 L_{fullscale}$) requires a doubling of the road-equivalent wind speed to match the Reynolds number ($V_{windtunnel} = 2V_{fullscale}$). In some cases this can be accomplished, but many wind tunnels cannot reach the speeds required when smaller-scale models (1/10 scale, for example) are used. For such a scale, even if the wind tunnel can reach such speeds, air compressibility effects, characterized by the Mach number (ratio of wind speed to speed of sound), will become a problem. For practical purposes, the Mach number should remain below a value of approximately 0.25 to minimize such complications (300 km/hr under standard atmospheric conditions).

Based on the arguments in a) and b) above, to simulate the aerodynamic performance of a road vehicle under representative conditions, for a typical highway speed of 100 km/hr, one should use a scale no smaller than 1/3. This, combined with a desire to keep the blockage of a tractor-trailer model no greater than 5% results in the need for a wind tunnel with a cross sectional area of approximately 70 m^2 (8 m x 8 m cross section) and a wind speed of 300 km/hr, a combination of which is difficult to find. The NRC-IAR 9m x 9m Wind Tunnel can accommodate this ideal scale and can approach the desired speed.

Under some conditions, Reynolds-number matching can be relaxed and reliable simulation for the purpose of comparative analysis is still possible. The Reynolds number sensitivity is caused primarily by the flow around rounded corners of the vehicle [77], and a thorough understanding of the implications of such changes is required before relaxing this condition. Older-model tractors that have flat surfaces and sharp corners are generally less sensitive to Reynolds number effects than are the new *aero* trucks.

a) Relative motion between the vehicle and the ground: Another important consideration for simulating the correct aerodynamic performance of road vehicles in a wind tunnel is the relative motion of a vehicle with respect to the wind and the road, and the effect of rotating wheels [78]. On the road, a vehicle moves relative to its surroundings (ground and air) whereas in a wind tunnel the ground is stationary in relation to the model. The aerodynamic performance of the lower part of a vehicle (bumper, underbody, wheels, trailer bogie, etc.) may be strongly influenced by this relative motion between the vehicle and the ground, as well as the associated wheel rotation. Different wind tunnels use various techniques to mitigate this relative-motion problem, if it is considered at all. Some wind tunnels use suction of the boundary layer immediately upwind of the model to create a thin boundary-layer that has negligible influence in the flow surrounding the model (NRC-IAR 2 m x 3 m and 9 m x 9 m Wind Tunnels). Others use rolling road system consisting of one or several belts that move the ground-plane at the same speed as the wind, relative to the vehicle, and rotate the wheels through roller systems or motors (e.g. NRC-IAR 9 m x 9 m Wind Tunnel, Pininfarina Wind Tunnel, Volvo Wind Tunnel). The NRC 9m x 9m Wind Tunnel uses the combination of both techniques.

b) Terrestrial-winds: In general, atmospheric winds are turbulent; they vary with height, and are of significant strength that large cross-winds are commonly encountered by road vehicles even at highway speeds. A cross wind generates an effective angle between the absolute truck motion and the wind vector (yaw angle). Under such cross-wind conditions, the aerodynamic characteristics of a ground vehicle, especially tractor-trailer combinations, behave differently than when the ambient winds are either static or when they are in line with the vehicle motion [78]. The general method to deal with the net effect of varying wind conditions is to define a wind-averaged-drag coefficient. This approach is based on combining the ground speed of the vehicle with a mean terrestrial wind speed that is equally probable to be blowing from any direction. A distribution of effective yaw angles can be combined with the vehicle drag polar (variation of drag coefficient with yaw angle) to define an effective drag coefficient to be encountered by the vehicle on the road. To obtain the wind-averaged-drag coefficient in a wind-tunnel simulation, drag measurements are made over a range of yaw angles (by rotating the vehicle relative to the wind direction). For highway speeds, yaw angles up to about 10 degrees are required to obtain a wind-averaged drag coefficient. At lower speeds, representing city and short-commute driving conditions, yaw angles up to 15 degrees are generally required [3]. Any asymmetry in a truck configuration then requires measurements representing cross-winds from both directions (+/- yaw range) to obtain a correct wind-averaged drag coefficient. For moderate cross-winds the yaw angle can exceed 10º, and under these conditions the drag of a tractor trailer can exceed 50% of its zero-yaw drag load. Therefore, the wind-averaged drag coefficient is the most critical aerodynamic performance indicator for long heavy vehicles such as trucks or buses because it represents an average of the typical wind conditions under which these vehicles will operate.

c) Wind turbulence: Although the wind-averaged-drag approach accounts for variations in the mean atmospheric winds, turbulence associated with these winds and from the wakes of other vehicles on the road is usually not simulated in wind tunnel test programs. It has long been recognized that turbulence can not only affect the magnitude of the drag experienced by a tractor-trailer combination, but can also affect the characteristics of the drag mechanisms and how they vary with wind direction [79], [80]. This applies also to the effects of drag-reduction devices. A drag reduction device may show negligible sensitivity to turbulence when winds are aligned with the truck motion, but can show different levels of drag reduction in cross-flows depending on the turbulence environment. The characteristics of the turbulence environment are important for adequately assessing the performance of drag-reduction devices for road conditions. Section 11.3.2 describes techniques to simulate them in a wind tunnel.

d) Wind profile twist: In general, wind speed increases with distance from the ground. This generates a variation with height of the wind-speed experienced by a road vehicle, as well as a variation in the wind direction with height when cross winds are present. The effect of such wind conditions on the aerodynamic performance of a tractor trailer is not known, but it is expected to be significant. Section 11.3.3 describes techniques for simulating this shear and twist of the wind profile in the wind tunnel.

10.3 Current State

In recent years, many drag reduction devices for tractor-trailer combinations have been demonstrated through full-scale wind tunnel testing, by matching road-condition Reynolds numbers, of which NRC-IAR has performed some of the work [6], [7]. These investigations have been intended primarily to examine the relative performance of the devices to a standard road configuration for such trucks.

This study by Leuschen and Cooper [6], [7] was done under close-to-real conditions (see Figure 24). However, some improvements to the simulation could be included for future work. The trailer lengths used for the study (28 ft and 40 ft) were shorter than the standard 53 ft trailers in use for most long-haul transport. Also, the tests were conducted in smooth-flow conditions and therefore the effects of atmospheric turbulence and vehicle-wake turbulence were not accounted for. This is a limitation of any full-scale wind-tunnel tests of tractor trailers. Appropriate turbulence conditions for road vehicles are difficult to achieve in wind tunnels for full-scale evaluations (see Section 11.3.2) partly due to the size of the equipment necessary to generate the turbulence. Despite these limitations, the results of Leuschen and Cooper showed the promise of such devices for drag-reduction of tractor-trailer combinations. From this study, incremental changes in the drag coefficient are likely realistic for low-turbulence conditions, but not necessarily the absolute levels.

More recently, a US Department of Energy (DOE) investigation of a full-scale tractor-trailer combination, using a 53 ft trailer, in the National Full-Scale Aerodynamics Complex (NFAC) Ames Research Center evaluated a number of drag reduction devices [8] (see Figure 25). Results have not yet been published, but press releases claim a 12% reduction in fuel consumption could result from the technology tested. Some results from the study have corroborated NRC-CSTT testing results indicating a 24 to 32 inch boat tail for the trailer is optimal for drag reduction and operational constraints [23], [32].

Figure 24 – Full-scale tractor-trailer testing in the NRC 9 m x 9 m Wind Tunnel

Figure 25 – Full-scale tractor-trailer testing in the NFAC 24 m x 36 m Wind Tunnel

10.4 Model Scale Evaluation of Drag Reduction Technologies

The largest detriment to wind-tunnel testing of full-scale heavy vehicles is the size of the vehicles and the time required to prepare them for testing. The two sets of full-scale tests described above [6], [7], [8] required the tractors and trailer to be lifted by crane into the wind tunnels. Safely rigging and lifting such vehicles is difficult and labour-intensive, resulting in expensive setup costs. Model changes are also time-consuming when dealing with full-scale parts. Model-scale testing eliminates some of these challenges. Combined with the ability to test scale models at or near design Reynolds numbers with ground effect simulation, model-scale testing will provide the best combination for systematically evaluating the effects of drag-reduction technologies for simulated road conditions. A scale model can be designed to be versatile for installation and model changes.

