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Test Report

Effects of Side Skirts and Wheel Covers on Heavy Trailers

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Technical Report

Rapport technique

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ABSTRACT

Many countries around the world mandate the use of side guards, principally aimed at preventing vulnerable road users, such as bicyclists and pedestrians, from being run over after colliding with heavy vehicles. Although side guards may be designed with aerodynamics in mind, there is no requirement for them to reduce the drag coefficient of the truck or trailer.

Conversely, many operators in North America have elected to fit flush mount side skirts on their van semi-trailers to reduce aerodynamic drag. However, they are not required to pass any strength testing and little is known of their ability to provide the side under run protection of European and Asian style side guards. It is also of interest to better understand the effects that side skirts may have on brake cooling.

Transport Canada engaged NRC-CSTT to perform a literature review of current side skirt technology, to perform a series of crash tests between a loaded bicycle and three sets of side skirts and to perform computer modeling of heat transfer on heavy truck brake drums and discs to better understand the side effects of mounting side skirts and wheel covers on trailers.

The methods, results and conclusions stemming from this research and testing are presented in this report.

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EXECUTIVE SUMMARY

Side skirts and wheel covers are known to reduce aerodynamic drag on heavy vehicles. However, the secondary effects, such as brake cooling and the ability to resist intrusion from an incident with a vulnerable road user are not as well documented.

The purpose of this project was to conduct a literature review of existing side skirt and wheel cover technologies to understand the manufacturer's claims and to review their current product lines along with their published costs and returns on investment for their products. Additionally, it was of interest to review the results of any testing or research that may have been performed to support, or refute, the claims of the manufacturers.

Secondly, a series of impact tests were conducted to determine the strength and behaviour of side skirts installed on van semi-trailers when subjected to a perpendicular impact with a loaded adult bicycle. The scope of work considered the strength and behaviour of the side skirt itself but did not include anthropomorphic test devices (dummies) therefore no attempt was made to understand what happens to a human rider once ejected from the bicycle.

Lastly, computer simulations using computational fluid dynamics (CFD) of the airflow around both a ventilated disc brake system and a drum brake system on vehicles with and without side skirts and wheel covers were conducted. The objective of the simulations was to determine if the use of side skirts and wheel covers could have any effect on brake cooling by either restricting or improving the air flow in and around the brake components. Calculations were conducted for 13 geometrical configurations.

Aerodynamic side skirt technologies are being used by truck fleets all across North America. Side skirts are commonly constructed of aluminum or plastic and add approximately 270 pounds to the tare weight of the trailer. They require roughly 3.5 person-hours to install, and are available in many designs, including flexible systems which allow the skirt panel to easily pass over obstacles such as snow banks. The estimated return on investment is between 4 and 24 months, with an average cost of $1675 per trailer. The fuel savings claims range between 4.0% and 7.5% per tractor, which translates to a potential reduction of up to 2 000 kilo tonnes per year in greenhouse gas emissions in Canada. These fuel savings claims, along with additional side skirt benefit claims, including reduced road spray and increased driver stability, are currently under evaluation through Canadian government funding programs.

The use of aerodynamic wheel cover technology in the North American market is quite limited. Factors such as a low fuel savings benefit of 0.25% per wheel, and limited product availability, may be discouraging truck owners/operators from installing them on their fleets. However, with a low average cost of $100 per cover, a high stated return on investment of 4 to 6 months, and an option to customize the covers with company branding, truck owners/operators may be see a benefit in their use. Wheels covers, available for most standard wheel sizes, are easy to install, using either a bracket and bolt or zipper-tarp tab system. The main cover, constructed mainly of metal or fabric, often limits access to wheel hub components; however unique designs such as clear polycarbonate covers and air valve extensions claim to minimize this concern. Limited testing and/or research is available to support these wheel cover claims.

Repeatable and realistic impact test apparatus and procedure were developed.

The tests produced estimated impact forces between 3 701 N and 9 142 N and decelerations of between 39.5 m/s^2 (~4g) and 97.67 m/s^2 (~10 g).

The test method was developed to demonstrate the strength of the side skirts under one specific type of collision, which may or may not be representative of how bicycles typically collide with heavy vehicles. For instance, under typical conditions, the bicycle and the trailer would each be moving, however, in order to facilitate testing the trailer remained stationary while the bicycle was impacted into the trailer. Under these conditions, the testing demonstrated that all three side skirts prevented the loaded bicycles from entering under the trailer. Furthermore, the bicycles did not become wedged underneath the skirts. In all tests, the bicycles were ejected rearward along their original path and away from the trailer and became tangled in the test fixture, which would represent an adjacent lane, be it oncoming traffic or a lane travelling in the same direction.

The three side skirts behaved somewhat differently from each other with respect to the amount of deformation, rebound, energy absorption and the amount of permanent skirt damage after the test. The aluminum panel design (#1) sustained the highest amount of permanent damage and deformation as a result of testing and clearly appeared damaged after each of the impact tests. The aluminum design's rigid diagonal tubular steel braces did not, themselves, absorb energy and simply transferred the energy and slid along the rails where permitted. The lack of elasticity in the system caused skirt #1 to remain in its final resting position once the impact was over. As a result of this motion, the distance between the ground and the bottom of the side skirt increased by approximately 7 cm to 10 cm as a result of the impact.

Conversely, the skirt that used individual plastic panels (#2) did not have diagonal members at all, and was able to absorb the energy of the impact elastically, and rebound back to its original location and condition with only minor tell-tale signs of impact. The continuous panel plastic side skirt (#3) did have diagonal braces, however, they were made of flexible fibreglass and were able to bend radically upon impact and absorb the energy, and then rebound to their original position, albeit requiring replacement due to bifurcation. With the exception of tire skid marks, the exteriors of both plastic designs did not show obvious signs of damage once the impacts were concluded. The vertical distance between the two plastic side skirts and the ground did not change as a result of the impact testing.

The point of impact on a side skirt, relative to the longitudinal position of the trailer, results in different effects depending on the type of skirt. Side skirts that use rigid diagonal bracing for support (e.g. tested skirt #1) behave differently if they are struck ahead of the trailer bogie slider rails when compared to impacts adjacent to the slider rails. When impacted near the bogie slider rail, the diagonal braces can only slide a few inches and are then driven into the outside edge of the slider rail. This prevents the side skirt from further movement and the bicycle is ejected rearward and the skirt absorbs less energy. Alternatively, when the bicycle impacts the side skirt ahead of the slider rail, the diagonal braces are free to slide along the cross members for as long as the impact force exceeds the clamping force between the side skirt clamps and the trailer's cross members. The testing revealed that some diagonal braces, torqued to 38 ft lb, can slide as much as 28 cm when struck by a loaded bicycle at approximately 21 km/h. The actual amount of sliding is highly dependent on the torque applied to the clamp bolts and the coefficient of friction between the clamps and the cross members.

Some side skirts do not exhibit external signs of damage after an impact. Therefore, it may be necessary to inspect the backside and securing hardware of side skirts on a yearly basis in order to determine if they have been impacted.

None of the side skirts were damaged to the point where they could become hazardous to other motorists should the trailer continue to be driven on the road after an impact with a bicycle. Side skirts #2 and #3 would only require minimal repairs in order to be returned to service after an impact. However, side skirt #1 would likely require partial, or complete, replacement after an impact in order to be returned to service.

The results of this comparative study conducted using computational fluid dynamics indicate that heavy vehicle trailer brake convective cooling can be negatively affected by the addition of side skirts and wheel covers under certain operational conditions, such as non-yaw airflow (no side wind). It is also apparent that the effect of side skirts on brake cooling is relatively similar for trailers equipped with drum brakes or disc brakes, but the effect of wheel covers on brake cooling is more pronounced with drum brakes on dual tire configurations than with disc brakes on single wide tire configurations. With non yaw wind conditions, wheel covers have very little impact on disc brake cooling, for the geometries examined in this study. The results of the computer simulations show trends that indicate that brake cooling could be reduced at highway speeds, however, on-road testing using vehicles with instrumented brakes would be required to quantify brake temperatures with, and without, the aerodynamic devices.

There was no net negative impact on convective cooling of the front or rear disc brakes due to side skirts when a 10 degree side wind was present, compared to a non-yaw condition. This is a significant observation since there is almost always a yaw wind component during normal trucking operations, and that side skirts are particularly beneficial from an aerodynamic perspective under these conditions. It is therefore recommended that further simulations be conducted over a range of yaw angles to determine at what angle this yaw component may cancel out any negative effects that the presence of wheel covers and side skirts might have on brake cooling.

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1 INTRODUCTION

1.1 Purpose

The purpose of this project was to conduct a literature review of existing side skirt and wheel cover technologies to understand the manufacturer's claims and to review their current product lines along with their published costs and returns on investment for their products. Additionally, it was of interest to review the results of any testing or research that may have been performed to support, or refute, the claims of the manufacturers.

Secondly, a series of impact tests were conducted to determine the strength and behaviour of side skirts installed on van semi-trailers when subjected to a perpendicular impact with a loaded adult bicycle.

Lastly, computer simulations using computational fluid dynamics (CFD) of the airflow around both a ventilated disc brake system and a drum brake system on vehicles with and without side skirts and wheel covers were conducted. The objective of the simulations was to determine if the use of side skirts and wheel covers could have any effect on brake cooling by either restricting or improving the air flow in and around the brake components.

1.2 Background and/or Previous work

NRC-CSTT has previously studied side guards and their effectiveness in protecting vulnerable road users from under run. The report [1] outlined the types of guards being used worldwide, particularly in Europe, Japan and Australia. The safety effects of side guards are out of scope for this project, however, the previous report did include a section describing the potential benefits of aerodynamic side skirts and their use in North America. However, the NRC-CSTT report [1] indicated that further testing would be required on side skirts to better understand their effects on brake cooling and their potential ability to reduce injury from side impacts, particularly for cyclists. Those recommendations led to the research and testing being performed in this project.

1.3 Limitations

Although ballast weight, to simulate riders, was attached to the test bicycles, the purpose of the study was not to measure the forces on the simulated riders as they struck the trailer/skirt nor was NRC-CSTT attempting to study the way in which the rider departs the bicycle after the impact. Studies of that nature would require anthropomorphic test devices (dummies) which were out of the scope of this project.

Rather, the purpose of this study was to qualitatively determine the strength of commercially available side skirts and to determine if their ability to resist intrusion of a loaded bicycle varies along their length for one specific type of collision, which may or may not be representative of how most bicycle-heavy truck collisions occur. Once these effects are fully known, further study ,through a combination of physical testing and computer modeling, would be required to properly assess how a human cyclist's body would behave once it strikes a side skirt and to possibly assess any potential safety benefits of aerodynamic side skirts in preventing cyclist under-run.

Additionally, this study dealt with upright bicycles that were impacted perpendicularly into side skirts. Tests involving impact angles between 1 and 89 degrees, bicycles that are not completely upright (i.e. sliding under the skirts) or collisions between moving bicycles and moving trucks may be studied in future phases of this project, if requested.

All of the testing was conducted in a controlled test environment at nominally +20 degrees C, without wind, ice, snow or road traffic. Ideally, the testing would have also been conducted at extremely cold temperatures to determine if the effectiveness of thermoplastic side skirts varies with temperature as they become brittle. If required, temperature testing could be performed in a future phase, inside a suitably sized and equipped climate chamber.

Although it is possible, through computer simulation, to determine the absolute values of heat transfer between the air and the brake components, the actual values themselves could certainly vary from what would be measured during on-road tests. This is because the numerical models are developed with assumptions of vehicle geometry, wind and driving conditions that could vary from situation to situation. Further, simplifications in the definition of model boundary conditions and physical models also prevent absolute levels of brake cooling to be determined. Therefore, representative cases were used in the heat transfer models and trends were developed to determine the relative gains or losses associated with adding or removing side skirts. As such, when reviewing the heat transfer results it will be important to review the trends and the percentage differences, rather than the absolute values of the results.

The calculations undertaken in this study were not intended to provide a comparison of disc brake to drum brake performance, as this would require extremely detailed geometrical representation of the brake systems and would require identical undercarriage and wheel station configurations, which is not realistic of real world conditions. Finally, the geometry is not intended to represent any particular manufacturer, but rather generic tractor-trailer and aerodynamic device combinations.

2 THEORY

The side skirts and wheel covers studied in this project are designed to save fuel via a reduction in aerodynamic drag on the trailer and truck. Some of the fundamental concepts behind these potential fuel savings have been described below:

2.1 Environmental benefits

2.1.1 *How fuel is consumed in a heavy truck*

Fuel is consumed by the engine as it propels the vehicle down the road. There are five major factors that the engine must overcome that contribute to this fuel consumption. In general, these can be categorized as follows:

- Aerodynamic drag losses;
- Rolling resistance;
- Changes in grade or elevation;
- Internal power train losses; and
- Accessory losses (e.g. air conditioning, alternator loads and, air compressors, etc.)

The percentage contribution to fuel burn for each of the five categories varies from vehicle to vehicle, and certainly the contribution from aerodynamics rises steeply with speed. The contribution to fuel burn from internal losses is generally modeled as a constant and the grade portion is obviously only present while the truck is ascending or descending a grade.

At 40 km/h, the power needed to overcome rolling resistance and accessory losses is nearly twice as great as the power needed to overcome aero drag. At 80 km/h, the power necessary to overcome aero drag is roughly equal to that of rolling resistance and accessories. At 121 km/h, the power necessary to overcome aerodynamic drag is approximately 2.5 times greater than rolling resistance and accessory losses. Table 1 illustrates the contributions to fuel burn at various speeds, assuming a zero grade and properly inflated tires, and assuming that the internal power train losses can be modeled as a constant relative to vehicle speed.

Table 1 – Distribution of power consumption at various speeds

Loss	40 km/h (25 mph)	80 km/h (50 mph)	121 km/h (75 mph)
Aerodynamics	35%	47%	72%
Rolling	53%	41%	18%
Accessory	17%	12%	10%

Since there is more than one form of energy drain, it stands to reason that reducing aerodynamic drag by 20%, for instance, will not result in a 20% reduction in overall fuel consumption. Rather, it will be 20% multiplied by the percentage contribution of aero effects at that particular speed. For example, a 20% reduction of aerodynamic drag via the use of an aerodynamic device would have an overall effect of reducing fuel consumption by 9.4% at

80 km/h. These fuel savings would rise as speed increased to a maximum value of approximately 14.4% at 120 km/h.

2.2 Aerodynamics and Drag Coefficient

All vehicles have an inherent drag coefficient (C_D). This is a number that describes the amount of aerodynamic drag caused by fluid flow over any body. More streamlined bodies have lower C_D, whereas more blunt bodies have higher C_D. Figure 1, taken from Scania trucks, illustrates some examples of C_D.

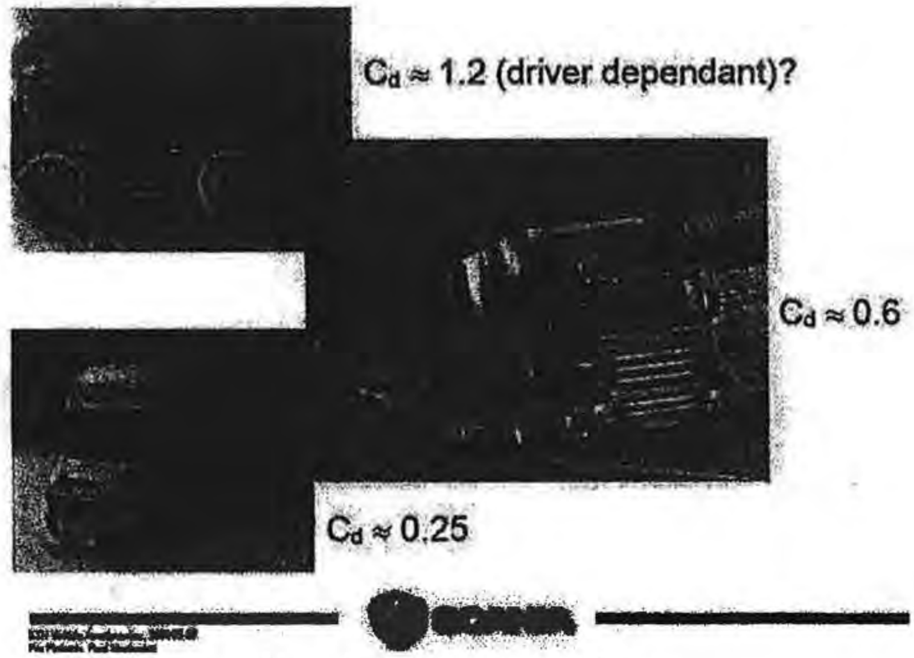

Figure 1 – Various drag coefficients

It is clear that the use of complete aero packages can drastically reduce a vehicle's overall C_D. However, the scope of this study is focused only on side skirts and wheel covers, which would play a role in the overall reduction but certainly not be the only contributors. It is estimated that C_D as low as 0.30 could be achieved with full aero packages installed on large heavy haul vehicles that currently have C_D as high as 0.6 (Figure 1 and Figure 2 taken from Scania). Note the full side skirts and wheel covers on both the tractor and trailer in Figure 2.