10.4.1 Tractor-Trailer Scale-Model Testing

The NRC 9m x 9m Wind Tunnel provides the ability to test quarter to half scale tractor-trailer models at representative Reynolds numbers, with ground-effect simulation and, with some additional effort, representative turbulence conditions. Recently, a correlation study between a half-scale tractor-trailer model and its full-scale equivalent was performed in the NRC 9m x 9m Wind Tunnel. After correcting for blockage and wall-interference effects, the results of the study showed good correlation between the two models and identified the importance of proper ground simulation for some changes in model configuration. The results indicated the importance of ground-effect simulation for assessing the effects of drag reduction technologies located in ground proximity. The study was a collaboration between NRC-IAR and a truck manufacturer and has not yet been published. Dissemination of the results into the public literature will occur within the next year. This study provides confidence that scale-model testing at representative Reynolds numbers will be efficient and provide adequate guidance for the design and evaluation of drag reduction technologies. The inclusion of representative turbulence and wind-profile conditions (see Section 11.3) would provide a reliable and systematic approach to the evaluation of tractor-trailer aerodynamic performance.

Front-surface modifications will be the most susceptible to Reynolds-number effects and therefore full-scale Reynolds number conditions are the ideal situation for examining such modifications. Testing of a half-scale model in the 9m x 9m Wind Tunnel can achieve full-scale Reynolds number conditions with the ground effect simulation system. For this scale, the wheels of the model straddle the edges of the 1 m wide ground-plane belt. Although this situation is better than a fixed ground plane, it is not ideal for examining under-body and rotating-wheel effects. Also, at half scale the trailer extends beyond the length of the NRC ground-plane belt, which is only 5.3 m long. At quarter scale, a full-length model (with equivalent 53 ft trailer) will sit within the confines of the ground-plane belt (belt equivalent to 21.2 m/70 ft scale) and will therefore allow fully-representative under-body simulation. Such a model could also allow the moving belt to drive the wheels and provide an improved simulation of the wheel-road interactions (further discussed in Section 11.3.1). The Reynolds number for this situation would be half of the full-scale conditions, but underbody flows are likely to be less susceptible to Reynolds-number effects due to the turbulent-wake-like characteristics of much of this flow. As noted above, it is primarily front surfaces that require the full-scale Reynolds numbers associated with a half-scale model. Although the large range of second-generation drag-reduction devices affect the gap and trailer flows, it is possible that insufficient Reynolds-number simulation of the forebody may have an effect on the downstream flows.

The arguments above lead to the conclusion that there is no optimum model scale for testing tractor trailers in the 9 m x 9 m Wind Tunnel with ground effect simulation. Quarter-scale models are the most appropriate for testing drag-reduction devices on a full-length trailer model, while properly simulating the underbody flows and ground. Half-scale models will provide adequate Reynolds-number simulation, important for the tractor forebody flows but will not provide full under-body ground effect simulation. Before an appropriate model scale is chosen for such studies, it will be important to understand the implications of this trade-off. Section 10.6 provides recommendations for such a trade-off study.

The NRC-IAR can also provide additional testing techniques to evaluate the effects of drag-reduction devices on tractor-trailer combinations. Section 11 describes additional technologies that the NRC-IAR can provide for scale-model testing, including aero-acoustic measurement capabilities and snow-ingestion evaluation. Aero-acoustic and snow-ingestion technologies are also available for full-scale testing, and novel technologies for improving road-test measurements and methodologies are considered.

Sections 9 and 10 describe drag reduction technologies for tractor trailers and buses that can be evaluated using scale-model wind tunnel testing with ground effect and turbulence simulation.

10.4.2 Intercity-Bus Scale-Model Testing

The ideal facility for aerodynamic development of intercity buses is the NRC 9m x 9m Wind Tunnel. Its test section is equipped with a Ground-Effect Simulation System (GESS) comprised of a 5.65 metre long, 1.1 metre wide moving belt preceded by two large porous suction plates ensuring a thin boundary layer at the moving belt leading edge. In order for the belt to completely cover the footprint of the bus model, the ideal model scale would be approximately one third. Figure 26 represents a schematic illustration of a ⅓-scale, large-size intercity bus of dimensions typical for North America. As shown, this model scale allows the reproduction of favourable flow conditions, since the moving belt extends well beyond the bus boundaries from all four sides. With an achievable wind speed of 200 km/h, the wind tunnel simulation would reach ⅔ of the full-scale Reynolds number corresponding to highway speed. For this reason, and considering the previously discussed sensitivity to free-stream turbulence and Reynolds number, such experiments would require careful reproduction of the free-stream conditions typically experienced by such vehicles on the road. NRC-AL has the experience and expertise to generate artificially free-stream turbulence conditions observed in the atmospheric surface layer, as described in section 11.3.2. In addition, previous experience on the control of boundary layer transition for bluff-body shapes would help ensure that critical flow patterns are faithfully reproduced at model scale. Field aerodynamic measurements, such as those conducted by Tanguay [105], carried out aboard a real bus would provide invaluable experimental data with which to validate the wind tunnel simulation for a baseline configuration. The ⅓-scale model is sufficiently large to enable the accurate reproduction of geometrical details that are of aerodynamic significance for a bus. Wind tunnel experiments would be made efficient by the use of the Aerodynamic Testing Infrastructure (ATI), described in Section Bus.4, coupled to client-provided modules (centre body, tail- and forebody-sections), enabling the testing of elements with different geometries. The model size would also enable the manufacturing of a modular engine cooling system by means of stereolithography, which would allow the testing of various cooling strategies aimed at minimizing cooling drag. Considering the importance of wheel rotation, onboard motors would drive all wheels so that their tangential speed matches the moving belt speed. The model would be held by streamlined outriggers straddling the belt and attached to the external balance. A small gap would remain between the wheels and the non-metric moving belt. An experimental configuration of this type would enable a comprehensive optimization covering all four aerodynamic aspects identified in Section 8, namely: external, appendage, underbody and cooling aerodynamics.

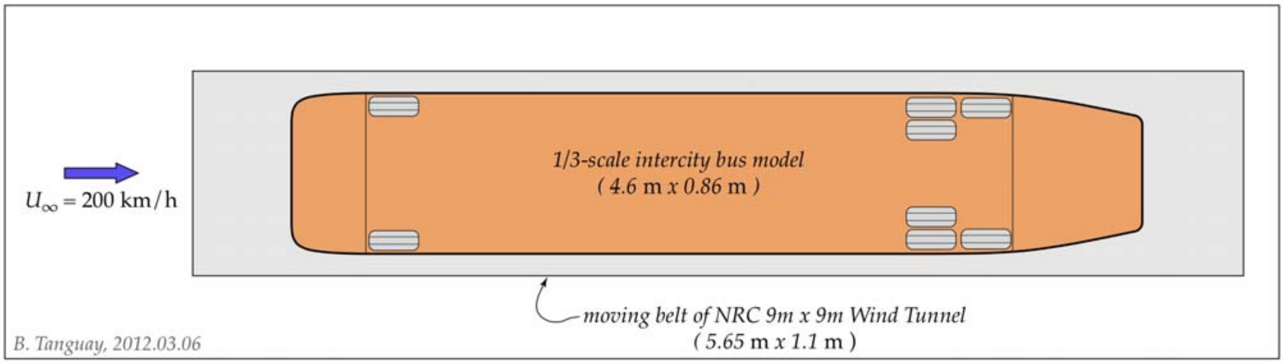

Figure 26 – Schematic of a ⅓-scale intercity bus model on the moving belt of the NRC 9m x 9m Wind Tunnel

10.4.3 Non-Aerodynamic Technologies for Wind Tunnel Evaluation

The development of technologies for reducing fuel consumption and emissions of heavy vehicles includes more than just drag-reduction technologies [2], and wind-tunnel testing can be used to assess the aerodynamic effects, whether positive or detrimental, of such technologies.

Low-rolling-resistance tires are commonly available for road vehicles, and one such technology for tractor-trailer combinations is the use of single-wide, also called super-single, tires instead of dual standard tires. Some evidence shows that these single-wide tires also provide an aerodynamic improvement but the influence combined with other-drag reduction technologies has not been systematically evaluated.

As engine/drive-train/auxiliary-device technology is improved, changes to the size and location of components in the engine bay can affect the through-flow of cooling air and the manner in which it exhausts from the compartment. Snow & Ice, and splash & spray could alter the aerodynamics through shape modification and blockage of cooling passages. A model-scale wind-tunnel evaluation of typical engine compartments layouts may provide some optimized configurations that improve the overall aerodynamic performance of the vehicle. The first tractor-trailer tests in the NRC 9 m x 9 m Wind Tunnel were performed to examine the cooling drag of an active cooling system. Cooling-system optimization can be an added benefit to be investigated with both full-scale and model-scale wind tunnel tests. Such technology is being introduced for passenger cars and the extension to trucks is worth investigating. Reynolds number effects are important when considering cooling-system aerodynamic performance.

10.5 Areas Recommended for Further Work

Aerodynamic drag is a dissipative, non-recoverable loss of energy and is one of the most important factors for reducing fuel consumption and emissions of heavy vehicles. Significant drag reduction can be obtained with current and emerging technologies, but the uptake is generally slow due to the requirements from operators for a timely return on their investment. Typical evaluation strategies by device developers and manufacturers can be skewed and not very representative of real-world conditions, which is one of the reasons operators can be hesitant towards new technologies. The industry therefore needs guidance in selecting appropriate technologies that will provide a net benefit to the reduction of fuel consumption and emissions in Canada. Similar to the EPA Smartway program in the US [30], certification of technologies is a good approach to providing the industry with such guidance.

Based on the information described in this report, the NRC recommends a systematic evaluation of the drag reduction potential for standard and proposed drag-reduction technologies for tractor-trailer combinations. This plan would provide Transport Canada with recommendations for the most effective combinations of drag reduction technologies for reducing the fuel consumption in the transport industry. Combined with consideration of operational requirements, recommendations for best-use technologies can then be provided to the transportation industry. The plan, summarized below, will be similar to the test program performed at NRC in collaboration with NRCan, the Canadian Trucking Alliance, and the US Department of Energy [23], [24], for which reliable estimates of fuel savings can be made. This new plan, based on scale-model wind-tunnel testing rather than full-scale testing, encompasses additional drag reduction technologies and will provide much improved simulation of the environment in which heavy vehicles operate in Canada. The benefit of scale-model testing over full-scale testing is the ability to provide a more representative environment (relative vehicle/ground/wind motions and terrestrial winds) as well as the ability to test equivalent full-length vehicles and long-combination vehicles. These issues provide much improved accuracy over past wind-tunnel campaigns. Another strong benefit of wind tunnel testing is the precision with which comparisons between technologies and configurations can be compared, by means of a systematically-controlled test environment.

Collaboration with operators, OEMs and device manufacturers can provide a thorough evaluation of such technologies. The NRC already has partners in the transportation industry that would be open to collaboration through the provision of specifications of tractor-trailer and device geometry for model manufacturing.

An overview of a proposed plan for the aerodynamic evaluation of drag-reduction technologies is as follows:

- Using aerodynamic measurements from wind-tunnel and track-test programs undertaken with various collaborators and partners (with permission), the potential impact of performing tests at lower than full-scale Reynolds numbers will be assessed. An optimized model scale (between ¼ and ½) for tractor-trailers combinations will be selected to best provide accurate results from an evaluation of drag-reduction technologies.

- Design the infrastructure to test scale models of North-American tractors and standard trailers (40 ft and 53 ft equivalent dry van, flatbed, tanker, long-combination vehicles). These models would be designed to accommodate a multitude of body shapes and drag-reduction devices/concepts to be evaluated. The models would be designed to be used with the ground-effect simulation system of the NRC 9 m x 9 m Wind Tunnel. This system provides a correct and important simulation of the relative motion between the vehicle, the terrestrial winds, and the ground.

- Design, development and fabrication of a turbulence-generation system to provide representative conditions that are encountered by tractor trailers under real road conditions. Turbulence has been demonstrated to be an important factor, generally neglected, when evaluating the drag-reduction potential of new technologies. Section 11.3 describes the requirements for this development project.

- Wind tunnel test program in the NRC 9 m x 9 m Wind Tunnel to evaluate the aerodynamic, and possibly the aero-acoustic (see Section 11.4) performance of drag reduction devices and vehicle combinations using the scale-model heavy vehicles. This program would consist of evaluating the performance of the drag-reduction technologies under smooth and turbulent-flow conditions, with and without ground simulation, to provide a correlation with other wind tunnel test programs that have already demonstrated some of the technologies under conditions with smooth flow and minimal or no ground-effect simulation.

- Dissemination of results and recommendations for optimum drag reduction combinations in the Canadian context, through reports and through presentations to the heavy truck industries at appropriate conferences and meetings. These results will be more representative in regards to fuel-reduction-potential than those of the standard recommended methods to evaluate heavy-vehicle aerodynamic performance now required by the US EPA.

11 TEST TECHNIQUES

11.1 Current Standard Techniques

The automotive industry uses a combination of road measurements, wind tunnel experiments and computational techniques to develop and evaluate the aerodynamic performance of their vehicles. After-market suppliers of drag reduction devices generally do not have the same level of resources to evaluate their devices and can thus have more difficulty in developing and verifying the effectiveness of their products. In the following, the current standard techniques for evaluating the aerodynamic performance of tractor trailers, and their associated drag-reduction devices, are described. Subsequent sections describe improvements to these techniques that the NRC has considered for evaluating the aerodynamic performance and behaviour of ground vehicles.

11.1.1 Road Testing

Road tests are common to all vehicle manufacturers and are often used as a final verification of the performance of a complete tractor trailer system. SAE procedures describe the recommended approach for performing such measurements (SAE J1321 [72]). These procedures provide fuel economy measurements for constant-speed conditions and can therefore only infer the effects of drag reduction devices on the overall system performance for the conditions encountered during the tests.

Benefits:

- Actual in-use performance and efficiency of the full system can be deduced.

Deficiencies:

- Only accounts for environmental conditions encountered during the test procedure.
- Difficult to evaluate systematically performance of many different tractor-trailer configurations due to changes in environmental conditions and time requirements for testing.
- Difficult to measure the effects of small changes, and therefore difficult to use for the development of a drag-reduction devices.
- Difficult to obtain the effects of a wind-averaged drag.
- Experimental error can be as high as the calculated savings of the drag reduction device (e.g. 2% savings with a 3% experimental error).

11.1.2 Coast-Down Testing

Coast-down testing provides a more precise measure than road testing of the aerodynamic performance of different tractor-trailer configurations. SAE procedures are also available for such testing (SAE J1263 [73] and J2263 [74]). The procedure for such tests is to allow a vehicle to coast from a high speed to a low speed with the drive-train disengaged. This provides a measure of the road load which is comprised primarily of aerodynamic resistance and rolling resistance. The coast-down behaviour, evaluated by measuring the change in vehicle speed with time, allows the road load to be characterized. The drag and rolling resistance can be deduced from these measurements by considering the dynamics of a moving body and the manner in which these two loads are known to behave with speed. From the speed-time signature of the coast-down test, the drag coefficient and the rolling resistance can be extracted from the measurements using regression techniques. For these tests, accurate vehicle speed, wind speed, and wind direction measurements are required; however some procedures limit the wind-conditions under which the test can be performed to eliminate their influence on the results. The tractor-trailer tires must be the same for all the configurations tested with a constant inflated pressure and the identical stretch of roadway must be used. This procedure is lengthy, requiring a minimum number of measurement runs (8 or 10 depending on the procedure used) in alternating directions for each configuration to be tested in order to obtain statistically significant results.

New Environmental Protection Agency (EPA) regulations in the United States will soon require truck manufacturers to report the aerodynamic performance of their vehicles, which will be periodically audited through coast-down testing [84]. The selection of the cost-down technique was based on consultation with truck OEMs, each of which has their preferred evaluation method (typically wind-tunnel testing or computational fluid dynamics), but none of which use coast-down as a primary method. As such, the OEMs agreed that the coast-down method provides a level playing field for them all. The OEMs will need to properly correlate their preferred aerodynamic-evaluation techniques against the EPA coast-down procedures to ensure their reporting is in compliance with the regulations. The EPA coast-down procedure limits the wind conditions under which the tests can be run such that they introduce a near-negligible effect on the results. Average cross-winds within a coast-down run cannot exceed 5 mph (8 km/hr).

Coast-down techniques will, in general, include the effects of terrestrial winds; a major difficulty is the measurement accuracy of the free-stream wind speed and direction, which can lead to important errors in the calculation of the aerodynamic drag coefficient. Tanguay [81] documents the difficulties in using standard wind measurement techniques, based on an analysis of constant-speed track test measurements performed with two tractor-trailer configurations. Two approaches are taken for such measurements. Road-side anemometers can be used to measure the winds without interference of the vehicle itself. However, if wind conditions are not constant or not spatially uniform, these measurements are only valid when the vehicle is in close proximity to the anemometers. The second approach involves mounting an anemometer on the vehicle to measure wind speed and direction (See Figure 27). This technique suffers from the local interference of the vehicle on the wind (bias of 10% on speed and direction is possible), as well as being intrusive to the flow encountered by the vehicle. A very long boom, longer than that shown in Figure 24, is required to place the measurement device sufficiently far from the body to obtain a non-intrusive measurement and to measure accurately the undisturbed wind flow. Such a long boom would also introduce an added drag increment.
Benefits:

- Actual in-use performance can be deduced
- Can account for real road and wind conditions.
- With accurate measurement of the vehicle speed, wind speed and wind direction, a good representation of the aerodynamic performance of the vehicle can be calculated which can provide a better prediction of drag reduction that can be achieved on the road.