C_d~0.3

Figure 2 – Example of prototype European complete aero package

2.3 Side Skirts/Belly Fairings

Aerodynamic side skirts, or belly fairings, are devices that are fitted to the longitudinal edges of a trailer and are intended to allow the air flow to pass alongside the trailer rather than underneath it. The skirts reduce vortices and prevent the air from contacting the underbelly, the spare tire, the rotating wheels and other running gear that are all relatively blunt. The addition of side skirts to highway trailers tends to smooth airflow and reduce cross-flow along and below the bottom edges of the trailer and entrain the air more efficiently around the trailer and keep crosswinds from causing turbulence under it.

The skirts typically clamp to the "I" beam frame rails of the trailer and are relatively easy to install. Side skirts are often paired with gap fairings, wheel covers and/or boat tails as part of a complete trailer aerodynamic package (See Figure 3). Properly installed side skirts do not alter the height, width or length of the trailer but do add approximately 270 lb to the tare weight of the trailer. As shown in Figure 4, it is customary to integrate lights and reflectors directly into the side skirt. If necessary, refrigeration equipment and landing gear crank handles can also be integrated into the side skirts, however this may reduce the effectiveness of the skirts.

Initially only found on trailers involved in pilot projects, side skirts are becoming increasingly popular in Canada as operators realise the effectiveness of the devices and the relatively short return on financial investment. One of the challenges regarding widespread incorporation of trailer skirts (as well as other aerodynamic trailer devices) is that in many instances, the tractor and trailer owners are not the same. As a result, the trailer owner may be reluctant to make the investment in the side skirts, knowing that only the tractor operator will benefit directly from the resultant fuel savings.

Figure 3 – Example of complete North American aero package (courtesy of ATDynamics)

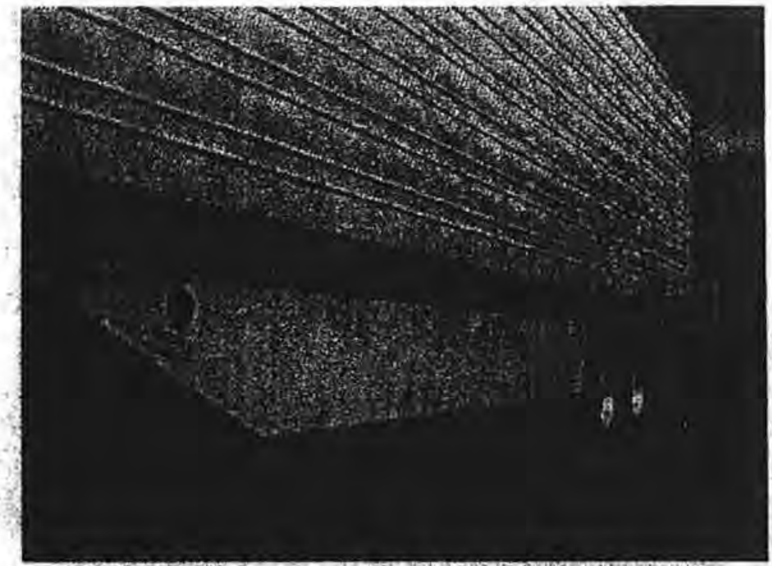

Figure 4 – Example of side skirt with integrated lighting

Many tests have been conducted with the aim of quantifying the potential fuel savings from the addition of side skirts.

A study [2] jointly performed by Technical University Delft in the Netherlands and TNT transport concluded the following: *Initial driving tests with a trailer equipped with the aerodynamic side skirts over a straight stretch of public road revealed a cut in fuel consumption of between 5% and 15%. Subsequent research comprising long-term operational tests by TNT displayed a fuel reduction of 10%. These results confirm the calculations and findings from the wind tunnel tests: these had already established that the observed 14 - 18% reduction in air resistance led to 7 - 9% less fuel consumption. In practice, the figures are in fact even better. Other tests have resulted in fuel savings in the 4% to 6% range based on the improved aerodynamic shape of the vehicles.* A similar study was conducted jointly between Freightwing Inc, Transport Canada, the National Research Council [3] and three major Canadian carriers. The aim of this project was to quantify any potential fuel savings as a result of installing belly fairings and low rider fairings (Figure 5) on 53-foot van semi trailers. Although all three carriers used their vehicles differently, the overall average fuel savings was 6.4% using both types of fairings.

Figure 5 – Example of low rider side skirt

As with most devices, there are compromises that should be considered. In order to maximize the effectiveness of side skirts, they should be mounted as low to the ground as possible. However, very low side skirts are prone to damage as trailers and trucks break over road disturbances such as rail road tracks and snow banks. It is generally accepted that most side guards and side skirts are mounted between 8 and 16 inches above the ground, depending on the application and the type of material used.

2.4 Wheel Covers

Wheel covers are another type of aerodynamic device that can be mounted to any wheel on the tractor (Figure 6) or the trailer (Figure 3). They are intended to reduce vortices inside the wheel and smooth out the flow of air and direct the air to slip past the wheel rather than become entrained within it. Wheel covers are relatively inexpensive, lightweight and easy to install. Although the drawbacks are minimal, most wheel covers do conceal the lug nuts and valve stems thus making it more difficult for operators to check for loose wheel nuts and confirm tire air pressure (Figure 6). These issues are minimized by using see-through wheel covers, (Figure 7) quick release covers, and air valve extensions. The effects on brake cooling have also raised concerns with operators and brake manufacturers.

Most manufacturers claim their devices reduce fuel consumption by approximately 1% to 2% at cruise, if installed on both the tractor and the trailer, which places these devices among the lower performing devices offered. However, their low initial cost yields payback periods that are comparable to other technologies, such as boat tails.

Figure 6 – Tandem drive tractor with one wheel cover on, and one off (courtesy of Deflektor)

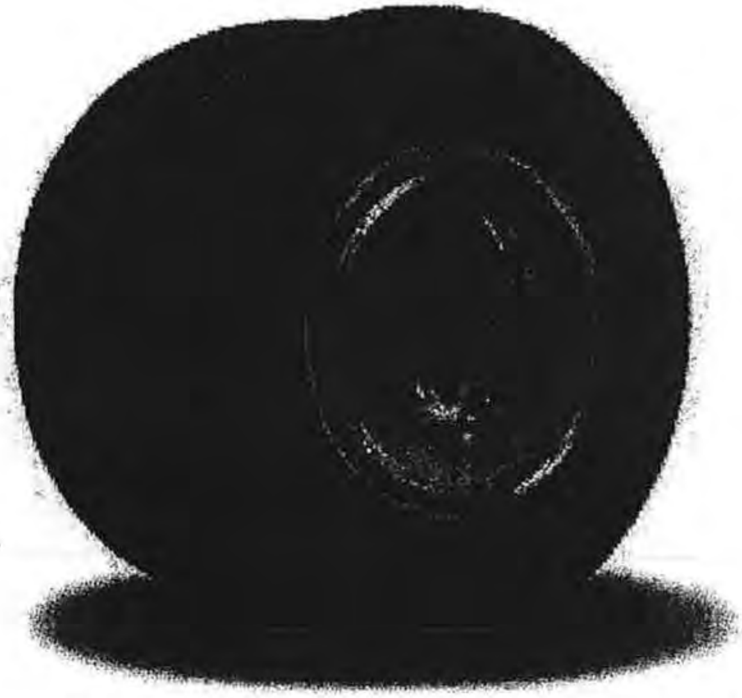

Figure 7 – Example of clear aero wheel cover (courtesy of Real Wheels)

3 APPARATUS AND TEST EQUIPMENT

3.1 Trailer

In order to provide a representative test scenario and to provide inputs for the computer models, two 53-foot van semi-trailers were leased from a main line operator for the duration of the project. The trailers were typical dry goods van semi-trailers built on aluminum frame cross members. One of the trailers was fitted with disc brakes and single wide tires whereas the other was fitted with the more traditional dual tires and drum brakes. Once the impact test trailer was positioned in place, the landing gear was lowered and the tractor un-hitched and departed the test area for the duration of the tests.

3.2 Side Skirts

NRC-CSTT believed that different side skirts may perform differently with respect to strength and energy absorption. Additionally, since each manufacturer uses their own proprietary mounting and installation design, it stands to reason that one manufacturer's side skirt could behave differently than another manufacturer's when impacted by a bicycle, at speed. NRC-CSTT performed a review of all the side skirts available in the North American market and purchased three sets that represented apparent differing technologies with respect to material composition, size, mounting, and symmetry (i.e. reversibility vs. dedicated right side/left side). From the list of available products, it became clear that many of the side skirts loosely fit into one of three major classes of side skirts: aluminum panel(s), narrow plastic panels and wide plastic panels. As such, two pairs of each of these three types of side skirts were procured for testing and analysis. The side skirts are described in Table 2. Additionally, one of the test trailers arrived to NRC-CSTT with a set of side skirts already mounted. Although not used for impact testing, these skirts were used as inputs for the brake cooling computer models and simulations; their properties are also listed in Table 2.

Many suitable skirts were not selected for testing simply due to similarity to the tested skirts and project cost and time limitations. The selection of side skirts was somewhat arbitrary as the aim of this project was not to rank commercial products, nor was it to endorse any particular manufacturer. Therefore, for the purpose of this report, the side skirts shall be known as #1, #2, #3 and #4 and all commercial branding was removed for the tests.

Table 2 – Specifications of side skirts used in testing

	Skirt #1	Skirt #2	Skirt #3	Skirt #4
Material	Aluminum	Injection-molded plastic	Automotive grade plastic	Aluminum
Height (inches)	29	32	35	30
Length (inches)	300 (25 feet)	300 (25 feet)	270 (22.5 feet)	236 (19.7 feet)
Support type	Diagonal, rigid tube	Vertical, injection-molded plastic	Diagonal fiberglass	Diagonal
Number of supports	6	9	8	6
Number of panels	3	8	3	3
Clearance to ground	~13 inches	~9 inches	~7 inches	~12 inches
Flexible base flap	Yes	Yes	No	No

3.2.1 *Skirt #1*

Skirt #1 consisted of three aluminum panels, one center section of five feet, and a rear and front section, each measuring ten feet in length. The rear and front sections were flared to accommodate wheels and landing gear, whereas the center section was rectangular. This skirt was attached to the trailer, following the manufacturer's instructions, as follows:

1. The tops of the aluminum panels were temporarily supported to the trailer using C clamps;
2. The skirts were then supported along the edge of the trailer using the hold down clamps and flange stiffeners (circled in Figure 9) provided by the manufacturer;
3. Next, the rigid tubular steel diagonal braces were attached to the bottom of the skirt panels and the upper ends were loosely attached to the trailer's aluminum frame rails using cross member clamps;
4. The skirt was then lined up longitudinally along the trailer and a bubble level was used to ensure the skirt was hanging plumb;
5. All fasteners were tightened;
6. The frame rail cross member clamps were torqued to 38 ft lb, as per the manufacturer's directions; and
7. Pre-test photos were taken.

Once assembled, the skirt sat approximately 13 inches above the ground. The longitudinal distance between the end of the skirt and the rear tires can vary depending on installation and trailer bogie setback. However, the longitudinal position of the skirt was determined in such a way to facilitate testing but may be more forward, or more rearward, when installed on an actual in-service trailer.

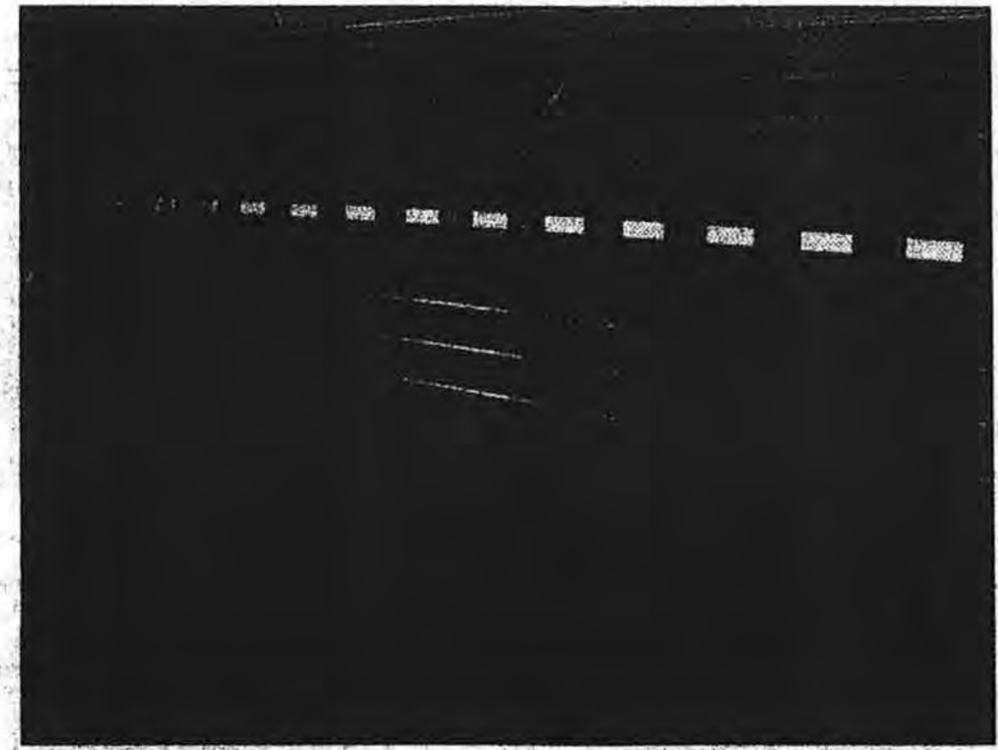

Figure 8 – Pre-test exterior view of skirt #1 (front and middle panel shown)

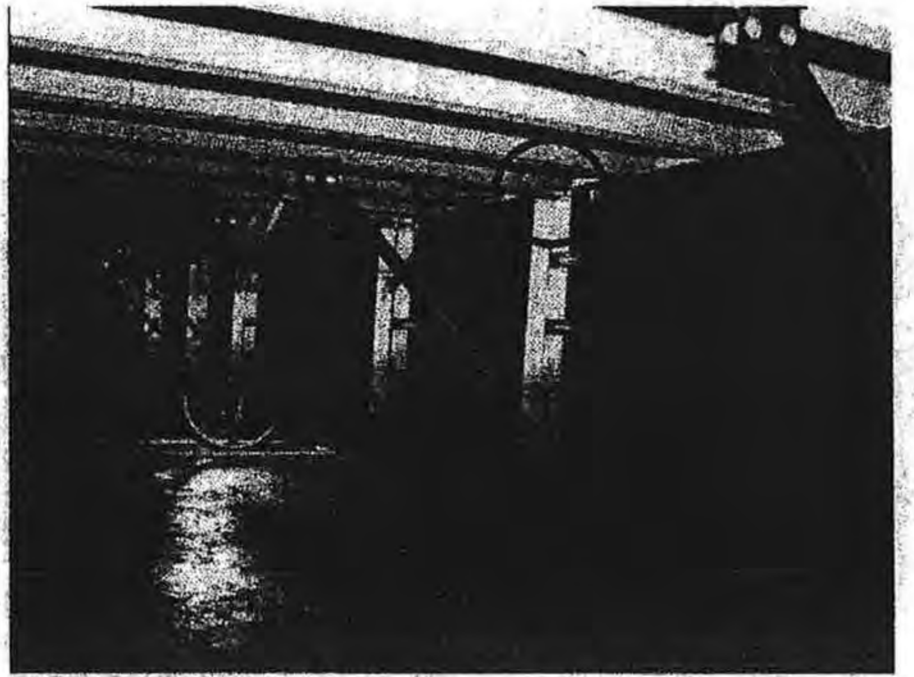

Figure 9 – Rigid diagonal braces and upper attachment flanges on skirt #1

3.2.2 *Skirt #2*

Skirt #2 consisted of eight individual injection molded plastic panels (Figure 10), each with a size of 37.5 inches wide by 28 inches tall. NRC-CSTT followed the manufacturer's recommended installation procedure and installed the skirt as follows:

1. The black hanger brackets were loosely installed and spaced appropriately (arrow in Figure 11)
2. The high end hanger supports were loosely fastened (circle in Figure 12);
3. The rear most panel was slid into place;
4. The hanger supports were tightened;
5. Steps 2 through 4 were repeated, moving forward, for the remaining seven panels;
6. The panel to panel hardware was installed, securing all eight panels to each other;
7. The upper hanger supports were torqued down to the manufacturer's specification;
8. The leading and trailing edge fairings were not installed as they are largely cosmetic and do not alter the strength of the skirt;
9. The mud flap strip was attached to the lower edge of the skirts;
10. Blind rivets were used to attach the lower edge of the vertical supports to the lower edge of the skirt;
11. All connections were verified and re-torqued prior to testing; and
12. Pre test photographs were taken.