Deficiencies:

- Difficult to systematically test different configurations due to the large number of measurement runs required to obtain a reliable averaged result.

- The wind conditions cannot be controlled and therefore the procedure can only provide measurements for the specific wind conditions encountered during the test.
- Actual wind speed and direction encountered by the vehicle are difficult to measure.
- Regulatory procedures limit the wind conditions for testing, and therefore results do not represent actual in-use conditions (wind-averaged drag).

Figure 27 – Wind speed anemometer mounted ahead of highway tractor

11.1.3 Wind Tunnel Testing

Chapter 10 described wind tunnel testing in detail, and therefore only a cursory overview is provided here. Often, small-scale (order of 1:10 scale) wind-tunnel testing is used in the early development process for tractor-trailer design. New EPA regulations require a minimum of 1/8-scale. These tests provide reliable means to optimize some of the aerodynamic features of a tractor and/or trailer and can be usually done at a reduced cost. Such tests are also generally performed with fixed-floor and low-turbulence conditions. Larger model scales, including full scale, are often used later in the design process to optimize and evaluate the aerodynamic behaviour. These larger scales provide better Reynolds-number matching between tests and full-scale. The major benefit of wind tunnel testing is the fact that the environment controlled, providing repeatable conditions that facilitate precise comparison of different configurations.

Benefits:

- Controlled wind conditions.
- Allows systematic evaluation of design or component changes, with precise measure of relative differences between different configurations.

- More cost-effective than road/cost-down tests for evaluating multiple configurations.
- Wind-averaged drag measurements are not expensive to obtain.

Deficiencies

- Most wind-tunnel facilities cannot match full-scale Reynolds numbers at low Mach number while minimizing blockage and wall-interference effects.
- The turbulence and the vertical variation of speed and direction of the atmospheric winds are currently not simulated in wind tunnels.
- Depending on the wind-tunnel facility, some aspects of the relative vehicle/road/wind motions are not fully simulated.

11.1.4 Computational Fluid Dynamics

Another approach often used to examine the aerodynamic performance of ground vehicles is computational fluid dynamics (CFD). This approach numerically simulates the flow field surrounding a vehicle to examine the aerodynamic performance. CFD has improved a great deal in the last couple of decades, but it still has a long way to go before it can compete with the efficiency and accuracy of wind tunnel testing.

The largest source of uncertainty with CFD is the modeling of turbulence in the shear layers that develop around the vehicle. The standard approach to CFD simulation for aerodynamic design and development is to perform steady-flow simulations that use mathematical models to represent the effect of turbulence on the mean flow field surrounding the vehicle [82]. The standard and most efficient models have been developed based on simple flow conditions (boundary-layer over a flat surface, wake in an idealized environment, etc.). These models can work well for streamlined objects, but suffer from large uncertainties when applied to problems such as the gap flow between a tractor and trailer, and the interactions of the rotating-wheel wakes with the under-body flows.

The Reynolds number effects also haunt CFD practitioners because turbulence models are generally based on high-Reynolds number flows where the turbulence tends to behave in a Reynolds-number-insensitive manner. These conditions also negate the characteristics of laminar and transitional shear layers that can be prevalent on the front face of many road vehicles. On heavy vehicles, the flows around the front faces of the tractor are generally low-Reynolds-number flows with much different turbulence characteristics, or possibly the absence of turbulence which can occur over a large part of the front face of coaches.

Techniques to simulate the large-scale unsteady motions of the flow around a vehicle (Large Eddy Simulation, LES, and Detached Eddy Simulation, DES) are available but these significantly increase solution times and are therefore much less efficient for design and development purposes. Even with advanced technologies, CFD must be validated against experiment to be sure it is providing accurate and representative results. Drag-reduction devices are generally used in regions of the flow where shear, flow unsteadiness and turbulence effects are important, and therefore the uncertainty of CFD for such flows negates it as a sole-method to examine drag reduction devices. The ship-building community, which encounters similar aerodynamic problems as truck builders, has standardized on time-accurate loads for design purposes. Computing resources for such simulations are required.

Benefits:

- Good for early design cycle evaluations.
- Results provide the full flow field surrounding the vehicle.

- Can examine gross effects of geometry changes on flow field.
- Vehicle size and geometry can easily be changed or substituted

Deficiencies

- Mesh generation can be very lengthy if good detail of the vehicle geometry is required.
- Simplified modeling of turbulence creates uncertainty in results.
- More accuracy requires greater computation time.
- Difficult to quickly evaluate design changes.
- Expensive per data point due to the large number of wind conditions required for wind-averaged-drag evaluations.
-

11.2 Coast-down Testing Improvements

As noted above in Section11.1.2, the major deficiency associated with coast-down testing techniques is the difficulty with which the wind speed and direction are measured [81]. With current technology, these measurements can be improved by providing either greater resolution of road-side wind measurements, or optimization of the mounting location for vehicle-referenced measurements. The former method can be accomplished with the use of a large number of accurate road-side anemometers. The spacing can be optimized to provide accurate interpolation of the wind conditions between measurement stations. The latter method can be accomplished one of two ways. If the vehicle-mounted anemometer is located in a region free of influence by the vehicle (far from the model), it can be used as a direct measure, however this would require an impractically long boom mounted to the front of the vehicle forebody. Such a structure would inevitably introduce a drag increment. Conversely, a close-proximity device can be calibrated, perhaps in a wind tunnel, to determine the influence of the specific vehicle on the ambient wind conditions [74].

The NRC has a proprietary concept for a new vehicle-mounted measurement technique. Although the technology cannot be described here, it consists of a fast-response, non-intrusive wind-speed and direction measurement system that can measure the wind conditions well ahead of the vehicle in a region not affected by its presence. This technology may also provide a measure of the turbulence characteristics of the wind to better characterize the vehicle performance. In addition, a system of this nature can provide improved performance characterization for the constant-speed road-test techniques described in Section 13.1.1.

11.3 Wind Tunnel Improvements

As noted in Chapter 10 regarding scale-model wind-tunnel testing, some deficiencies and challenges exist when attempting to simulate road conditions in a wind tunnel. In an attempt to improve the simulation of ground-vehicle aerodynamics, the NRC-IAR has identified several technologies that can be refined or developed for providing enhancements to the environment experienced by such vehicles in a wind tunnel. The following describes four technologies that are either in-use in NRC-IAR wind tunnels or that can be developed for its wind tunnels.

11.3.1 Ground Simulation

The NRC 9 m x 9 m Wind Tunnel has a Ground-Effect Simulation System (GESS) with which the relative motion between the vehicle, the wind, and the ground can be simulated for some idealized wind conditions. The system is composed of:

- A turntable on which the vehicle is mounted that provides changes in the relative wind direction experienced by the vehicle;
- A boundary-layer suction system, installed in the floor upwind of the model and turntable, to thin the floor boundary layer and thereby better represent the near-ground flow properties of the wind;
- A moving ground plane, consisting of a belt underneath the vehicle model, that moves the ground surface at the same speed as the wind; and
- Control of the ground-plane and wheel speeds, if rolling wheels are simulated, based on the most appropriate wind speed experienced by the model (that being the blockage-corrected wind speed which accounts for the effect of the flow being confined by the wind tunnel walls).

The initial design of the GESS was for full-scale cars for which the 1 m-wide belt is situated between the wheels, and the wheels are rotated by four individual roller mechanisms. The system was modified for use with half-scale tractor-trailer models, for which the wheels do not completely straddle the belt, and motors within the model were used to drive the wheels. Figure 28 shows a half-scale model (with proprietary cab design blocked out) in which the 1 m wide limit of the belt in relation to the model width is visible, as is the extension of the model beyond the downwind end of the turntable and GESS.

For smaller-scale tractor-trailer testing (one-third scale or smaller), the GESS simulation of the relative flow over and below the vehicle model may be improved by mounting the entire model over the belt. It may be possible to have the wheels driven directly by the belt. This may better reproduce the aerodynamic interaction effects between the wheels and the road, but this effect is not yet known. Such a technique would require an assessment of the loads transferred from the wheels to the belt, either through characterization under no-wind conditions with the wheels and belt moving, or by mounting multi-component load cells to the wheels to directly measure the loads transferred to the belt. The NRC-IAR has experience with small load cells or balances that can be used for such purposes. For mounting models directly over the belt of the GESS, a mounting system to support the model and ensure that the loads are transferred correctly to the under-floor balance is required. This will require first an evaluation of the benefits of such an approach, compared to the wheel-motor concept.