Once assembled, the skirt sat 9 inches above the ground. The distance between the end of the skirt and the rear tires can be varied depending on installation and trailer bogie setback. However, the longitudinal position of the skirt was installed in such a way to facilitate testing, but may be more forward, or more rearward, when installed on an actual in-service trailer.

Figure 10 – Pre-test exterior view of plastic panel skirt #2

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Figure 11 – Pre-test interior view of plastic panel skirt #2

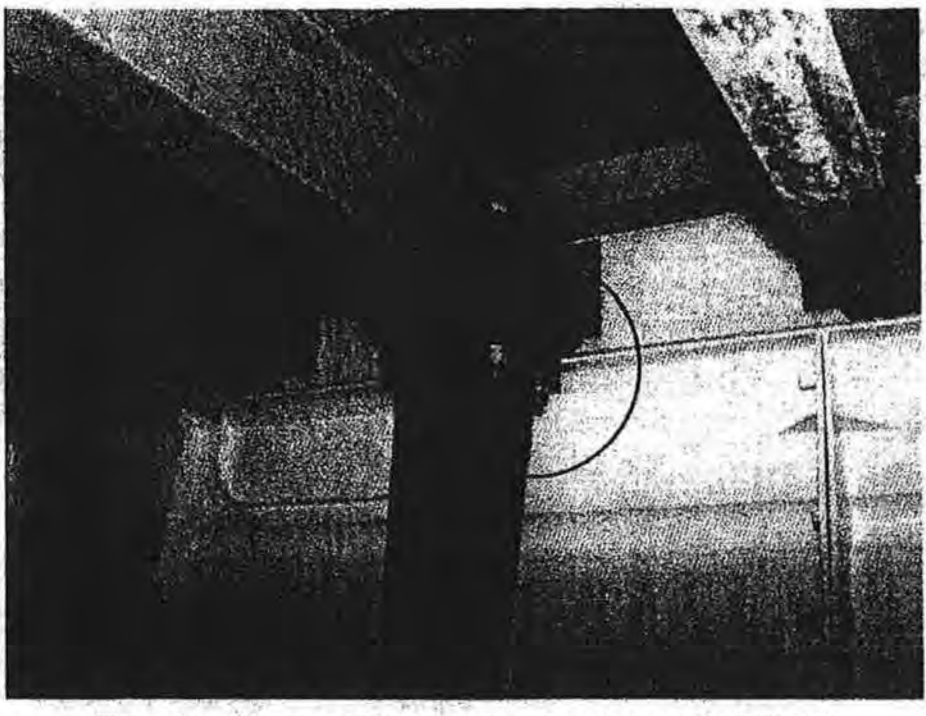

Figure 12 – Close-up of hanger support on frame rail of skirt #2

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3.2.3 *Skirt #3*

Skirt #3 consisted of three individual plastic panels (Figure 13), each with a size of 93 inches wide by 35 inches tall and all secured to the trailer with a high mount continuous hinge. Skirt #3 was the only skirt that required permanent alteration of the trailer. NRC-CSTT followed the manufacturer's recommended installation procedure and installed the skirt as follows:

1. All three panels were temporarily held into place with C clamps;
2. The rear panel was secured to the middle panel with bolts;
3. The front panel was secured to the middle panel with bolts;
4. Holes were drilled into the trailer's cross members;
5. The hanger supports were secured and tightened;
6. The fiberglass diagonal braces (Figure 14) were loosely connected to the trailer frame rails;
7. The fiberglass diagonal braces were loosely connected to the skirt panels;
8. All connections were tightened, verified and torqued prior to testing; and
9. Pre-test photographs were taken.

At seven inches from the ground, skirt #3 had the least ground clearance of the three models. The distance between the end of the skirt and the rear tires can be varied depending on installation and trailer bogie setback. However, the longitudinal position of the skirt was determined in such a way to facilitate testing, and may be more forward, or more rearward, when installed on an actual in-service trailer.

The manufacturer's installation instructions indicated that the skirt should be flared inboard toward the centerline of the trailer (Figure 15), starting with the rear edge of the panels. NRC-CSTT did not follow this instruction as it would have prevented testing in the flared section due to the likelihood of severe damage to the trailer once the ballast block was ejected and interference between the trailer and the bicycle's handlebars. As a result, all tests were conducted with the skirt in flush mode, as shown in Figure 13.

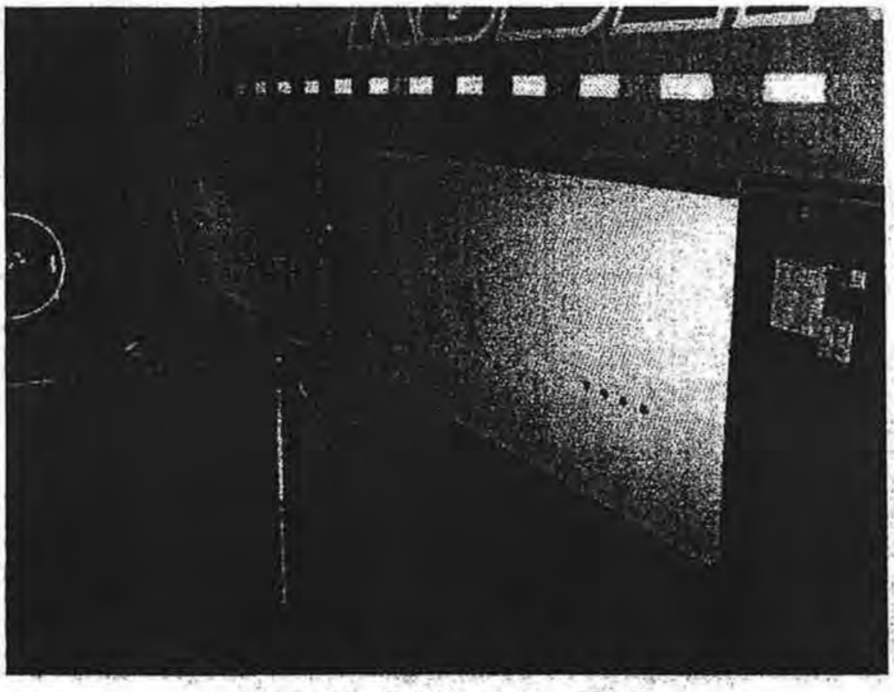

Figure 13 – Outside of side skirt #3

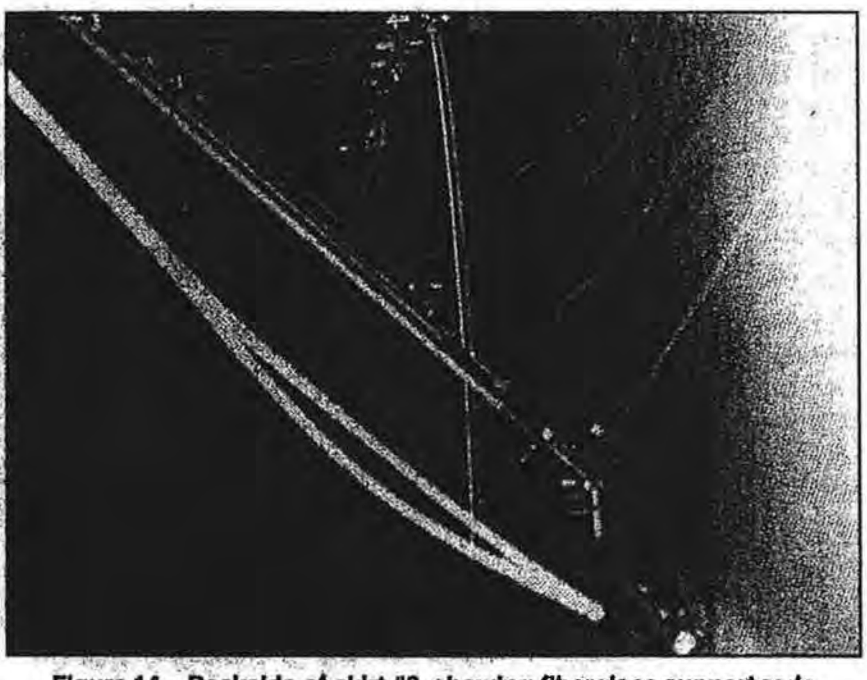

Figure 14 – Backside of skirt #3, showing fiberglass support rods

Figure 15 – Manufacturer's preferred installation angle for skirt #3

3.2.4 *Skirt #4*

Skirt #4 was similar to skirt #1 with a slightly different front taper. This skirt was used for brake cooling simulations and modeling and not used for impact testing. Figure 16 is a photo of skirt #4. The installation instructions for this skirt were not available therefore they have not been included in this report.

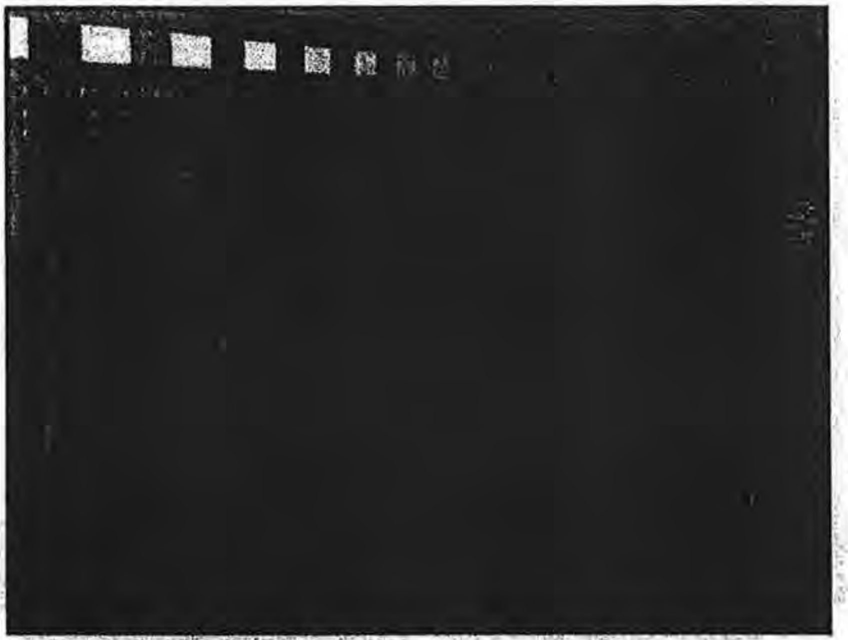

Figure 16 – Aluminum side skirt #4 used for modeling

3.3 Bicycles

In order to represent a realistic impact, NRC-CSTT acquired 10 full-size adult mountain bikes. The specifications of the bicycles are shown in Table 3 and a photo of a bicycle is shown in Figure 17.

Table 3 – Specifications of test bicycles

Specification	Details
Overall length	168.9 cm (66.5 inches)
Wheel diameter	63.5 cm (25.0 inches)
Number of gears	18
Frame height	45.7 cm (18.0 inches)
Frame construction	Welded tubular steel
Make and model	CCM FS 26
Year of manufacture	2010
Empty weight	15.5 kg (34.0 lb)

Figure 17 – Side view of test bicycle, simulated load (arrowed) and platform

3.4 Impact Ramp

Basic physics was used to determine the theoretical starting height required for the bicycle to impact the trailer with the design speed of 20 km/h. A variance of +/- 2 km/h was allowed. Once the height was calculated, an impact ramp facility was designed and fabricated.

The impact ramp consisted of two courses of standard construction scaffolds to achieve a height of 3.0 metres. Aluminum channel and cross braces were then welded and bolted together to form a trackway. The trackway descended off the scaffold at an angle of 37 degrees until reaching the floor level, approximately 5.0 metres from the base of the scaffold. The trackway then followed the floor until it reached the trailer, approximately 2.0 metres from the point at which it intersected the floor.

A trolley car was fabricated from plywood and a steel super structure; steel wheels and axles were mounted to the base of the steel and plywood to allow it to follow the trackway.

Since the trackway and trolley raised the bicycle by approximately 27 cm above the ground, it was necessary to raise the trailer, using floor jacks, by the same amount so that the bicycle could strike the trailer side skirt at the same vertical location compared to an actual impact. Similarly, the trolley and track were designed such that the trolley could not pass under the trailer which could have allowed the bicycle's rear wheel to pitch down, which would differ from a real impact. A rendering of the impact ramp and trolley are shown in Figure 18 and Figure 19.

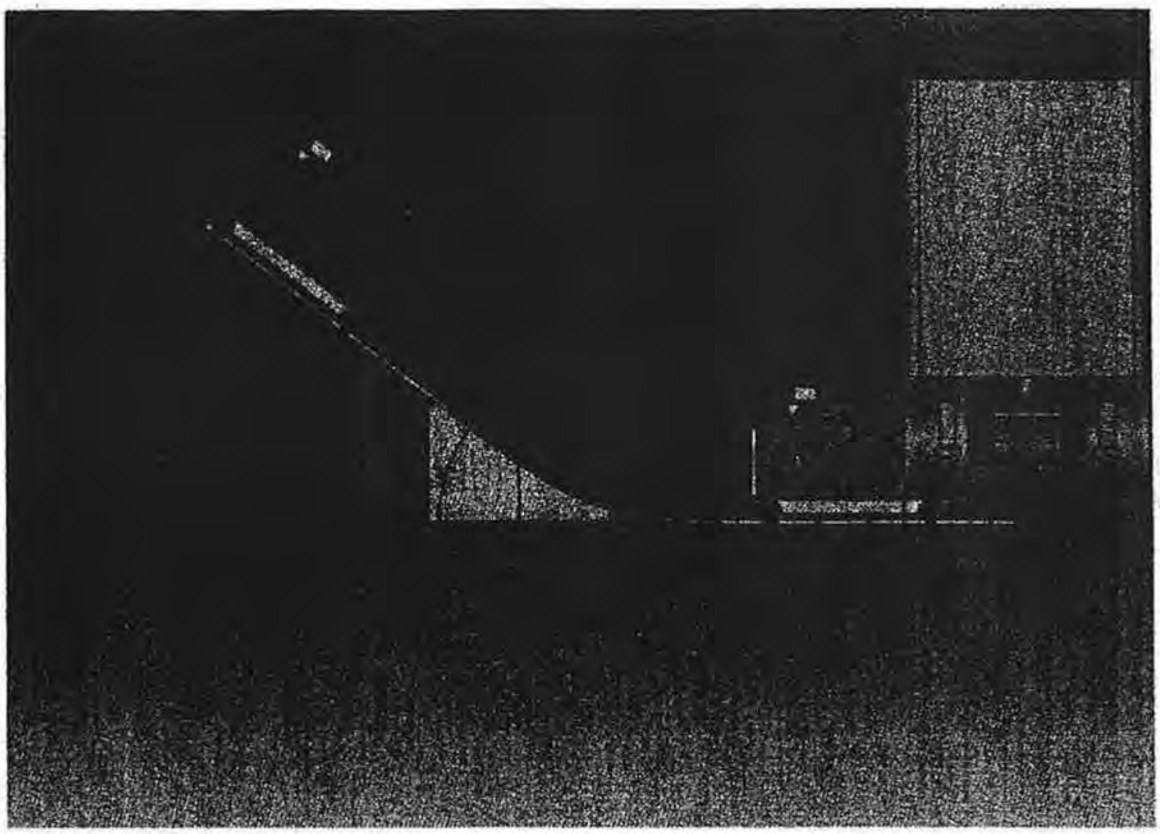

Figure 18 – Side view rendering of trolley and ramp system. Dimensions in mm and [ft].

Figure 19 – Isometric rendering of bicycle mounted on trolley and ramp system

3.5 Simulated Cyclist

As presented in Section 1.3, it would have been technically possible to mount an anthropomorphic test device (dummy) on the bicycle and attach its hands and feet to the handlebars and peddles, respectively. This method would have allowed NRC-CSTT to investigate how a human cyclist's body would behave during, and after, an impact with a side skirt equipped trailer. However, the purpose of this phase of testing was to develop a test facility and to investigate the strength and absorption properties of side skirts rather than the trajectory and final condition of the human rider. The costs to acquire proper crash test dummies was too high for this phase but could be considered for future phases.

Therefore, it became critical to design a simulated passenger that could remain on the bicycle as it travelled down the ramp but also departed the bicycle upon impact. Having no rider would have created a falsely light impact whereas having blocks of steel permanently fastened to the seat and handle bars would have created an impact that was significantly more destructive to the side skirt than in a real situation.