Figure 28 – Half-scale tractor-trailer model with GESS in NRC 9 m x 9 m Wind Tunnel (shaded due to proprietary tractor design)

Currently, control of the floor belt and model wheel speeds with the GESS is done to match the wind-speed experienced by the vehicle model. Under cross-wind conditions, simulated by rotating the turntable and changing the relative direction of the wind to the model, the ground-speed could be adjusted to represent the wind-speed component that is in-line with the effective vehicle motion, at least for a typical terrestrial wind speed. The control system of the 9 m x 9 m Wind Tunnel has the capabilities to perform the necessary calculations to adjust the belt and wheel speeds accordingly. This is a possible future upgrade to the simulation when using the GESS.

To improve the GESS in the manner described above the following tasks would be required:

1) Determine the benefits of a belt-driven wheel system over a motor-driven wheel system. If beneficial, design a model mounting system for models smaller than half scale and evaluate its potential aerodynamic interference with the flow over and underneath model-scale tractor trailers. This may also require the design of a wheel balance system to measure the loads transferred between the wheels and the belt.
2) Update the GESS control system to account for the change in ground-referenced wind speed as the model is yawed.

11.3.2 Turbulence

The influence of atmospheric turbulence on the aerodynamic behaviour of tractor trailers and the new generation of drag-reduction devices is not well understood. Cooper [83] demonstrated in the 1980s the influence of turbulence on some basic truck configurations and showed that the effect of turbulence, relative to smooth flow, can change depending on the wind angle and the type of geometry-change being evaluated.

The biggest challenge in simulating atmospheric turbulence in a wind tunnel is to replicate appropriate spectra for the wind fluctuations [84], [85]. Some studies have measured or estimated the turbulence spectra encountered by cars over a region approximately 1 m from ground level [86]. For tractor trailers, it will be important to examine the wind characteristics over a greater height; perhaps up to 4 m. The length scales associated with atmospheric turbulence are generally much larger than those that can be reproduced in a wind-tunnel simulation using standard techniques (grids, screens, meshes), and the size of the largest length scale defines the strength of wind gusts experienced by the vehicle. The smaller length-scales that can easily be generated in a wind tunnel, which are turbulent eddy sizes much smaller than the size of the truck, contain only a small part of the turbulence energy encountered by a vehicle on the road.

Active turbulence-generation technology is likely required to simulate appropriate wind spectra for tractor-trailer testing. At NRC, Cooper demonstrated such a technique using an oscillating grid with hinged plates that were driven by either white noise or sinusoid of various frequencies [87]. This technique was effective in increasing the effective length scales of the turbulence. Cooper [84] notes that the Pininfarina automotive wind tunnel uses a similar technique, in this case, with tapered hinged vanes that also provide a change in mean wind speed with height.

The scales of turbulence for their concept are representative of those experiences in the wake of another vehicle. Additional challenges in the simulation of the wind turbulence are the difficulty to replicate long length scales in a wind tunnel as a result of limited spacing and possible unrealistic spatial correlation, and the target spectrum for all 3 wind components may not be possible to achieve.

The NRC-IAR has a strong background in wind engineering for structures, such as buildings and bridges, that has for several decades required the simulation of appropriate turbulence spectra to adequately characterize the wind loads and aero-elastic phenomena associated with such structures. In recent years, the NRC-IAR has applied this knowledge to other areas. Measurements in a speed skating oval were used to tailor wind-tunnel turbulence to that experienced by speed-skaters [88]. The NRC-IAR has also applied turbulence generation in the 9 m x 9 m Wind Tunnel with spires or turbulence grids that extend from the floor to more than half the wind-tunnel height [89] (see Figure 29). It is believed that the aerodynamics expertise within NRC-IAR would allow the development of a turbulence generation system for ground-vehicle simulation in both its 2 m x 3 m Wind Tunnel and its 9 m x 9 m Wind Tunnel.

Figure 29 – Partial-height turbulence grid in NRC 9 m x 9 m Wind Tunnel

The following tasks would be required to develop turbulence simulation for automotive purposes:

1) ***Measurement of the wind turbulence conditions experienced by tractor trailers***: Similar to the technique used by Wordley and Saunders [86] to measure the turbulence experienced by cars in Australia, an array of fast-response multi-component pressure probes can be used to measure the wind spectrum and its vertical and/or horizontal distribution as experienced by tractor trailers in a Canadian environment. The NRC has this equipment. The results would be a representative wind spectrum.

2) ***Evaluation of the performance sensitivity of a tractor-trailer to turbulence***: It is not known how sensitive the aerodynamic behavior of a tractor-trailer will be to variations in the "target" wind spectra noted above. Measurements of a standard model in various turbulence environments, all of which are available already in the NRC wind tunnels, will provide a tolerance level to which the turbulence simulation can be designed.

3) ***Development of simulation techniques for the NRC 2m x 3m Wind Tunnel***: The technology to generate the "target" wind spectrum as measured from the field study noted above, which will likely require active methods, would best be developed in one of the smaller NRC Wind Tunnels (1.0 m x 0.8 m Wind Tunnel, or 2 m x 3 m Wind Tunnel). Final demonstration with an automotive model, to demonstrate the differences with and without turbulence, would best be done in the 2 m x 3 m Wind Tunnel that has an accurate balance for measuring the wind loads.

4) ***Extension of simulation techniques to the 9 m x 9 m Wind Tunnel:*** With a suitable technology and concept demonstrated in the 2 m x 3 m Wind Tunnel, the system can be scaled up for the 9 m x 9 m Wind Tunnel to allow turbulence simulation for scale models with proper ground simulation, as well as for full sized vehicles.

11.3.3 Sheared and Twisted Flow Profile

As a result of the variation in atmospheric wind speed with height, combined with effective wind speed associated with the vehicle motion, a road vehicle will experience a variation of wind speed, wind direction, and turbulence with height in the presence of a terrestrial wind. For some atmospheric wind conditions, a tractor trailer can experience a twist from ground to roof level in excess of 5 degrees and a change in wind speed in excess of 5%, even at typical highway speeds [90]. The effect of such wind conditions on the aerodynamic performance of a tractor trailer is not known, but it is expected to be significant.

Sheared and twisted wind profiles have been simulated in other wind tunnels for the purpose of simulating the winds experiences by sailing yachts [91], [92]. In those wind tunnels, an array of twisted vertical vanes was placed upwind of, or within, the test section to vary the horizontal wind angle approaching the yacht models. It would not be difficult to adapt those concepts for tractor-trailer wind-tunnel testing.

As part of the turbulence simulation approach described in Section 11.3.2, flow-twist capabilities can be included. Demonstration of the effect of wind-profile twist on a tractor trailer model can be done through the developmental studies in the 2 m x 3 m Wind Tunnel (coincident with task 3 in Section 11.3.2), with the results determining the importance with which such testing should be performed at larger scales in the 9 m x 9 m Wind Tunnel (coincident with task 4 in Section 11.3.2).

11.3.4 Blockage and Interference Corrections

As described in the last chapter, blockage and wall-interference corrections are important for comparing wind-tunnel measurements to what is experienced on the road. Through a yet unpublished study comparing various blockage corrections to full- and half-scale models of the same tractor trailer combination, the NRC has identified correction methods, that, when combined with standard wall-interference techniques, collapses data sets to nearly the same drag-coefficient versus yaw-angle curve [93]. Despite the good results for the vehicle loads, the methods have shown to provide some discrepancy for correcting surface-pressure coefficients, based on a comparison of full-scale wind-tunnel and track measurements for the same tractor-trailer combination [81]. Although the discrepancy is not assumed to be fully-related to the blockage-correction technique, due to differences in wind conditions between the wind tunnel and the coast-down tests, there is some evidence that a refinement to blockage correction techniques could be made for surface pressures. The methods examined in the yet unpublished study are based on a limited number of measurements and model geometry, with empirically-determined coefficients based on correlation for other types of bodies. Optimization of a blockage correction method may be possible for a typical heavy-duty truck configuration.

Another technique that is often used with aircraft testing when large blockage levels are present is a method based on a three-dimensional potential flow solution that provides, with one calculation, the net effect of blockage on the wind speed and wall interference on the flow angularity. The Mokry Two-Variable Interference Method [94] makes use of wall-pressure measurements within the wind tunnel, and determines an effective potential-flow configuration that will provide the same wall-pressure signature. The result is a potential flow field that best reproduces the wind speed-up and flow-angularity changes experienced by the wind tunnel model. This field solution can provide a specific correction for each surface-pressure measurement based on each pressure-tap location within the wind tunnel. This technique has been shown to correct adequately the measurements for a streamlined body but has not yet been validated for a bluff body.

Some preliminary measurements using the Mokry method have already been performed in the NRC 9 m x 9 m Wind Tunnel. The largest source of uncertainty in this method was a drift in the pressure measurements as a result of low-magnitude pressure signatures for some of the measurements. The uncertainty in the pressure measurements provides a large uncertainty in the correction parameters. It is conceivable that the two methods described above (Maskell III and Mokry) could be combined such that the repeatable and consistent Maskell III method can provide a reference to which the Mokry method can be calibrated. This combination could adjust for the pressure-drift uncertainty of the Mokry method, providing a combined method for accurately correcting both the aerodynamic-performance and the pressure measurements. Track measurements, such as those examined by Tanguay [81], can be an additional source of validation data for developing these techniques.

11.4 Aero-Acoustics

In the NRC 9 m x 9 m Wind Tunnel, an added benefit to testing the aerodynamic performance of tractor trailers is the ability to evaluate the aero-acoustic performance of the vehicles or any of its components. As part of a program to develop aero-acoustic measurement capabilities for aircraft landing-gear systems in smaller NRC wind tunnels, it has been demonstrated that we can also use the acoustic-measurement system with automotive models including a full-scale tractor trailer in the 9 m x 9 m Wind Tunnel. Such measurements can assess the change in noise levels and associated frequencies from the various truck components, including new drag-reduction technologies.

Typical acoustic evaluations for automotive purposes make use of measurements made inside the cabin to measure the noise experienced by the driver and passengers. The NRC Aero-Acoustic System makes use of *phase microphone array technology* (with 64 microphones) to measure the frequency, magnitude, and spatial distribution of noise sources within the wind tunnel. Figure 30 shows the array mounted to the wall of the NRC 9 m x 9 m Wind Tunnel and a preliminary sample of measurements for the A-pillar and mirror region of a class 8 tractor. The sample measurements clearly show strong noise sources from the A-pillar, the sun visor, and the top & bottom of the mirror. Background noise cancellation technology can also be implemented with the system to remove the noise associate with the wind tunnel walls and structure.

Figure 30 – NRC aero-acoustic array mounted to side-wall of 9 m x 9 m Wind Tunnel (left) and subset of preliminary acoustic measurements for a tractor (right).

11.5 Snow Ingestion

An important atmospheric phenomenon typical of Canadian winters is the snow storm. Depending on the characteristics of the snow (quantity, flake size, clumping, stickiness, etc.), ingestion of snow into the air filters can reduce the performance and efficiency of an engine. The NRC-IAR has developed and demonstrated a prototype Snow Storm Simulator (S^3) for the 9 m x 9 m Wind Tunnel. The system, which uses synthetic snowflakes, was developed for testing cars, but can be adapted and fully-commissioned for tractor-trailer testing. The S^3, shown in operation in Figure 31, can provide a quantitative measure of the snow ingested by the air intakes and can be used to modify the intake design to minimize performance and efficiency degradation.

Figure 31 – Snow-storm simulation in 9 m x 9 m Wind Tunnel

The prototype technology for the S^3 requires some additional tasks before a commissioned system can be implemented in the NRC-IAR 9 m x 9 m Wind Tunnel:

1) The characterization of synthetic snow flake aerodynamics has been initiated to select the most appropriate snowflakes for the commissioned S^3. The sensitivity of snow-ingestion to synthetic snow-flake characteristics are likely low, so this may be a quick process.
2) Finalize the design for a snow-capture device to prevent the synthetic snowflakes from circulating through the wind tunnel circuit.
3) Modify the design of the snow distribution system to fully envelope full-scale tractor-trailer models.

12 OVERALL CONCLUSIONS

General

For heavy vehicles such as tractor-trailer combinations and buses, pressure drag is the dominant component due to the large surfaces perpendicular to the main flow direction and due to the large wake resulting from the bluntness of the back end of such vehicles.

In cold Canadian climates, the aerodynamic drag in winter can be nearly 20% greater than at standard conditions, due to the ambient air density. For highway tractor-trailers and intercity buses, this results in about a 10% increase in fuel consumption from drag when compared to the reference temperature, further emphasizing the importance of aerodynamic drag reduction strategies for the Canadian climate.

Long Combination Vehicles

The results of one study indicated that an LCV's drag coefficient while pulling two trailers can be as little as 0.05 higher than a conventional vehicle pulling one trailer at 0 deg wind yaw angle. This number increases to 0.13 higher at a yaw angle of 5 degrees. Therefore, adding a second trailer to form an LCV, and thus doubling the freight capacity, results in a very modest increase in drag coefficient of approximately 10% at zero yaw angles and 22% at five degree yaw angles when compared to the single trailer vehicle. Or put in other terms, the drag coefficient on an LCV is only marginally more than half of the sum of the drag on the two vehicles it replaces when wind angles are at zero degrees.

As vehicle length increases, the percentage contribution to overall drag from friction drag rises slightly since there is so much more planar surface aligned with the wind, yet the blunt front face of the vehicle remains unchanged. A study concluded that the percentage contribution of pressure drag on the baseline vehicle was 93.3% whereas the contribution of pressure drag on the LCV was 91.7%. The significance of this is that as vehicle length increases, strategies to reduce friction drag become more effective in reducing fuel consumption. However, it is clearly still more beneficial to reduce pressure drag, regardless of vehicle configuration. The authors of one study concluded that some vehicle combinations can show an increase of 40% in friction drag with only a corresponding increase of 8% in pressure drag. However, this is still 40% of a very small number, and 8% of a very large number but the fact remains that increasing vehicle length increases the relevance of frictional drag reduction strategies and has much less effect on pressure drag.

The size of the gap between the lead and trailing trailer plays a significant role in the amount of drag experienced by the combination vehicle, particularly at higher yaw angles.

It is estimated that one LCV would burn approximately 23,200 fewer litres of fuel when compared to two conventional vehicles, assuming an annual distance of 100,000 km at highway cruising speeds.

Camera Mirrors

CMVSS compliant mirrors are responsible for approximately 2% of the overall drag on a conventional tractor and trailer. A study concluded that if a tractor's two side mirrors were removed, the tractor would burn 938 fewer litres of fuel annually based on current fleet wide average fuel consumption values. Some manufacturers are currently designing prototype vehicles that use rear facing cameras and in-cab video screens that replace the side view mirrors. However, these systems cannot be used independently without mirrors, under the current CMVSS regulations.

A cursory review of in service tractors in Ontario confirmed that drivers are currently accustomed to using mirrors that are nearly three times larger than what is required under CMVSS regulations. Therefore, it is not likely that reducing the minimum amount of glass required under CMVSS would result in any drag savings since most drivers would be reluctant to reduce their field of vision from what they are currently using.

Side view mirrors are considered 'fail-safe' devices. Replacing side view mirrors with rear view cameras will most certainly reduce the mean time between failure (MTBF) of the tractors and could fail when a driver must quickly assess the traffic situation in the left hand lane. However, further work would be required to compare the MTBF of conventional mirrors versus the MTBF of a camera system.

Some drivers may require more time to adjust to the concept of looking to the right into a video screen, rather than looking left and right into mirrors, particularly when required to do so in the event of an emergency lane change.

Platooning

Several research studies have demonstrated that platoons can be effective at reducing the drag on all of the vehicles in the platoon, even the lead vehicles. However, the largest reduction in drag occurs for the vehicles between the first and last vehicle. It is estimated that vehicles in a platoon could experience between a 9% and 25% reduction in fuel consumption, depending on spacing, vehicle speed, vehicle position and vehicle mass.

It is clear that platooning requires significant changes to the road infrastructure and would also require a significant change in driving behaviour for drivers in other vehicles who are surrounding the platoon but not actually in the platoon.

Tractor and Trailer add-on Devices

Trailers and tractors are not always owned by the same operators therefore there may be reluctance on the part of trailer owners to pay for devices that will benefit the tractor owners.

The results of aerodynamic testing on heavy duty front bumpers have been scattered with some results showing modest reductions and some showing modest increases in fuel consumption. Similarly, modest aerodynamic improvements may be achieved with the use of wheel covers and slotted mudflaps.

Superhydrophobic coatings could be used to reduce the likelihood that water and ice could build up on a trailer. However, this technology remains largely un-tested on road vehicles.

Base bleeding has been shown to reduce drag in laboratory settings, however, the need for electrical devices (which then become an electrical drain on the charging system and thus a parasitic loss to the engine) to provide airflow and the need to tune the ducting of passive systems makes base bleeding a much less practical alternative to drag reduction.

Cab underbody treatments have been shown to decrease the aerodynamic drag of tractors, however, testing should be performed using a rolling road type wind tunnel to quantity these effects.