It was also necessary to determine the typical weight and balance of the test bicycles. In order to determine this, two different riders, one weighing 188 lb and one weighing 240 lb, were asked to sit on the bicycle in a comfortable and typical riding position while each bicycle wheel was situated on a load scale. Using these two weights, and knowing the initial axle loads of the empty bike, it was determined that the test bicycles with riders, achieved a 40:60 axle load ratio, front to back. Therefore, any representative load was added slightly ahead of the saddle position such that the resultant axle loads, including the tare weight of the bicycle, were 40%/60%, front to back. The frame platform that supported the simulated load was fastened to the bicycle and therefore remained on the bicycle after the impact. The weight of this device was approximately 12.2 kg (27.0 lb) and was deemed acceptable for testing as it could represent accessories such as loaded side bags on a typical bicycle.

Figure 20 – Simulated load and platform at the top of the ramp (view 1)

3.6 Handle bars and brakes

Although not entirely realistic, NRC-CSTT elected to lock the rotation (yaw) of the handle bars in order to improve repeatability of the tests. If the handle bars had been allowed to rotate, the exact collision attitude may have been different for each of the tests as some may have rotated to the left, some to the right and some not at all. This may have led to erroneous conclusions regarding the relative merits of one style of guard compared to another if rotating handle bars had been allowed to absorb more energy on one test run compared to another test run. Therefore, the steel platform was secured to the handle bars with "U" bolts, effectively locking the rotation of the handle bars.

The brake cables were disconnected for the impact testing to ensure that the bicycle's wheels were free to rotate.

3.7 Instrumentation

Ideally, a set of string pot displacement transducers would have been mounted to the side skirts to measure the vertical and lateral displacement of the side skirts as a result to the collision. However, little was known of the severity of the impacts and NRC-CSTT believed that the side skirts would likely have been ripped off the trailer due to the impact, thus eliminating the effectiveness of a string pot transducer. Additionally, since the side skirts behaved like a spring, it would have been pointless to mount accelerometers on the skirts as much of the acquired data would have been 'noise'. The high speed camera, and its ability to view and analyze the impacts frame by frame, was used in place of accelerometers and strong pot transducers. The following instruments were used during testing:

Table 4 – List of Instruments

Instrument	Make	Model	Scale	Error
Load Pads	IRD	IRD-WW-6100	0-10 000 kg	< 1%
Inclinometer	Mitutoyo	360Pro	0-360 deg	0.2 deg
High Speed Camera	Canadian Photonics	MK70S	0-105 000 fps	NA
Pressure paper	Fuji	Two sheet	2.5 to 10.0 MPa	Colour scale

4 PROCEDURE

4.1 Survey

A short survey was conceived and written by NRC-CSTT and posted on an Internet based survey site. Trailer manufacturers who belong to the Canadian Transportation Equipment Association (CTEA) were then asked to respond to the survey to assist NRC-CSTT in understanding the trends towards the use, or non-use, or disc brakes and aerodynamic packages on new trailers. The survey questions are outlined in Table 5.

Table 5 – Survey Questions

Question Number	Question
[illegible] Information	
1	Name of company?
2	Primary technical contact?
3	What type of products to you produce?
4	How many units did you manufacture in 2010?
Braking	
5	Do you offer disc brakes on your trailers?
6	If, yes, do you also offer drums on your trailers?
7	If no to Q5, why not?
8	Have you delivered a trailer with disc brakes?
9	If yes to Q8, what percentage of trailers left the factory in 2010 with disc brakes?
10	Why did the consumers choose disc brakes over drum brakes?
11	If no to Q8, why not?
Aerodynamics	
12	Do you offer aerodynamic packages on your trailers?
13	If yes to Q12, what types of devices are offered?
14	If no to Q12, why not?
15	Have you ever delivered a trailer with aerodynamic package?
16	If yes to Q15, how many trailers left the plan with at least one aerodynamic device?
17	If no to Q15, why not?
18	Do you educate your customers on the benefits ofaerodynamic packages?
19	Why do customers not want aerodynamic packages?

4.2 Setup for Impact Testing

The test area was prepared as follows:

1. Two 53-foot van semi trailers were leased for the duration of the project, one for modeling and one for testing. The trailers are representative of the most common type of trailer in Canada and are the types of trailers normally fitted with commercially available side skirts. The impact test trailer was backed into building U-89C at NRC-CSTT facilities, the landing gear was deployed and the tractor departed the test scene.
2. The test team, in consultation with Transport Canada, determined that the impact speed should be approximately 20 km/h;
3. Design engineers at NRC-CSTT calculated the size and height of a ramp required to provide an impact speed of 20 km/h;
4. The ramp and trolley system was designed in a 3-D design environment such that the impact between the bicycles and the side skirts was as realistic as possible with respect to impact height, speed, bike attitude and weight and interaction between the bicycle wheels and the platform/trolley;
5. The left side skirt set #1 was attached, as per the manufacturer's instructions, on the left side of the trailer;
6. The empty bicycle was placed on load cells and the load over the front and rear tires was measured;
7. A 188 lb human rider mounted the bicycle and the front and rear axle loads were re-measured to determine the weight distribution on the bicycle with a typical male rider in normal riding position;
8. Step 7 was repeated with a 240 lb rider;
9. The results of steps 6, 7 and 8 were used to determine the amount of load that should be added to the saddle, and to the handle bars, to properly represent a loaded bicycle.
10. An allowance was made to have a simulated human on the bike that would depart the bike at the moment of impact. Failure to do so would have caused an excessive load to strike the side skirt, thus creating an unrealistic test environment;
11. A high speed camera was leased from NRC-IAR to capture the moment of impact;
12. Pressure sensitive paper mats were attached to the side skirts to measure the amount of force imparted from the bicycle to the side skirt; and
13. The trailer was raised above the ground by the exact amount of the height of the trolley and rail system such that the bicycle could strike the side skirt in the same location as it would in a real collision.

4.3 Test Concept

The results of the nine successful tests have been presented in Section 5. However, there were numerous experimental tests required to confirm that the testing was achieving the desired results and repeatability. This is a normal procedure for the commissioning of a newly designed and constructed test apparatus.

Early experimental tests were found to be inadequate because the bicycle's front tire was impacting the skirt while the trolley was still moving at the target speed. As the wheel impacted the skirt it tended to stop, yet the rolling high speed trolley underneath tended to turn the bicycle wheel in the opposite direction and the trolley tended to pull down on the bicycle effectively adding weight to the impact. In essence, due to friction between the bicycle wheel and trolley, the 92 kg trolley had become part of the bicycle thus creating a more severe impact. In order to solve this issue, the bicycle was moved rearward on the trolley and the arresting system on the tracks was altered such that the trolley was arrested approximately 30 cm before the bicycle struck the side skirt. This resulted in a much more realistic impact since the trolley stopped well short of the trailer which caused the bicycle to continue moving along the stationary trolley, with both wheels turning freely in the correct direction until impact with the trailer.

The experimental tests also revealed a tendency for the bicycle to roll to the side off the trolley system, sometimes well before the impact. Therefore, a set of welded steel "A" brackets were attached to the rear of the trolley. The brackets were spaced far enough away from the bicycle to prevent binding, but close enough to resist the natural rolling moment of the bicycle.

Although initially intended for the purposes of test analysis, the high speed camera proved to be invaluable for assessing the effectiveness of the test method and was instrumental in honing the procedure. Once the test procedure was verified, all nine tests were conducted as per Section 4.4.

The many experimental tests not used for data analysis were a critical step in the process and will allow for repeatable tests and very quick setup time for future tests of this nature.

4.4 Impact Testing

The tests used for analysis have been coded as T1 through T9. The procedure used for these tests was as follows:

1. The left side skirt of skirt #1 was mounted to the trailer following the manufacturer's printed instructions;
2. The side skirt was inspected for integrity and strength of attachment;
3. The impact ramp was positioned beside the trailer and locked into place so that it lined up precisely mid span between two major side skirt supports;
4. The simulated load was placed on the bicycle;
5. Small dowels were driven into the plate to prevent the load from slipping off the bike while on the slope;

6. The bicycle was winched into place on the top of the ramp (Figure 21);
7. The high speed camera was cued and started;
8. All other cameras were started;
9. The pin underneath the trolley was released and the bicycle was allowed to strike the trailer side skirt midway between two supports;
10. The high speed camera was turned off;
11. Still photos were taken;
12. The deflection of the side skirt was measured;
13. The steel plate was removed from the test bicycle and mounted on a new bicycle;
14. The new test bicycle was prepared for testing;
15. Steps 1 through 13 were repeated with impacts against a major side skirt support;
16. Steps 1 through 14 were repeated on the remaining side skirt makes and models;

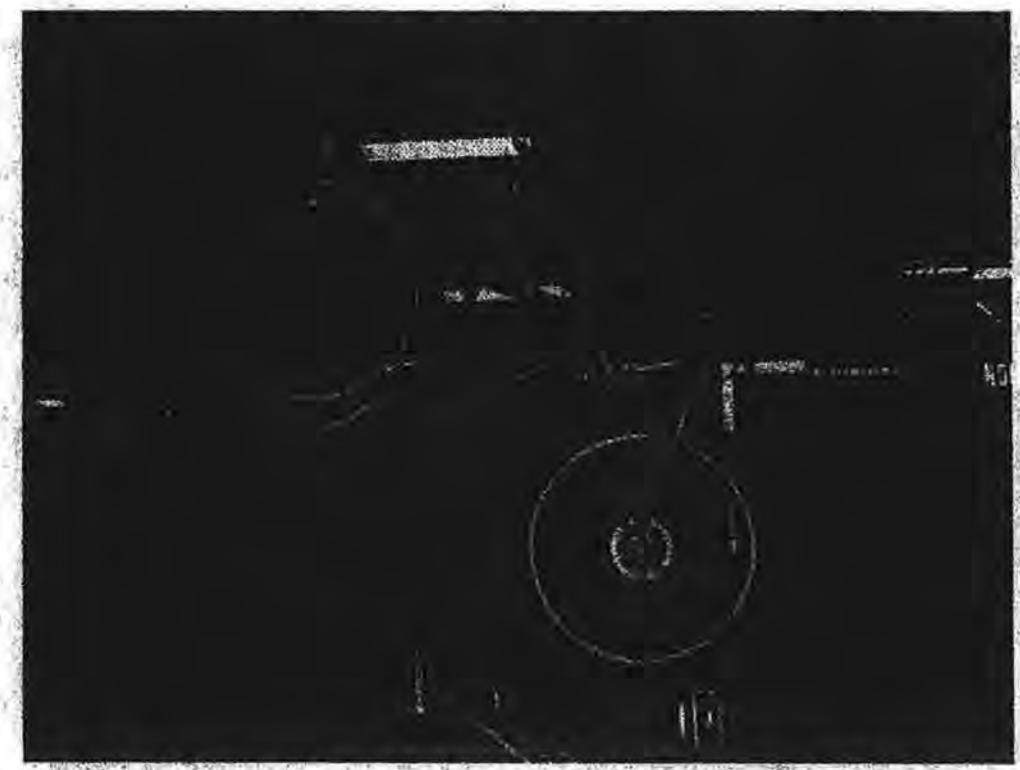

Figure 21 – Bicycle and simulated load at the top of the impact ramp (view 2)

The order of testing is illustrated in Table 6:

Table 6 – Test Sequence

Test #	Date and Time	Skirt #	Skirt Material	Strike Location	Bike #
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
T1	Feb 11, 2011; 11 AM	1	Aluminum	Front panel at support	2
T2	Feb 11, 2011; 2 PM	1	Aluminum	Mid panel between supports	3
T3	Feb 14, 2011; 10 AM	2	Plastic panel	At a support	4
T4	Feb 14, 2011; 11:30 AM	2	Plastic panel	Between two supports	5
T5	Feb 14, 2011; 2 PM	3	Plastic continuous	At a support	6
T6	Feb 14, 2011; 3:20 PM	3	Plastic continuous	Between two supports	7
T7	Feb 15, 2011; 10:45 AM	3	Plastic continuous	Between two supports	8
T8	Feb 15, 2011; 1:30 PM	1	Aluminum	Rear Section at slider rail	9
T9	Feb 15, 2011; 2:20 PM	1	Aluminum	Rear Section at slider rail	9

4.5 Effect of Side Skirts and Wheel Covers on Brake Cooling – Computer Modeling

4.5.1 *Overview of the Approach*

High temperatures in the wheel end geometry can lead to negative effects that directly impact vehicle safety. Tire ablation, hub grease melt-out, brake lining failure and thermal cracks and distortions have all been linked to excessive temperature and brake failure [22]. Excessive heating of disc brake components combined with temperature gradients can also produce circumferential disc thickness variations which in turn lead to brake judder, a highly undesirable forced vibration with a frequency directly related to vehicle speed [20].

The primary mechanism responsible for drum or ventilated disc brake cooling at highway speeds is convective heat transfer, that is, heat removed by air flowing around the brake drum or through the vaned passages and around the surfaces of the ventilated discs [19],[21]. For effective cooling, the brake drums or rotors require sufficient air flow to remove the heat through convection.

In this study, computer simulations using computational fluid dynamics (CFD) of the airflow around both a ventilated disc brake system and a drum brake system on vehicles with and without side skirts and wheel covers were conducted. The objective of the simulations was to determine if the use of side skirts and wheel covers could have any effects on brake cooling by either restricting or improving the air flow in and around the brake components.
Calculations were conducted for 13 geometrical configurations:

Case 1: Drum brakes on baseline trailer
Case 2: Drum brakes on trailer with side skirts and wheel covers
Case 3: Drum brakes on trailer with wheel covers only (no side skirts)
Case 4: Disc brakes on baseline trailer
Case 5: Disc brakes on trailer with side skirts and wheel covers
Case 6: Disc brakes on trailer with wheel covers only (no side skirts)
Case 7: Disc brakes on trailer with side skirts only (no wheel covers)
Case 8: Disc brakes on baseline trailer, with positive yaw side wind
Case 9: Disc brakes on trailer with side skirt and wheel covers, with positive yaw side wind
Case 10: Disc brakes on trailer with wheel covers only (no side skirts), with positive yaw side wind
Case 11: Disc brakes on baseline trailer, with negative yaw side wind
Case 12: Disc brakes on trailer with side skirt and wheel covers, with negative yaw side wind
Case 13: Disc brakes on trailer with wheel covers only (no side skirts), with negative yaw side wind

To evaluate the effect of side skirts and wheel covers on the airflow around the brake systems, the brake drum/disc surfaces were maintained at a constant temperature and the steady-state convective heat transfer from the drum and disc surfaces was calculated for the given vehicle speed. This approach represents a "snapshot" in time following a significant braking event, for example, braking while descending an inclined stretch of highway, and provides an understanding of the instantaneous cooling effects that, were they to be measured in a field or laboratory environment, would be time-averaged over some finite period. With this approach, the convective heat transfer from the brake drum/disc surfaces is the metric by which the airflow available for cooling is measured, and the tendencies for improved or reduced cooling capacity based on geometrical configurations (with or without side skirts and wheel covers) can be examined. While this approach is a simplification compared to real-life braking events, it has nonetheless been demonstrated through comparison with laboratory scale experiment to be a valid methodology for comparative brake cooling and design studies [15],[18],[19],[20].

The calculations undertaken in this study were not intended to provide a comparison of disc brake to drum brake performance, as this would require extremely detailed geometrical representation of the brake systems. Similarly, the calculations were not intended to provide absolute levels of heat transfer, but rather engineering estimates of the relative cooling performance (i.e., improvement or deterioration, and to what extent) based on the addition of the aerodynamic enhancement devices. Finally, the geometry is not intended to represent any particular manufacturer, but rather generic tractor-trailer and aerodynamic device combinations.

The remainder of this section outlines the details of the modeling methodology – the geometry, the computational mesh and the physical models employed. The results of the simulations are discussed in Section 5.4.

4.5.2 *Geometry*

Solid models of the tractor and trailers were created using the 3D modeling tool Solid Edge.

A Class-8 tractor with roof fairing geometry was used in all of the simulations. The tractor geometry is based on a White Road Boss vehicle that was created from dimensional drawings under a previous study [14].

The trailer models were created based on physical measurement of actual, full scale tandem axle 53-foot trailers that were leased by NRC-CSTT for this project. The trailer equipped with drum brakes was typical of standard tandem axle, dual tire configurations while the trailer equipped with disc brakes was typical of tandem axle, single-wide tire configurations.

The main trailer undercarriage components (landing gear, suspension, mud flaps, etc.) were included in the models, but were de-featured to simplify computational mesh and numerical modeling effort by removing elements such as hoses and clamps. Figure 22 and Figure 23 show the actual and modeled geometry, respectively, in the region of the rear suspension for the drum brake trailer. This level of geometrical accuracy was chosen to ensure that the primary flow characteristics due to the blockage caused by undercarriage components was captured in the simulations, thereby allowing a meaningful comparative study while keeping the numerical model computational effort to a reasonable level. A similar level of geometrical representation in the numerical models of the disc brake trailer was employed.