It has been shown that the gap begins to have a significant impact on vehicle drag once it is greater than about 0.45m, with the drag increasing by about 2% for every 0.25 m of increased gap beyond approximately 0.75 m. Research has suggested that by completely addressing the gap issue, drag savings on the order of about 6% could be achieved for a typical tractor-trailer. This would amount to an approximate 3% improvement in fuel consumption at 98 km/h (60 mph). At least one manufacturer is developing a tractor fifth wheel that would move longitudinally to effectively reduce the tractor-trailer gap at high speed.

Several manufacturers have commercial products for the gap regions on the market today that claim fuel savings on the order of 2%. The percentage savings are, however, highly dependent of the test procedure chosen, including initial gap size, and test speed.

Numerous academic studies have investigated the potential fuel saving effects of tractor-trailer gap devices. It is, however, appropriate to first investigate the theoretical maximum benefit of completely closing the gap. Studies have suggested that the upper limit of aerodynamic improvement expected was in the range of a 7% drag reduction. At a typical speed of 55 mph, this would translate to an approximate 3.5% fuel saving.

Recently, Mercedes introduced a concept trailer that is reported to provide an 18% reduction in drag for a full European tractor-trailer combination (consist of a cab-over tractor).

Side skirts are used to prevent air flow from entering the under-trailer region. In recent years, these have been widely adopted and are commonly observed on many trailers. Fuel consumption reductions on the order of 3-7% have been reported.

Side underbody boxes have also been shown to reduce drag by as much as 10% to 15% and can be used to store equipment that would normally be strapped to the outside of the tractor or the underside of the trailer. Side underbody boxes could also be used in place of traditional side guards. However, they add weight to the trailer and could also affect the breakover angle as trailers pass over railroad tracks and other obstacles.

Wind-tunnel and road tests have demonstrated that a boat tail with a length of 24 to 32 inches is optimal for drag reduction purposes and typical length restrictions. As with side skirts, the interaction of boat tails with other devices is important for optimization.

Currently, limited evidence exists in peer-reviewed scientific sources to indicate that vortex generators have a significant impact on fuel savings for heavy vehicles.

Retractable trailers (i.e. trailers whose height reduces by a wide margin) are being prototyped in Canada but testing has yet to be performed to quantify the potential for drag reduction.

Aero-tractor models provide a reduction in aerodynamic drag, over the classic style, on the order of 30%. This is accomplished primarily through rounding of the front surfaces, the use of roof air deflectors, and the use of fairings over the fuel tanks between the steering axle and the drive axles.

Aerodynamic Devices for Buses

The applicability of aerodynamic add-on devices for use on long haul intercity motor coach buses has been less well studied than those of class 8 tractor trailers. The North-American bus fleet is much smaller than the tractor- fleet and consequently, the annual fuel consumption and GHG emissions by intercity buses are significantly lower.

A typical highway coach exhibits a number of aerodynamic advantages over a class 8 tractor-trailer: there is no gap; the body comes lower to the ground effectively incorporating side skirts; and a flat front end eliminates the multiple aerodynamic discontinuities typically caused by radiator-hood, hood-windscreen and windscreen-fairing locations. Consequently, a stock long haul highway coach may have a C_D as low as 0.384.

By virtue of its lower ratio of rolling-to-aerodynamic resistance (the drag density parameter), the aerodynamic losses of an intercity bus outweigh the mechanical losses at a significantly lower vehicle speed than for a tractor-trailer. For a given percent-reduction in drag coefficient, the net percent-reduction in fuel consumption is larger for a bus than it is for a tractor-trailer.

The dominant contribution to the aerodynamic drag of an intercity bus is the pressure differential between the forward- and rearward-facing surfaces of the body, with a minimal contribution from skin friction.

About 60 to 70 percent of the total wind-averaged drag of a bus is attributed to pressure loads acting on the vehicle forebody, making it the principal area for drag reduction strategies. By far the most efficient method of reducing forebody drag is to minimize flow separation by combining the rounding of the forward corners (sides and top) with the tapering of the forebody.

Underbody aerodynamics is becoming increasingly important, in the quest to reduce fuel consumption of surface vehicles. Wind tunnel tests showed a drag reduction reaching about $\Delta C_D \approx -0.012$, as a result of the underbody panels. In addition, it was found that streamlining the wheels with hub covers further reduced C_D by 0.022. Although the undersides of buses are already quite aerodynamically ‘clean’, research could be conducted to investigate channeling the underbody flow towards the vehicle rear end. Air must be diverted into the engine for cooling purposes and this can be a significant factor. Bus undersides with minimal obstruction could provide the opportunity to utilise the kinetic energy of the flow to enhance the efficiency of engine cooling (partial RAM effect), and/or direct this channelled flow into the wake region.

Finally, an area of possible aerodynamic benefit is by re-profiling the roofline. As coach buses do not have the same cargo capacity constraints, it is believed that the rear roofline could be modified with minimal impact to passenger comfort. Operational issues should not be a concern.

Snow and Ice Accumulation and Shedding

Very little information could be found regarding test or modeling results of how ice and snow can accumulate on aerodynamic devices.

Boat tails can significantly affect the flow field directly behind a van semi-trailer and it is also expected that snow could accumulate on top of the bottom boat tail panel. However, very little relevant work could be located to quantify how this change in flow field would affect vehicles following behind a trailer equipped with a boat tail or the way in which snow and ice accumulates and sheds from truck aerodynamic devices.

13 RECOMMENDATIONS

Long Combination Vehicles

Large reductions in pressure drag can be achieved by using LCVs and these reductions are well documented and understood using European vehicles with fixed yaw angles. However, there are very little data pertaining to North American LCVs experiencing variable wind yaw angles corresponding to an annual wind averaged drag. Wind tunnel testing could be used to quantify the drag reduction of a North American type LCV taking wind averaged drag into consideration.

There are still opportunities for incremental decreases on LCV drag. Further study could be performed on Canadian LCVs to better understand the relationship between gap size and drag to demonstrate if devices that are currently designed to be installed in the gap between conventional tractors and trailers could also be used between the two trailers of an LCV. And if so, what configuration would be best suited to optimize drag reduction between the two trailers of an LCV. This study could be performed at both gaps to quantify the incremental effect of add on devices, compared to the large reductions that are achieved when using an LCV instead of a conventional tractor-trailer combination.. Ideally, a study could be conducted whereby a variety of gap fillers, side skirts and boat tails are sequentially added to the LCV in order to determine if the effects of these devices on LCVs is similar to their effect on conventional vehicles.

Camera Mirrors

The drag reduction potential of removing the side view mirrors is understood, quantified and well documented by lab testing therefore there would likely be little benefit to reproducing those tests. However, there seems to be little documented testing with regards to the performance and reliability of rear cameras and driver acceptance of their use. If this is an area Transport Canada wishes to pursue, NRC recommends developing a study to determine the benefits and drawbacks of side view mirror replacement for aspects other than the well known aerodynamic benefits. These would include, reliability and maintainability, the weight of the added devices, the need for redundancy, the speed at which the drivers can view objects in the left lane, and driver acceptance, particularly for those drivers who have been using mirrors for many years. If it was determined that side view mirrors could be removed without any negative safety side effects it would be worthwhile to investigate a pilot project to better understand the potential fuel savings as well as any unforeseen logistical issues under actual revenue driving conditions.

The benefits of infrared cameras could also be studied to determine if they could be combined with camera mirrors to enhance the vision of the drivers during inclement weather or if they would be more of a distraction than an aid.

Platooning

Although platooning appears to have a great potential to reduce aerodynamic drag it does not appear to be a practical solution to Canadian trucking in the near future due to the size of Canada's road network and the immature status of the technology. There are too many logistical and infrastructure barriers that must be overcome to make this a viable concept for the near future. Even if technology could allow two or more heavy vehicles to be electronically connected, the logistics of integrating these vehicles into existing traffic flows will prove to be extremely difficult. Further testing and understanding of the recently adopted LCVs would be a more practical approach to multi vehicle aerodynamic reductions until platooning has been perfected in smaller countries in Europe.

It would appear that many of the research studies focused on vehicles that were lighter than typical heavy vehicles found in Canada. The results of platooning can be more favourable when using lighter vehicles since a higher percentage of fuel consumption can be attributed to aerodynamic effects. The effects of platooning with vehicles loaded to the maximum Canadian legal weight would provide more useful information about the potential for platooning on Canadian roads.

Given the complexity of platooning and the relative simplicity of LCVs, it would be useful to quantify the differences in fuel consumption reduction from vehicles in a platoon versus an LCV. The study could begin by comparing an LCV against a two vehicle platoon and then against platoons with increasingly higher numbers of vehicles.