[redacted]

Figure 22 – Trailer equipped with drum brakes

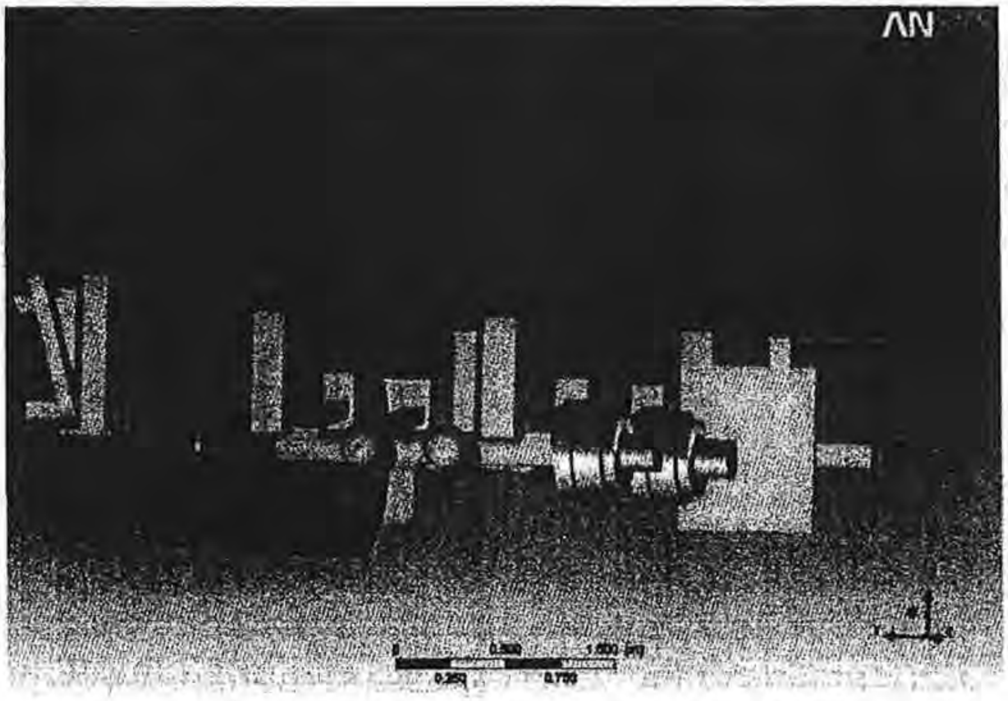

Figure 23 – Solid model of trailer equipped with drum brakes

Additionally, the interior surfaces of the brake drums were not included in the simulations, as the gap between the dust shield and drum opening was very small. This is a reasonable approach for a comparative study of the flow field around the brake drum system as influenced by upstream trailer components. In the case of the ventilated disc brake, air flow through the vaned passages was included in the models, since approximately 60% of the convective heat transfer from disc brakes occurs in this region [21].

The geometry of the side skirts was taken from measurement of an actual device that was acquired by NRC-CSTT (Skirt #4). Wheel covers were approximated by "closing off" the exterior surface of the wheel hub using a flat plane section of material having a negligible thickness, representing a typical aluminum wheel cover construction. shows solid models of a trailer with and without the side skirts and wheel covers.

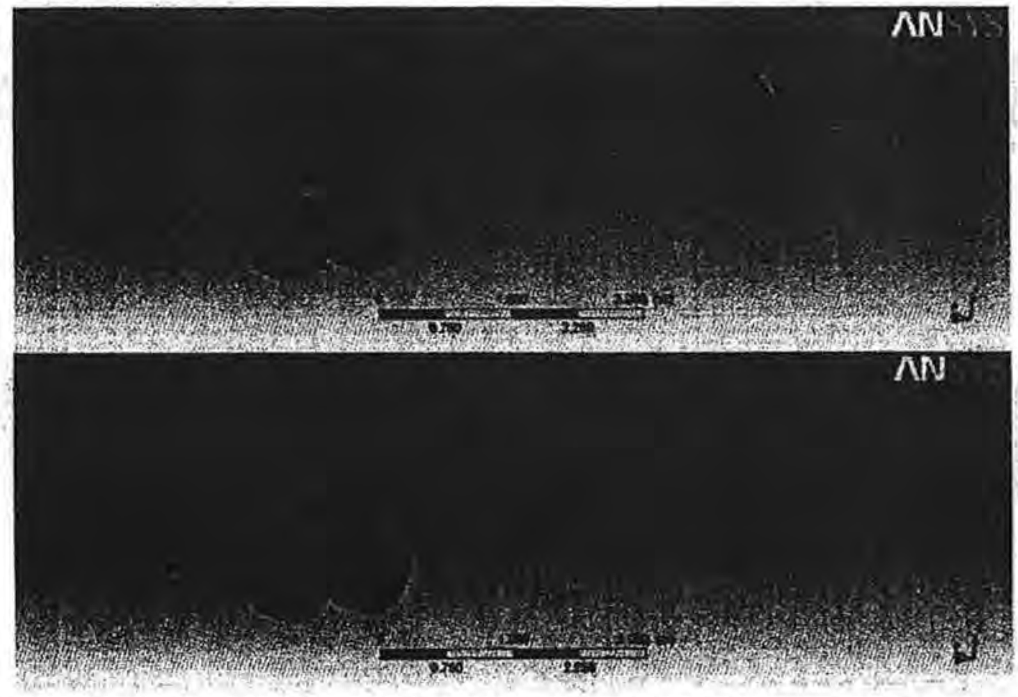

Figure 24 – Solid model disc brake trailer, with and without side skirts and wheel covers

The wheel hubs of the dual tires and drum brake system contained two openings through which air could travel, as shown in Figure 25. The relative angular position of the openings was arbitrarily chosen to be at the 3 o'clock and 9 o'clock positions when viewed from the side. While it is understood that the location of the holes relative to the ground or trailer under-body could result in a different flow pattern, a single position is sufficient for comparative studies such as the one conducted in the present work. The wheel hubs of the single-wide tires and disc brake system contained 10 circular openings through which air could travel; as such, the relative angular location of the openings was even less important for the intent of these comparative studies due to the axis-symmetric nature of the geometry.

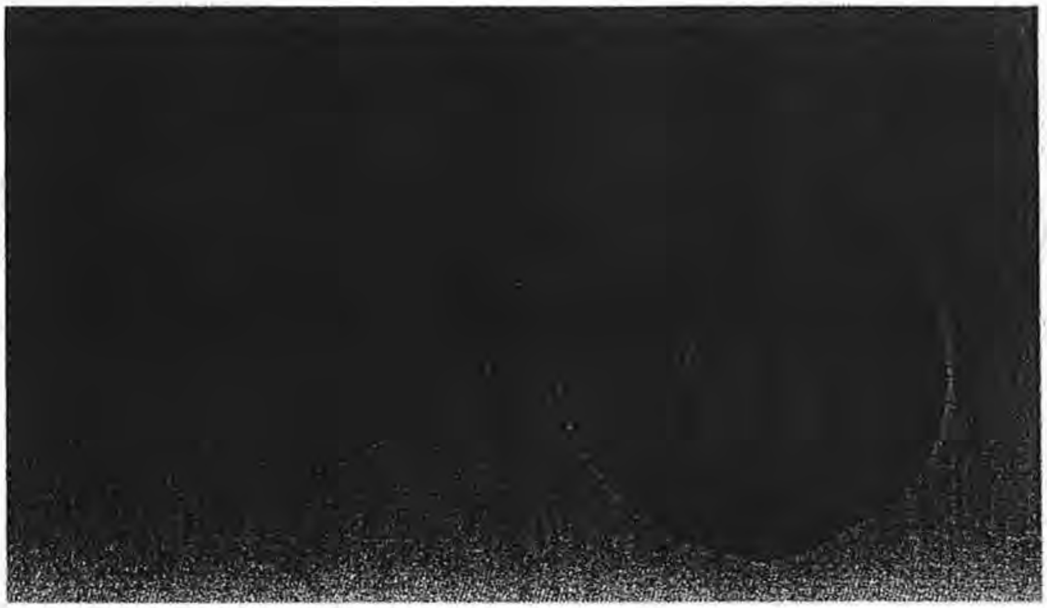

Figure 25 – Dual and single-wide tire geometries

4.5.3 *Computational Mesh and Domain*

Unstructured, mixed-element computational meshes containing tetrahedral, hexahedral and prismatic elements were created for the various geometrical configurations. A relatively coarse mesh was constructed on the tractor and main trailer surfaces (maximum element size of 6 inches full scale), since the intent of the geometry in this area was only to capture the gross flow features. The mesh was refined in the regions in and around the rear brakes, with a minimum surface element edge size of 0.06 inches full scale typically applied in key areas such as the brake pad-disc interface. A typical computational mesh consisted of approximately 2.5 million nodes (approximately 13 million elements) for a half-vehicle model. Figure 26, Figure 27, Figure 28 and Figure 29 show typical surface meshes in various locations.

Figure 26 – Typical surface mesh on tractor

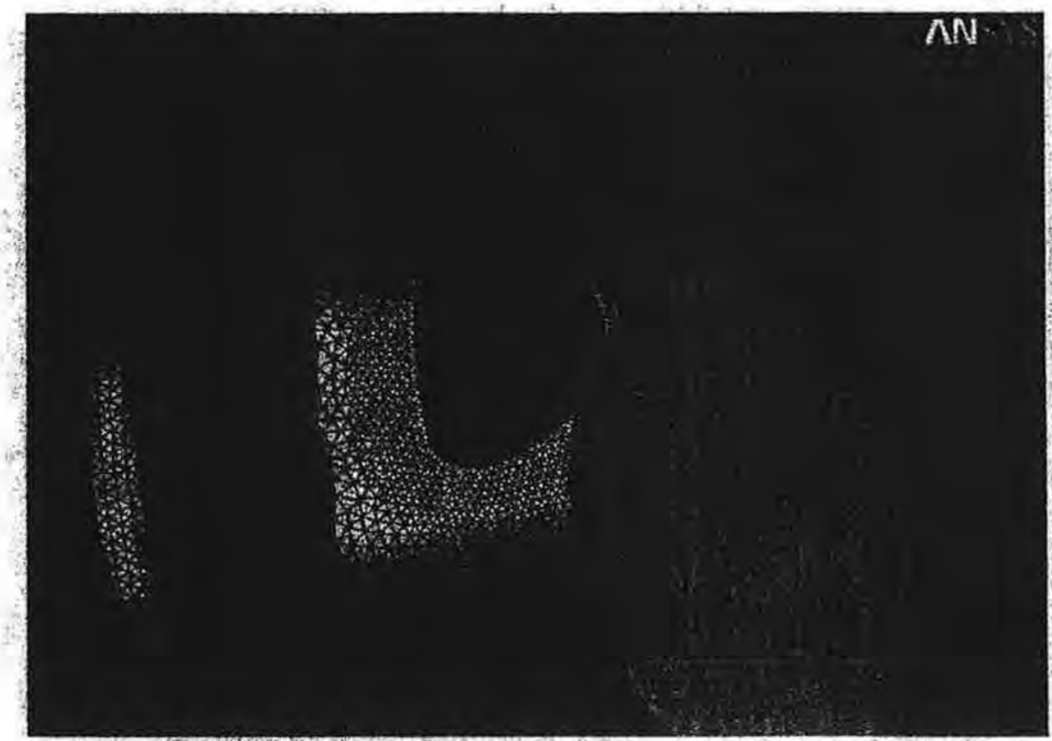

Figure 27 – Typical surface mesh around wheel hub, drum brake configuration

Figure 28 – Typical surface mesh around wheel hub, disc brake configuration

Figure 29 – Surface mesh through vaned passages of ventilated disc brake

The computational domain was created with far-field external boundaries. Figure 30 shows a side view of the computational domain.

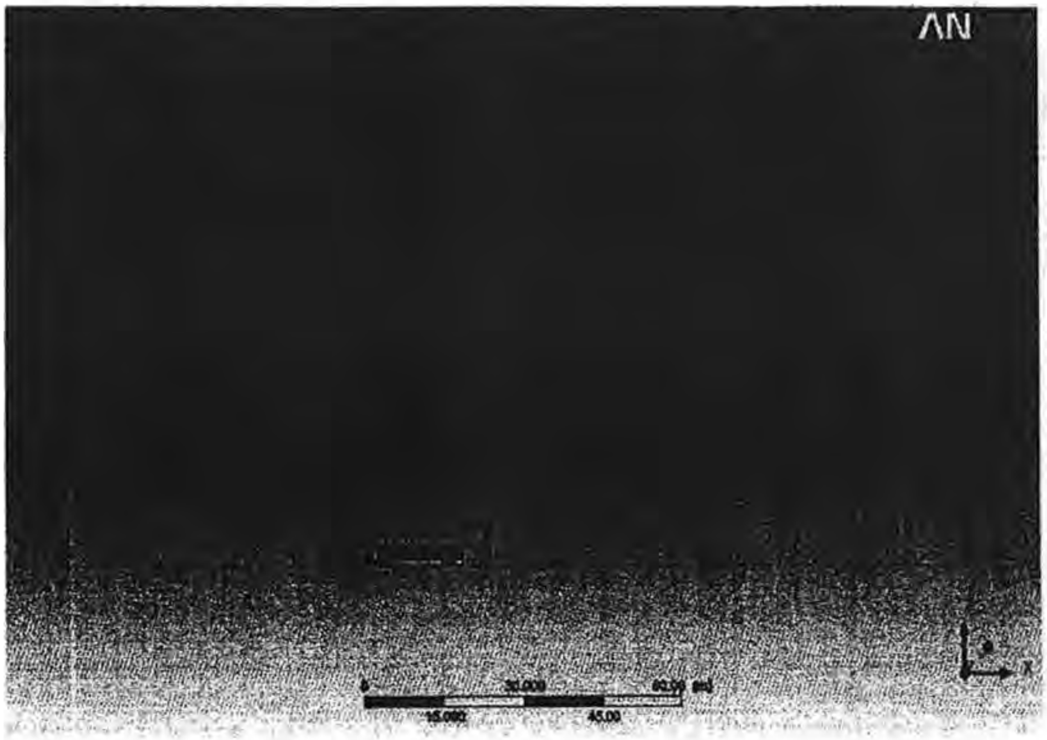

Figure 30 – Extent of computational domain

4.5.4 *Physical Modeling Approach*

Steady state flow simulations were conducted with the ANSYS CFX solver. This software package has been used extensively for brake cooling analyses, and has been validated in published works [16], [17]. All of the simulations conducted in this study used a high resolution advection scheme and first order turbulence numerics. Turbulence was modeled using the 2-equation k-ω based Shear Stress Transport model with wall functions and automatic near wall treatment in low-Reynolds number regions.

The inlet boundary condition was configured as velocity-specified air at 20 deg. Celcius. The air velocity was 100 km/h with no lateral component for the zero-yaw cases (Cases 1 through 7), and for the cases involving side wind, a positive (Cases 8 through 10) or negative (Cases 11 through 13) lateral component of 17.63 km/h was included, which represents a wind yaw angle of ±10 degrees. This angle was chosen because it represents a realistic upper bound on wind yaw experienced at normal highway cruising speeds, based on hourly-mean wind statistics for North America [23]. Turbulence boundary conditions were set to 5% turbulence intensity.

The outlet boundary was configured as an average relative static pressure. The far field boundaries were configured as free-slip (frictionless) surfaces. The ground boundary was configured as a translating surface equivalent to the vehicle forward speed of 100 km/h.

The wheel and brake drum/disc surfaces were modeled as rotating with constant rotational velocities that matched the forward vehicle speed based on the tire diameter. The surfaces of the brake drums and discs were modeled as isothermal at 400 deg. Celcius. While the actual absolute value of the temperature is not critical for the purpose of a comparative study, this temperature was chosen based on published data for automotive disc brakes [15] and heavy vehicle drum brakes [22], and is a reasonable approximate average temperature for a heavy vehicle disc brake undergoing steady-state cooling.

All of the zero-yaw cases were run with a half-model of the vehicle. A symmetry plane boundary condition through the centerline of the vehicle was employed in these cases. The non-zero yaw cases were run using a full vehicle model; however, one half of the vehicle was defeatured in order to simplify meshing and solver computational effort. All post processing of cooling performance results was conducted on the fine-grid portion of the models.

In the case of the disc brake configuration, the airflow in the vaned passages was modeled in a rotating frame of reference. This approach is necessary to accurately capture the additional sources of angular momentum due to the effects of the centrifugal and Coriolis forces in this region. A "frozen rotor" interface was specified between the stationary and rotating frames of reference. This steady-state interface allows for both meridional and circumferential flow profiles to develop (i.e., without circumferential averaging), and is a reasonable approach when the number of vanes is relatively high and when the upstream or downstream geometry is non-uniform, as is the case for the brake disc system modeled in this study.

For all of the calculations, equation residuals and integrated wall heat flow values on the brake surfaces were monitored. The solution was considered "converged" when RMS residuals for mass, momentum and thermal energy approached 1E-4 or below and when integrated wall heat flows varied by less than 2% typically, based on a minimum 200-iteration moving average.

5 RESULTS

5.1 Literature Search

The results of the literature search are presented in Sections 5.1.1 and 5.1.2.

5.1.1 *Side Skirts*

5.1.1.1 Side Skirt Search Sources

The primary source used in the review of commercially available side skirts was the United States (US) Environmental Protection Agency (EPA)'s SmartWay Program. SmartWay is the only government program in North America that has established a formal certification process to reflect the performance of various energy efficient technologies for heavy vehicles, including side skirts [4]. The EPA maintains a list of side skirt models that have been verified as aerodynamic technologies (either "standard" or "advanced", with estimated fuel savings of >4% and >5% respectively), based on the results of a modified TMC/SAE J1321 Type II Fuel Consumption Test [5]. This verified side skirt list, presented in Table 7, was the basis for all subsequent searches.

Secondary search sources for side skirts included Natural Resources Canada (NRCan)'s FleetSmart Technology Fund program (linked to SmartWay technologies through a formal Memorandum of Understanding with the EPA) [6] and the Government of Alberta's Trucks of Tomorrow rebate program [7]. Both programs encourage the adoption of energy efficient technologies for heavy duty trucks by offering reimbursements or rebates to commercial truck owners and operators who install aerodynamic devices on their fleets. A list of eligible side skirt technologies was identified through each program – these lists form part of the review presented in Section 5.1.1.1, below. (Note: Other similar Canadian rebate programs were reviewed; however, no side skirt lists were available.)

In addition, a study carried by the US National Research Council (under the National Academy of Sciences, Transportation Research Board) in conjunction with the US Department of Transportation (DOT)'s National Highway Traffic Safety Administration (NHTSA) was used as a benchmark resource for this review. The study, entitled *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles* 0, included a review of side skirt technologies for heavy-duty trailers, based on feedback from market surveys. A limited number of manufacturers responded to the survey, however, the ensuing discussions surrounding the use of these side skirts in the North American market were directly in line with the desired outcome of this review.

5.1.1.2 Side Skirt Search Procedure

The side skirt search was conducted as follows:

1. Compiled a list of available side skirts from the sources noted in Section 5.1.1.1;
2. Performed a general web-based search to identify any additional side skirt technologies – key words/phrases included: side skirt, side fairing, belly fairing, aerodynamic tractor trailer, trailer air flow deflection, and undercarriage airflow;
3. Established a list of side skirt specifications to be reviewed (e.g. material, design, cost, etc.);
4. Performed a search of original equipment manufacturer (OEM)'s websites; and

5. Conducted telephone interviews with OEMs to verify website data and gather detailed product specifications.

The results of the side skirt search are presented in Sections 5.1.1.3 and 5.1.1.4.

5.1.1.3 Commercially Available Side Skirts

The search outlined in Section 5.1.1.2 resulted in a list of 30 commercially available side skirt models, available through 16 different suppliers, all of which are verified as energy efficient technologies under EPA's SmartWay Program (Table 7). Further investigation revealed that two of the 16 suppliers are not OEMs and their side skirts (three models in total) are simply re-branded as a result of a partnership with an OEM. Furthermore, five of the 27 remaining models are either discontinued or have become obsolete based on greater fuel savings from improved models. This re-evaluation resulted in a total of 22 models available for review; however, due to the similar specifications of some of the models offered by OEMs (e.g. models only differed aesthetically), a shortened list of 19 unique side skirt models will be used for the remainder of this review.

Of the 13 OEMs identified, three are Canadian: Laydon Composites of Oakville, Ontario; Transtex Composite of Montreal, Quebec; and AirFlow Deflector, also of Montreal, Quebec. All three sell and distribute their products throughout North America.

Note: Side skirts used for the impact testing outlined in Section 4 are denoted with "⅃" in Table 7.

Table 7 – Aerodynamic side skirt availability and program eligibility

EPA SmartWay Verified Side Skirts			Eligible Side Skirts Under Canadian Programs	
Supplier		Product Model	Gov. Alberta Rebate	NRCan FleetSmart
[redacted]			[redacted]	
1	Carrier Transicold	Belly Fairing[1]	Yes	Yes
2	Fleet Engineers	[redacted]	-	-
3	FreightWing	Belly Fairing[1]	Yes	Yes
4	Laydon Composites[3]	6 or 7 Panel Trailer Skirts	Yes	Yes
5	Ridge Corporation	Green Wing, RAC0002 ***	Yes	-
6	Silver Eagle	Mid-Length Skirt ***	Yes	-
7	Silver Eagle	Mini-skirt ***	-	-
8	Transtex[3]	Trailer Skirts	Yes	Yes
9	Utility Trailer	Side Skirt 120	Yes	-
[redacted]			[redacted]	
10	Aerofficient	Aero-Slide	-	-
11	Aerofficient	Fixed Side Fairing - Wrap panel	-	-
12	Aerofficient	Fixed Side Fairing - Toe-in panel	-	-
13	AirFlow Deflector[3]	Deflector	-	-
14	ATDynamics[2]	ATD-Transtex Trailer Side Skirt	Yes	-

EPA SmartWay Verified Side Skirts			Eligible Side Skirts Under Canadian Programs	
Supplier		Product Model	Gov. Alberta Rebate	NRCan FleetSmart
15	Atlantic Great Dane	AeroGuard – AGD400-43	-	-
16	Carrier Transicold	Aeroflex Fairing[1]	Yes	-
17	FreightWing	[redacted]	Yes	-
18	Laydon Composites[3]	[redacted]	Yes	-
19	Laydon Composites[3]	7-Panel Trailer Skirt	Yes	-
20	Laydon Composites[3]	Hybrid, 24ft	Yes	-
21	Ridge Corporation	GreenWing, RAC0003	Yes	-
22	Ridge Corporation	GreenWing, RAC0012 ***	-	-
23	Silver Eagle	AeroSaber	-	-
24	Strehl	Model 715	-	-
25	Sweet Bottom	Trailer Skirt ***	-	-
26	Transtex[2]	MFS Trailer Side Skirt	Yes	-
27	Utility Trailer	Side Skirt 160	Yes	-
28	Wabash National	DuraPlate AeroSkirt - Standard	Yes	-
29	Wabash national	DuraPlate AeroSkirt - Angled	Yes	-
30	Windyne	Flex-Fairing	Yes	-

*** Not available for purchase (will not be included in side skirt specification review)

Ⅎ Model used in impact testing outlined in Section 4

[1] Carrier Transicold skirts are produced by FreightWing (from this point forward, the 'FreightWing' model will be used)

[2] ATDynamics skirts are produced by Transtex (from this point forward, the 'Transtex' model will be used)

[3] Canadian manufacturers

5.1.1.4 Side Skirt Specifications

The 19 side skirt models presented in Table 7 serve a common aerodynamic function, however, their specifications differ. These specifications are summarized in Sections 5.1.1.4.1 through 5.1.1.4.4, with a focus on the following: (1) material and weight, (2) aerodynamic performance and cost, (3) design, mounting, and installation, and (4) unique product claims.

5.1.1.4.1 *Material and Weight*

Side skirt panels are primarily available in three materials: aluminum, thermoplastic olefin (TPO) and fiberglass reinforced plastic (FRP). TPO and FRP, common plastics often used in the automobile industry, have similar properties – they are flexible, durable, lightweight, temperature resistant, ultraviolet (UV) stabilized and often recyclable [10]. In comparison, aluminum, a metal known for its overall strength and relative lightweight, is less elastic than plastic, and tends to be heavier than TPO or FRP.

The average total weight of the 19 models listed in Table 7 is 272 lb (includes two skirts and mounting hardware), with a range of 138 lb to 435 lb. Aluminum side skirts are the heaviest with an average weight of 355 lb, followed by TPO at 290 lb, and FRP with the lightest average of 200 lb.

Side skirts cost between $750 and $3600 (US/CAD $ taken at par), with an average cost of $1 675. There is no evident relationship between the cost and material; the cost range appears to be related to the specific design and function of the side skirts (see Table 9).

Examples of aluminum side skirts may be seen at Figure 8 and Figure 16, TPO side skirts are shown in Figure 10 and Figure 13, and FRP side skirts are shown in Figure 31 and Figure 32 .

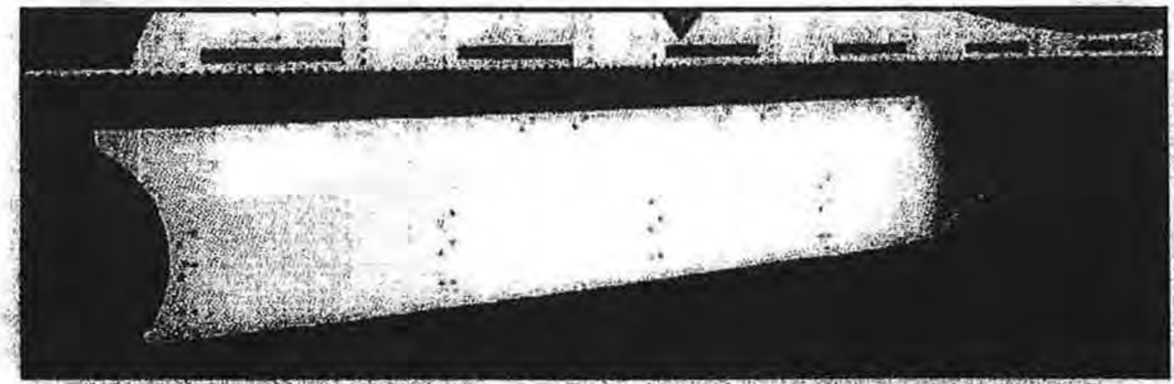

Figure 31 – Example of fiberglass reinforced plastic side skirt (courtesy of Transtex)

Table 8 – Side skirt material and weight

Model		Panel Properties		Cost ($)	
		Material	Weight (total - lb)		
[redacted]		[redacted]		[redacted]	
Fleet Engineers	[redacted]	Aluminum	340-400	1300	CAD
FreightWing	Belly Fairing	Aluminum	300	[1]1700	USD
Laydon Composites	6 or 7 Panel Trailer Skirts	TPO	240-272	1700	CAD
Transtex	Trailer Skirts	FRP	140-176	1795	USD
Utility Trailer	Side Skirt 120	FRP	300	[2]750	USD
[redacted]		[redacted]		[redacted]	
Silver Eagle	AeroSaber	Aluminum	390	1800	USD
Aerofficient	Aero-Slide	TPO	330	*	*
Aerofficient	Fixed Side Fairing	TPO	220	*	*
FreightWing	[redacted]	TPO	320-360	1450	USD
Laydon Composites	[redacted]	TPO	272-320	1950	CAD
Laydon Composites	Hybrid, 24ft	FRP	185	1200	CAD
Ridge Corporation	GreenWing, RAC0003	FRP	190	1600	USD
Transtex	MFS Trailer Side Skirt	FRP	140-176	1795	CAD
Utility Trailer	Side Skirt 160	FRP	300	[2]750	USD
Windyne	Flex-Fairing	Polycarbonate	435	3600	USD
AirFlow Deflector	Deflector	Unique Fiberglass Composite	260	2200	CAD
Atlantic Great Dane	AeroGuard – AGD400-43	Unique Fiberglass Composite	138-204	1800	USD
Wabash National	DuraPlate AeroSkirt	Steel and Plastic Composite	260	1625	USD
Strehl	Model 715	Polyester-Coated Steel, LPDE Core	236	1450	USD

[‡] Model used in Impact testing outlined in Section 4

[*] Price not available - OEM is only offering seeded units at this time

[1] EPA SmartWay Finance Website [11]

[2] Price as sold on Utility Trailers only – aftermarket prices vary

5.1.1.4.2 *Aerodynamic Performance and Cost*

The aerodynamic trailer side skirts, as presented in Table 7, offer an average fuel savings of 6.0%, with a range of 4.0% to 7.5%. These fuel savings values are the result of the SmartWay-mandated TMC/SAE J1321 Type II testing, discussed in Section 5.1.1.1. This testing, although standardized in theory, can vary in terms of exact track conditions, weather, trailer configuration and tractor speed. As such, OEMs prefer to use in-service, real-world testing results, which range from 5.0% – 9.0%, when promoting their products. However, since in-service results cannot be verified or compared, and TMC/SAE test results are the basis of SmartWay verification and fuel savings classification, TMC/SAE results will be used for the review.

Approximately one-third of the side skirts are classified as "advanced" technologies, yielding an estimated fuel savings of 5% or more. In addition, two of the five models classified as "standard" (>4%) have actually achieved a fuel savings greater than 5%, due to a model upgrade that has not yet been verified by SmartWay (see Table 9).

As noted in Section 2.2.1, side skirts can be combined with other aerodynamic trailer technologies (e.g. gap or tail fairings) as part of an aero package in order to achieve greater fuel savings. Aero packages (Figure 3) have become increasingly more popular since the announcement of the California Air Research Board (CARB)'s *Heavy-Duty Vehicle Greenhouse Gas Emission Reduction Regulation* in 2010, which requires all long-haul tractor trailer combinations, including those from Canada travelling through California, be equipped with SmartWay certified low rolling resistant tires as well as SmartWay verified aerodynamic devices with a total of 5% of more in fuel savings [12]. The 5% total savings can be achieved through a combination of aero technologies, including SmartWay "standard" side skirts, or simply through the installation of a SmartWay "advanced" side skirt. Approximately half of the side skirts in Table 9 are offered as part of an aero package.

The average cost of side skirts, as noted in Section 5.1.1.4.1, is $1 675 (US/CAN dollars at par). There is no conclusive relationship between the cost of side skirts and their estimated fuel savings. The cost of side skirts appears to be related to their specific design and function (Table 10). Side skirt OEMs commonly offer warranties between one and 10 years, with some limited lifetime warrantees available.

The stated return on investment (ROI) of side skirts is between 4 and 24 months. These values are not explicitly presented in tabular form as each OEM has chosen to use different parameters and assumptions in their calculation (e.g. average number of kilometers travelled, cost of fuel, driving/driver conditions, etc.), and therefore the claimed ROI values cannot be compared directly. In order to obtain accurate ROI values, trailer owners and operators must use their own parameters in the calculation. Many side skirt OEMs offer online calculators to help predict ROI for their products.

Table 9 – Side skirt aerodynamic performance and cost

Model		Fuel Savings[4] (%)	Cost ($)		Warranty (years)	Aero Package (Y/N)
[redacted]						
FreightWing	Belly Fairing	4.0	[1]1700	USD	1	Y – Gap
Utility Trailer	Side Skirt 120	4.0	[1]750	USD	5	N
Transtex	Trailer Skirts	4.39	[1]1795	USD	5-7	N/Y – Tail[**]
Laydon Composites	6/7 Panel Trailer Skirts	5.5[2]	1750	CAD	1	Y – Gap
Fleet Engineers	[redacted]	6.0[2]	1300	CAD	1	N
[redacted]						
Aerofficient	Fixed Side Fairing	5.2	[*]	[*]	5	Y – Gap/Tail
Ridge Corporation	GreenWing, RAC0003	5.2	1600	USD	5	N
Atlantic Great Dane	AeroGuard – AGD400-43	5.5	1800	USD	1	N
Wabash National	DuraPlate AeroSkirt	5.6	1625	USD	1-5	N
Silver Eagle	AeroSaber	5.7	1800	USD	Limited Lifetime	N
Laydon Composites	[redacted]	6.4	1950	CAD	1	Y – Gap
Laydon Composites	Hybrid, 24ft	6.67	1200	CAD	1	Y – Gap
AirFlow Deflector	Deflector	6.8	2200	USD	5	N
Windyne	Flex-Fairing	6.86	3600	USD	10	N
Strehl	Model 715	7.15	1450	USD	1	N
Aerofficient	Aero-Slide	7.2	[*]	[*]	5	Y – Gap/Tail
Transtex	MFS Trailer Side Skirt	7.35	[1]1795	USD	5-7	N/Y – Tail[**]
FreightWing	[redacted]	7.4	1450	USD	3	Y - Gap
Utility Trailer	Side Skirt 160	7.5	[3]750	USD	5	N

[‡] Model used in bicycle impact testing outlined in Section 4
[*] Price not available - manufacturer is only offering seeded units at this time
[**] Available though ATDynamics dealer only
[1] EPA SmartWay Finance Website [11]
[2] Fuel saving % value for upgraded model (not yet verified by EPA SmartWay)
[3] Price as sold on Utility Trailers only – aftermarket prices will vary
[4] Fuels savings from EPA SmartWay modified TMC/SAE J1321 Type II testing

5.1.1.4.3 *Design, Mounting and Installation*

As shown in Table 10, the various side skirt models vary not only in material composition, but also in design and installation. Side skirts are available in single-panel or multi-panel designs. Single-panel designs, offered only in TPO or FRP, tend to be less complicated to install than multi-panel designs; however, multi-panel designs can be broken down for shipping and can be easily replaced in panel units if damaged, rather than replacing the entire skirt.