Tractor and Trailer add-on Devices

It is suggested that all the tractor and trailer add on devices described in this report could be worthy candidates for further study with the exception of the base bleed devices and active flow control technologies. Furthermore, an integrated study of all the devices could be made to ensure that the aerodynamic gains of one device does not reduce the aerodynamic performance of another device installed downstream on the vehicle.

The suggested process would involve scaled wind tunnel tests involving the sequential addition of each device until the vehicle was equipped with all of the above mentioned devices. Following that preliminary stage, full scale prototypes could be developed and tested in real world driving situations, or controlled track testing. Application to different trailer types (dry van, tanker, flatbed with and without representative cargo) should also be evaluated to identify the benefits to the overall transportation industry.

In order to best serve the trucking community, and meet overall fuel consumption improvement goals, it is suggested that effort be focused more on developing tractor-based drag-reduction solutions. That said, there is still a strong benefit to trailer based devices such as side skirts and boat tails due to their demonstrated drag-reduction potentials.

In any of these future studies, the approach should first be to understand the operational concerns and barriers to commercial entry, prior to undertaking any aerodynamic experimentation or simulation.

Aerodynamic Devices for Buses

Given the secrecy characterizing the bus industry, it is clear that the optimization process taking into consideration aerodynamic performance objectives and operational constraints would remain the responsibility of the Canadian bus manufacturers. In this respect, and outside the scope of this program, the NRC and Transport Canada could contribute, upon client request, to this process as an advisor providing aerodynamic expertise and guidance to the industry.

An area that could require further investigation within the context of the ecoTECHNOLOGY for Vehicles II program, is a *recommendations document* to Canadian bus manufacturers and operators that can help guide their development and selection efforts, respectively, towards reducing the fuel consumption and emissions from intercity buses. Such a document can be based on information contained within this report.

Snow and Ice Accumulation and Shedding

NRC-CSTT recommends performing a similar study to the NRC-IAR study in which many aerodynamic devices were sequentially added to a tractor and trailer combination. However, for this study, the emphasis would be on ice and snow accumulation and shedding, rather than aerodynamic drag. Ideally, a scale model vehicle would be placed in a high speed wind tunnel at sub zero temperatures and snow and ice would be blown against the model vehicle. The amount of snow accumulation and shedding could be measured against a baseline vehicle that was placed beside the test vehicle. Downstream effects on a scale model passenger car following the trailer could also be monitored to determine if the snow and ice would be more likely to accumulate on a trailing vehicle and also to determine if the forward vision of drivers in trailing vehicles is affected in any way.

Ultimately, track testing or road testing on actual highway tractor trailers could be performed to determine if devices such as boat tails were likely to accumulate amounts of snow that could eventually become ejected onto the road surface or other vehicles in the surrounding area.

Scale Model Testing

Aerodynamic drag is a dissipative, non-recoverable loss of energy and is one of the most important factors for reducing fuel consumption and emissions of heavy vehicles. Significant drag reduction can be obtained with current and emerging technologies, but the uptake is generally slow due to the requirements from operators for a timely return on their investment. Typical evaluation strategies by device developers and manufacturers can be skewed and not very representative of real-world conditions, which is one of the reasons operators can be hesitant towards new technologies. The industry therefore needs guidance in selecting appropriate technologies that will provide a net benefit to the reduction of fuel consumption and emissions in Canada. Similar to the EPA Smartway program in the US [30], certification of technologies is a good approach to providing the industry with such guidance.

Based on the information described in this report, the NRC recommends a systematic evaluation of the drag reduction potential for standard and proposed drag-reduction technologies for tractor-trailer combinations. This plan would provide Transport Canada with recommendations for the most effective combinations of drag reduction technologies for reducing the fuel consumption in the transport industry. Combined with consideration of operational requirements, recommendations for the best technologies to use can then be provided to the transportation industry. The plan, summarized below, will be similar to the test program performed at NRC in collaboration with NRCan, the Canadian Trucking Alliance, and the US Department of Energy [23], [24], for which reliable estimates of fuel savings can be made. This new plan, based on scale-model wind-tunnel testing rather than full-scale testing, encompasses additional drag reduction technologies and will provide much improved simulation of the environment in which heavy vehicles operate in Canada. The benefit of scale-model testing over full-scale testing is the ability to provide a more representative environment (relative vehicle/ground/wind motions and terrestrial winds) as well as the ability to test equivalent full-length vehicles and long-combination vehicles. These issues provide much improved accuracy over past wind-tunnel campaigns. Another strong benefit of wind tunnel testing is the precision with which comparisons between technologies and configurations can be compared, by means of a systematically-controlled test environment.

Collaboration with operators, OEMs and device manufacturers can provide a thorough evaluation of such technologies. The NRC already has partners in the transportation industry that would be open to collaboration through the provision of specifications of tractor-trailer and device geometry for model manufacturing.

An overview of a proposed plan for the aerodynamic evaluation of drag-reduction technologies is as follows:

- Using aerodynamic measurements from wind-tunnel and track-test programs undertaken with various collaborators and partners (with permission), the potential impact of performing tests at lower than full-scale Reynolds numbers will be assessed. An optimized model scale (between ¼ and ½) for tractor-trailers combinations that will best provide accurate results from an evaluation of drag-reduction technologies will then be selected.

- Design the infrastructure to test scale models of North-American tractors and standard trailers (40 ft and 53 ft equivalent dry van, flatbed, tanker, long-combination vehicles). These models would be designed to accommodate a multitude of body shapes and drag-reduction devices/concepts to be evaluated. The models would be designed to be used with the ground-effect simulation system of the NRC 9 m x 9 m Wind Tunnel. This system provides a correct and important simulation of the relative motion between the vehicle, the terrestrial winds, and the ground.

- Design, development and fabrication of a turbulence-generation system to provide representative conditions that are encountered by tractor trailers under real road conditions. Turbulence has been demonstrated to be an important factor, generally neglected, when evaluating the drag-reduction potential of new technologies. Section 11.3 describes the requirements for this development project.

- Wind tunnel test program in the NRC 9 m x 9 m Wind Tunnel to evaluate the aerodynamic, and possibly the aero-acoustic (see Section 11.4) performance of drag reduction devices and vehicle combinations using the scale-model heavy vehicles. This program would consist of evaluating the performance of the drag-reduction technologies under smooth and turbulent-flow conditions, with and without ground simulation, to provide a correlation with other wind tunnel test programs that have already demonstrated some of the technologies under conditions with smooth flow and minimal or no ground-effect simulation.

- Dissemination of results and recommendations for optimum drag reduction combinations in the Canadian context, through reports and through presentations to the heavy truck industries at appropriate conferences and meetings. These results will be more representative in regards to fuel-reduction-potential than those of the standard recommended methods to evaluate heavy-vehicle aerodynamic performance now required by the US EPA.

LIST OF ACRONYMS/ABBREVIATIONS

ADR	Australian Design Rule
C	Degrees Celsius
C_D	Drag Coefficient
CISTI	Canadian Institute for Scientific and Technical Information
MPH	Miles Per Hour
CMVSS	Canadian Motor Vehicle Safety Standards
CO_2	Carbon Dioxide
CSTT	Centre for Surface Transportation Technology
CTA	Canadian Trucking Alliance
DES	Detached Eddy Simulation
DOE	Department of Energy
EPA	Environmental Protection Agency
NHTSA	National Highway Traffic Safety Administration
GESS	Ground-Effect Simulation System
GVW	Gross Vehicle Weight
GVWR	Gross Vehicle Weight Rating
IAR	Institute for Aerospace Research
Km/h	Kilometers Per Hour
LCV	Long Combination Vehicles
MTO	Ministry of Transportation of Ontario
LES	Large Eddy Simulation
MPG	Miles per Gallon
MTBF	Mean Time between Failure
SARTRE	Safe Road Trains for the Environment
MTO	Ministry of Transportation of Ontario
NAS	National Academy of Sciences
NFAC	National Full-Scale Aerodynamics Complex
NO_x	Oxides of Nitrogen
NRC	National Research Council
NRCan	Natural Resources Canada
OEM	Original Equipment Manufacturer
PART	Platform for Aerodynamic Road Transport
SAE	Society of Automotive Engineers
SWIR	Short Wave Infrared
TVC	Towed Vehicle Controller
CFD	Computational Fluid Dynamics
OEM	Original Equipment Manufacturer
VRU	Vulnerable Road User

LIST OF SYMBOLS

F_D	Drag force
ρ	Density of the air
U_∞	Speed of the object, relative to the surrounding air
ψ_∞	Effective yaw-angle of the surrounding air relative to the vehicle motion
$C_d\,(\psi_\infty)$	Drag coefficient, which varies with yaw-angle
A	Projected frontal area of the vehicle
Q	Dynamic pressure of the oncoming wind
L	Length scale representative of the body

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