The side skirt panels are available in both rigid and flexible designs. The more common flexible design (13 out of 19 models) allows the trailer to easily pass over obstacles, such as railroad crossings, snow banks and high curbs, with little to no permanent damage to the side skirt (See Figure 32 and Figure 33). Some models include a bendable rubber extrusion (Figure 8) that can help to minimize and/or prevent damage to the bottom of the main panel. Although this flexible panel may still provide aerodynamic benefit it would likely not provide any safety related benefits as it would simply bend up and out of the way upon impact with a VRU.

Most side skirts are fairly rectangular in shape. Some are designed with angled (Figure 13) or curved (Figure 16) ends, and a few OEMs offer end caps that are mainly for aesthetic appeal.

Side skirts are compatible with various sized trailers, including 48-foot, 53-foot, reefer and pup trailers, and a number of OEMs can customize skirt size to the needs of the buyer (see Section 5.1.1.4.4 for more on custom side skirts). For a standard 53-foot trailer, the average side skirt length is 280 inches (~23 feet) with an average height of 33 inches (2.75 feet).

The majority of side skirts are supported by diagonal (Figure 9 and Figure 14) or vertical (Figure 11) supports that attach to the backside of the skirt and are mounted to the trailer cross members. Various models have flexible diagonal supports that allow the skirt to flex both inwards and outwards (Figure 14 and Figure 32 and Figure 33), and return the skirt back to its original position. More than three-quarters of the side skirts listed in Table 10 have a no-drill, clamp mounting system that affixes the side skirt support to the I-beams on the underside of the trailer (Figure 9); the remaining models require permanent alteration to the trailer cross members.

Table 10 details a few innovative side skirt designs that include pivot and spring supports, telescoping/slide and flip panels (Figure 34), and hinged-panel systems (Figure 35). One final design to note is pictured in Figure 36. This aero device, although listed in the SmartWay "advanced" side skirt category, is a unique undercarriage belly fairing system. If differs from a side skirt in that its large body shape (mounted in the middle of the trailer underbody) works with the positive and negative wind pressures to achieve its fuel efficiency.

The installation time for the side skirts listed in Table 10 ranges from 2 to 8 person-hours, with an average time of 3.5 person-hours.

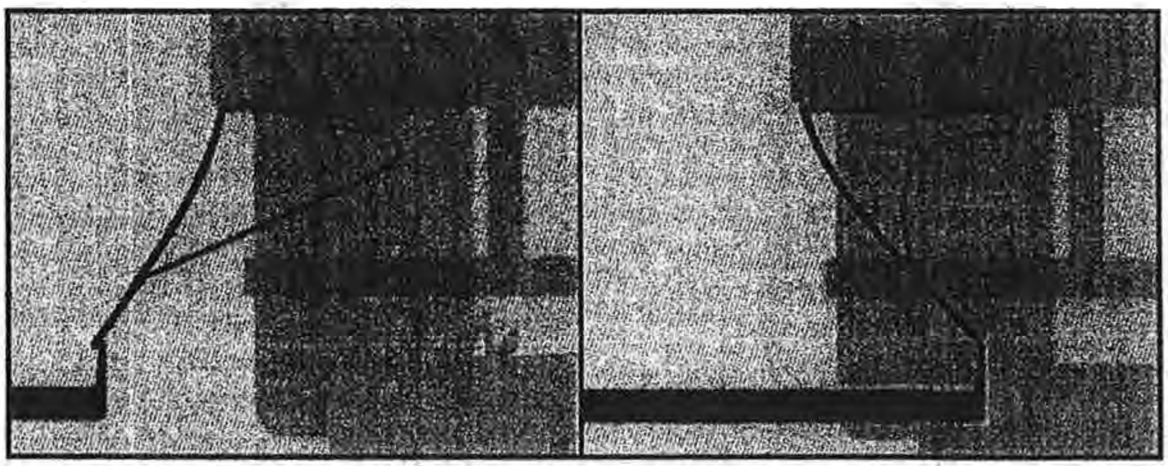

Figure 32 – Inward and outward flex potential of side skirts (courtesy of Utility)

Figure 33 – Side skirt in contact with snow bank (courtesy of ATDynamics)

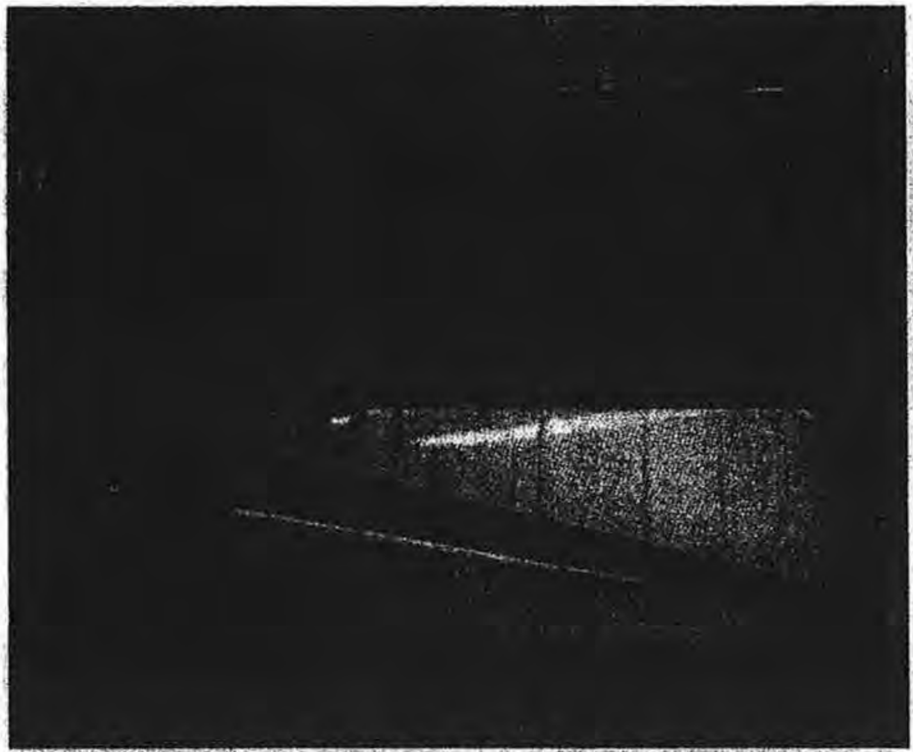

Figure 34 – Combination telescoping/sliding and vertical flip side skirt (courtesy of Windyne)

(Top: 3-panel full slide extension, Bottom: 2-panel vertical flip)

Figure 35 – Mid-level hinge side skirt (courtesy of Aerofficient)

(Fixed top panel, rigid and hinged lower panel, and bottom rubber extrusion)

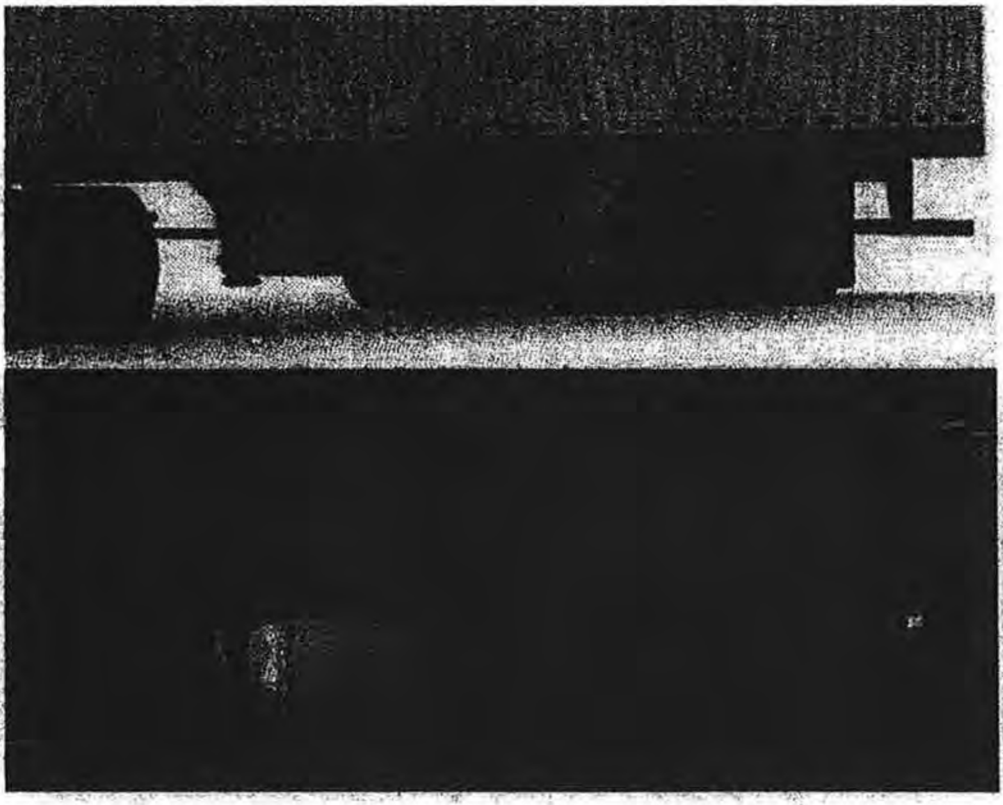

Figure 36 – Belly fairing verified as advanced SmartWay trailer skirt (courtesy of AirFlow Deflector)

Table 10 – Side skirt design and installation

Model		Material	Design			Mounting			Install Time (man-hrs)
			Panel (per side)	Rigid/Flex Slide/Lift	Length/ Height (inches)	Method	Trailer Drilling (Y/N)	Brace/ Hardware Material	
STANDARD (>4% fuel savings)									
Fleet Engineers	Extended Air [illegible]	Aluminum	• 3 Panels • Rigid vertical bracing	• Main: Rigid • Extrusion: Rubber	300/ 29	• Diagonal support • Clamp to I-beam – 2 locations/support	N	Aluminum, steel, zinc	3-4
FreightWing	Belly Fairing	Aluminum	• 5 Panels • Rigid triangular bracing	• Main: Rigid • Extrusion: Angled, riveted support braces	247/ 30	• Triangular support • Clamp to I-beam – 3 locations/support	N	Aluminum	3-4
Laydon Composites	6 or 7 Panel Trailer Skirts	TPO	• 6/7 Panels (+ end caps) • Vertical braces	• Main: Rigid • Extrusion: Rubber	262/ 32.9	• Vertical support • Clamp to I-beam – 1 location/support	N	Stainless steel, zinc	6
Transtex	Trailer Skirts	FRP	• 1 Panel • Point bracing	• Main: Inward flex	276/ 30	• Diagonal flex support • Clamp to I-beam – 2 locations /support	N	FRP, galvanized steel	4
Utility Trailer	Side Skirt 120	FRP	• 1 Panel • Point bracing	• Main: Inward and outward flex	276/ 35	• Diagonal support • Clamp to I-beam – 1 location/support	N	Galvanized steel	2-4
ADVANCED (>5% fuel savings)									
Silver Eagle	AeroSaber	Aluminum	• 6 Panels (+ 2 lead-out panels, 1 hinged) • Point bracing	• Main: Rigid • Extrusion: Rubber	341/ 36.5	• Diagonal supports, attached to inner rail • Clamp to I-beam – 2 locations/support	N	Steel	8
Aerofficient	Aero-Slide	TPO	• 3 Panels (+ 2 optional: toe-in and wrap) • Point bracing, with hinged midsection	• System: Sliding panel • Top: Rigid • Middle: Hinge, 90° flex • Extrusion: Rubber	300-350/ 36	• Diagonal supports • Clamp to I-beam (compression) - 1 location/support	N	Aluminum, stainless steel	4
Aerofficient	Fixed Side Fairing	TPO	• 2 Panels (+ 2 optional: toe-in and wrap) • Point bracing, with hinged midsection	• Top: Rigid • Middle: Hinge, 90° flex • Extrusion: Rubber	250-300/ 36	• Diagonal supports • Clamp to I-beam (compression) - 1 location/support	N	Aluminum, stainless steel	2

Model		Material	Design			Mounting			Install Time (man-hrs)
			Panel (per side)	Rigid/Flex Slide/Lift	Length/ Height (Inches)	Method	Trailer Drilling (Y/N)	Brace/ Hardware Material	
[redacted]	[redacted]	TPO	• 3 Panels • Hinged point bracing	• Main: Inward and outward flex • Top Hinge: 180° pivot	270/ 35	• Diagonal, flex rod and hinge supports • Drilling into trailer frame edge • Clamp to I-beam, 1 location/support	Y	Fiberglass, aluminum	4-6
[redacted]	[redacted]	TPO	• 7/8 Panels (+ end caps) • Vertical braces	• Main: Rigid • Extrusion: Rubber	275-338/ 32.9	• Vertical support • Clamp to I-beam – 1 location/support	N	Stainless steel, zinc	6
Laydon Composites	Hybrid, 24ft	FRP	• 1 Panel • Point bracing	• Main: Inward and outward flex	288/ 33	• Diagonal flex support • Clamp to I-beam – 1 location/support	N	Stainless steel, zinc	2
Ridge Corporation	GreenWing, RAC0003	FRP	• 1 Panel • Point bracing	• Main: Inward and outward flex	278/ 36	• Diagonal flex support • Clamp to I-beam – 2 location/support	N	FRP, Stainless steel, aluminum, zinc	2-4
Transtex	MFS Trailer Side Skirt	FRP	• 1 Panel • Point bracing	• Main: Inward flex	276/ 30	• Diagonal flex support • Clamp to I-beam – 2 locations /support	N	FRP, galvanized steel	4
Utility Trailer	Side Skirt 160	FRP	• 1 Panel • Point bracing	• Main: Inward and outward flex	252/ 34	• Diagonal flex support • Clamp to I-beam – 1 location/support	N	Galvanized steel	2-4
Windyne	Flex-Fairing	Polycarbonate	• 3 Panels • Hinged/lift system	• System: Slide and lift • Main: Rigid • Extrusion: Rubber	300-438/ 36	• Hinged/lift support • Diagonal supports • Clamp to I-beam, multiple locations	N	Aluminum	4.5
Atlantic Great Dane	AeroGuard – AGD400-43	Fiberglass	• 1 Panel	• Main: Inward flex	275/ 30	• Diagonal flexible support	N/A	Fiberglass	N/A
Wabash National	DuraPlate AeroSkirt	Steel and Plastic Composite	• 3 panels • Spring bracing	• Main: Spring flex • Extrusion: PVC flex	288/ 32.5	• Vertical spring support • Bolted to cross-members	Y	Galvanized steel	2
Strehl	Model 715	Polyester-Steel, LPDE Core	• 3 Panels • Pivot pillar support	• Main: Articulating flex • Extrusion: TPV	288/ 32	• Vertical pivot pillar • Bolts to cross-members	Y	Steel	3
Airflow Deflector	Deflector	Fiberglass Composite	• 1 unit - belly fairing • Under-mount	• System: Under- mount	168/ 33	• Bolted to bogie frame	Y	Stainless steel	2

5.1.1.4.4 *Custom Side Skirt Designs*

Dry van semi-trailers represent the largest portion of heavy-duty trailer types in Canada; however, there are many other types on the road today, including tanker, flatbed, and container chassis. Some manufacturers have developed custom aerodynamic side skirt models for use on these other trailer types, with similar material and weight specifications to the side skirts presented in Table 9. The fuel savings claims for these custom skirts are between 3% and 6%, however they do not qualify for SmartWay verification and there has been limited testing to substantiate these claims.

Examples of custom side skirts for tankers, flatbeds and container chassis are shown in Figure 37, Figure 38, and Figure 39, respectively.

Figure 37 – Custom side skirt installed on a tanker (courtesy of FreightWing)

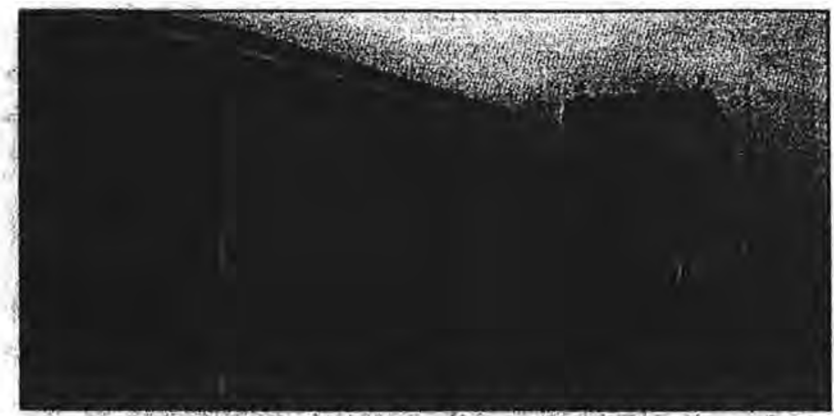

Figure 38 – Custom side skirt installed on a flatbed (courtesy of FreightWing)

Figure 39 – Custom side skirt installed on a container chassis trailer (courtesy of FreightWing)

5.1.1.4.5 *Unique Side Skirt Claims*

Side skirt OEMs often present claims about their side skirts, in addition to the principal fuel savings benefit. Table 11 presents a list of the various claims, offered by some, but not all, OEMs. Claims 1 through 6 could apply to most side skirt models listed in Table 7, however, claims 7 and 8 are unique to specific designs. It is important to note that claim 8, related to modifications to the trailer skirt panels (e.g. customizing the shape or size to accommodate under body accessories), may render the side skirt disqualified by the SmartWay program.

Table 11 – Unique product claims for side skirts

	OEM Product Claims	Details
1	Increased safety – visibility	Road spray suppression
2	Winter weather resistant	Minimal snow and ice build up on/under skirt Ability to overcome snow banks and withstand snow bank impact
3	Increased driving stability	Less aero drag at increased speeds
4	Increased safety – coverage	Reduced side under-run accidents
5	Trailer undercarriage protection	Minimizes corrosion of trailer underside
6	Environmentally friendly	Recyclable skirt material
7	Intermodal capable	Will not impede transfer/lift of trailer
8	Modifications to suit all trailers	Number of panels and skirt cut-outs[1]

[1] Modifications often disqualify side skirts from EPA SmartWay verification

Claims 1 through 3 were substantiated in a case study carried out by NRCan's Council of Energy Ministers, as part of a guide for purchasing aerodynamics for heavy-duty tractors and trailers, entitled "*On the Road to a Fuel-Efficient Truck*". The case study concluded the following:

> *"Most drivers find that trailers with skirts see a considerable reduction in spray when travelling in wet road conditions. During the winter months, drivers noted less build up of snow and ice underneath the trailers, as well as less snow spray. Furthermore, drivers have commented that when pulling a skirt-equipped trailer, they have increased stability in windy conditions and they have noticed an immediate improvement in fuel consumption."* [13]

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It is important to note that, similar to the observations made in the US study: *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, peer-reviewed data related to the measure of fuel savings and OEM claims for side skirts is limited. This raises a question about accuracy and reliability. The US study notes the following:

> *"There is a tendency among researchers to evaluate technologies under conditions which are best suited to that specific technology. ...One result is that the reported performance of a specific technology may be better than what would be achieved by the overall vehicle fleet in actual operation. Another issue with technologies that are not fully developed is a tendency to underestimate the problems that could emerge as the technology matures to commercial application."[9]*

Additional research would be required to further verify side skirt performance and product claims as they relate to in-service conditions in Canada. One initiative currently in progress is NRCan's FleetSmart SmartWay Technology Fund program. The purpose of this $1-million program is to provide contribution funding to Canadian-owned commercial trucking operators, for the purchase and installation of known fuel savings technologies, including aerodynamic devices or low rolling resistant tires that have been certified by the EPA SmartWay Program and supported by the CARB regulations. Through monthly reporting and multiple surveys (between April 1, 2010 and March 31, 2011), this program will enable NRCan to gather information on the use of these technologies in a Canadian context, from the experience of the 12 participating trucking operators. The results, based on pre-established baseline data, will be shared with the Canadian trucking industry through the FleetSmart website, to outline the positive (and negative) aspects of these fuel savings technologies [7].

5.1.1.5 Side Skirt Use in North America

Trailer side skirts are being used by many fleets all across North America in order to comply with CARB and SmartWay regulations, as well as to achieve notable fuel savings. In Canada, the potential for fuel savings, and in turn, the potential reduction in greenhouse gas emissions, from the use of side skirts is relatively significant. For instance, a tractor and standard van trailer cruising at highway speeds for 120 000 km per year, with an average fuel consumption rate of 45 litres per 100 km, and fuel savings of approximately 4.0% and 7.5% (based on OEM claims in Section 5.1.1.4.2), could save between 2 160 litres and 4 050 litres of fuel per year. In terms of greenhouse gas emission reductions, this could result in a savings of between 5 788 kg and 10 854 kg of carbon dioxide equivalent (CO_{2e}) per year, per tractor.

These savings could translate into significant reductions in greenhouse gas emissions on a national scale. According to Statistics Canada's annual Canadian Vehicle Survey, there were an estimated 232 489 tractors registered in Canada in 2007 [13]. Assuming that between 50% and 80% of these tractors are pulling standard van trailers and each trailer is equipped with one of the side skirt models listed in Table 9, a total potential fuel savings of between 670 kt and 2 000 kt of CO_{2e} per year could be realized in Canada.

5.1.2 *Wheel Covers*

5.1.2.1 Wheel Cover Search Sources

Aerodynamic wheel covers have only recently become available in the North American heavy-duty truck market, with the rising cost of fuel and the desire for more energy efficient trucking technologies. Preliminary searches and discussions with various industry professionals revealed that there are no established programs or regulations related to the aerodynamic testing or use of wheel covers in North America. As such, the review of commercially available wheel covers was performed through general web-based searches and OEM telephone interviews, as outlined in 5.1.2.2.

5.1.2.2 Wheel Cover Search Procedure

The wheel cover search was conducted as follows:

1. A general web-based search was performed to identify aerodynamic wheel cover OEMs – key words/phrases included: tractor trailer/semi-truck/heavy duty truck wheel covers, aerodynamic trailer wheels, aerodynamic trailer options;
2. Multiple tractor trailer manufacturers were interviewed regarding wheel cover availability;
3. A list of commercially available wheel covers was compiled;
4. A list was established of wheel cover specifications to be reviewed (e.g. material, cost, etc.);
5. A search was performed of OEM's websites; and
6. Telephone interviews were conducted with OEMs to verify website data and gather detailed product specifications.

The results of the wheel cover search are presented in Sections 5.1.2.3.

5.1.2.3 Commercially Available Wheel Covers and Specifications

The search outlined in Section 5.1.2.2 resulted in a list of five commercially available aerodynamic wheel cover models, available through three different OEMs (Table 12). Further investigation revealed that one model has been discontinued due to product deficiencies; however, a new, very similar product is being developed for release in the near future. As such, all five wheel cover models will remain as part of this review.

The five wheel cover models presented in Table 12 serve a common aerodynamic function, however, their specifications differ. These specifications are summarized in Sections 5.1.2.3.1 - 5.1.2.3.3, with a focus on the following: (1) material, weight, and compatibility, (2) aerodynamic performance, cost, and availability, and (3) design, mounting, and installation.

Table 12 – Commercially available aerodynamic wheel covers

	OEM	Model	Material	Weight [illegible]	Wheel and Tire Compatibility
1	Deflektor	Deflektor 101	Truck Tarp	< 2	• 22.5" • Aluminum or steel • Wide-based tires
2	Real Wheels	Aero Stainless	Stainless Steel	6	• 22.5"/24.5"

	OEM	Model	Material	Weight (lb per cover)	Wheel and Tire Compatibility
		Aero Aluminum	**Aluminum**	**3**	• **Aluminum or steel** • **Wide-based tires** • **Air valve kit available**
		Aero Clear	**Polycarbonate, aluminum**	**4.5**	
3	**ATDynamics**	**WheelShield** ***	**Aluminum**	**< 5**	• **22.5"/24.5"** • **Aluminum or steel** • **Wide-based tires**

***Discontinued product

5.1.2.3.1 ***Material, Weight and Compatibility***

Aerodynamic wheel covers are available in four materials: truck tarp (Figure 6 and Figure 40), stainless steel, aluminum, and a clear polycarbonate/aluminum combination (Figure 41). The wheel covers weigh between 2 lb and 6 lb each, with the truck tarp being the lightest and the stainless steel being the heaviest.

All wheel cover models are compatible with 22.5" aluminum or steel wheels, as well as wide-based; however, only the metal and polycarbonate models can be customized to fit the larger 24.5" wheels. Both 22.5" and 24.5" wheel sizes are used in the Canadian trucking industry.

Figure 40 – Example of tarp and zipper wheel cover (courtesy of Deflektor)

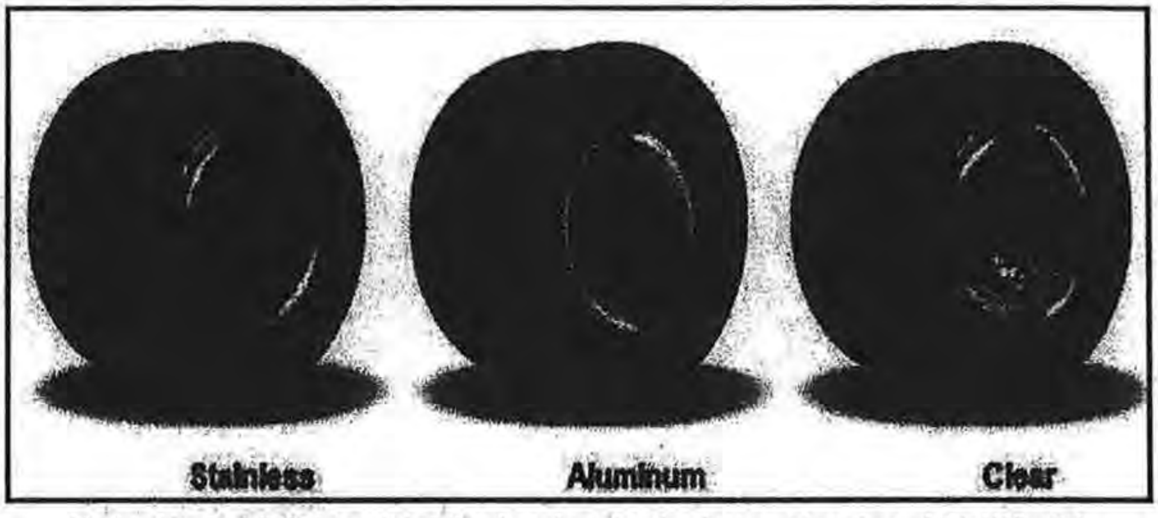

Figure 41 – Example of metal and polycarbonate wheel covers (courtesy of Real Wheels)

5.1.2.3.2 *Aerodynamic Performance and Cost*

All five wheel covers offer a similar predicted fuel savings of 0.25% per wheel. If installed on both the tractor and the trailer, a total fuel savings of up to 2.0% can be achieved. As noted in 5.1.2.1, there are no established guidelines for testing wheel covers; however, two of the three OEMs have carried out the TMC/SAE J1321 Type II Fuel Consumption Test as part of their product development and testing procedures. The challenge with using the TMC/SAE test for wheel covers is that the experimental error (~1%) is approximately equal to the potential fuel savings; therefore, it is difficult to determine an accurate result. Field and wind tunnel tests have also been conducted by the OEMs to obtain additional fuel savings values.

The average cost of wheel covers is approximately $100 per cover. There appears to be notable relationship between product cost and material quality, with the truck tarp at the minimum cost of $50 per cover, and the stainless steel at $135 per cover. The warranties offered by each of the three OEMs are quite different – the truck tarp model has a one-year limited warranty; metal/polycarbonate covers sold by Real Wheels have a 10-year warranty on the hardware (based on 100 000 miles travelled per year), as well as a lifetime warranty on the stainless steel finish; and the discontinued model had a three-year warranty.

The average stated ROI of the wheel covers is between four and six months. These values are not explicitly presented in tabular form as each OEM has chosen to use different parameters in their calculation (e.g. average number of kilometers traveled, cost of fuel, driving/driver conditions, etc.), and therefore the claimed ROI values cannot be compared directly. In order to obtain accurate ROI values, tractor trailer owners must use their own parameters in the calculation.

Table 13 – Wheel cover aerodynamic performance and cost

	[illegible]	Model	[illegible]	[illegible]	Warranty
1	Deflektor	Deflektor 101	0.25	50/cover	Limited 1-year
2	Real Wheels	Aero Stainless	0.25	240/axle (22.5") 301/axle (24.5")	1 000 000 miles on hardware – Lifetime on stainless finish
		Aero Aluminum		163/axle (22.5") 194/axle (24.5")	
		Aero Clear		217/axle (22.5") 248/axle (24.5")	
		Air valve kit	-	74/axle 50/super singles	
3	ATDynamics	WheelShield ***	0.25	250/set of 4 (22.5")	3-year

***Discontinued product

5.1.2.3.3 *Design, Mounting and Installation*

Wheel cover systems consist of two main elements – the front cover (constructed from the various materials discussed in Section 5.1.2.3.1) and a mounting system.

The mounting systems for the models in Table 13 vary significantly. The tarp cover uses a zipper and tab method (Figure 40 and Figure 43), where a zippered tarp ring is inserted into the wheel hub using built-in tabs, and the flexible tarp cover is then zippered onto the ring to create a taut surface. In contrast, the other three models use a bracket and bolt method (Figure 43), where a stainless steel bracket is bolted to the wheel hub, and the rigid cover is affixed to the bracket. The installation time is between one and 10 minutes per cover.

OEMs offer unique claims about each of their models. The truck tarp model's zippered design allows for easy access to the wheel for inspection, and its mounting method is fast, simple, and does not require special tools. The metal models have ventilation ports under the rim to eliminate moisture and corrosion, and an optional air valve extension can be installed to allow for tire air-pressure checks and refill. Also, the aluminum/polycarbonate model is clear for visual inspection of the wheel's oil cap, axle hub, lug nuts and air valves. Finally, all models can be customized with company branding for aesthetic appeal (Figure 6 and Figure 42).

Table 14 – Wheel cover design, mounting and installation

	OEM	Model	Unit Design	Mounting	Install Time
1	Deflektor	Deflektor 101	• Tarp cover with zipper • Tarp ring with zipper	• No hardware • Tarp ring secures on rim • Front cover zippers to tarp ring	1 min/ cover
2	Real Wheels	Aero Stainless	• Stainless cover with bolt holes • 1 mounting bracket • Ventilation ports on outer edge	• Stainless steel, zinc plated hardware	10 min/ cover
		Aero Aluminum	• Aluminum cover with bolt holes • 1 mounting bracket • Ventilation ports on outer edge		
		Aero Clear	• Polycarbonate cover/aluminum frame with bolt holes • 1 mounting bracket • Ventilation ports on outer edge		
3	ATDynamics	WheelShield ***	• Aluminum cover with bolt holes • 1 mounting bracket	• Hardware type unknown	30 min/ total set

***Discontinued product

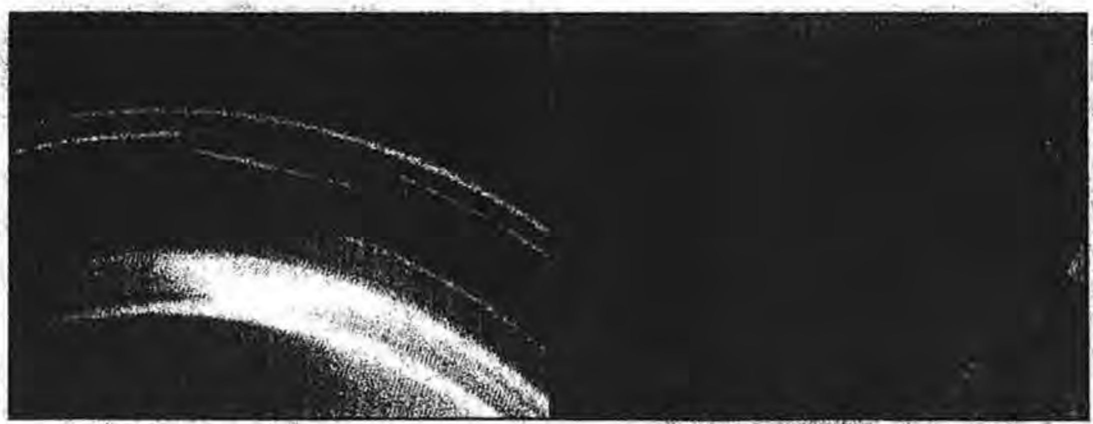

Figure 42 – Examples of wheel cover ventilation ports and air valve extensions (Real Wheels)

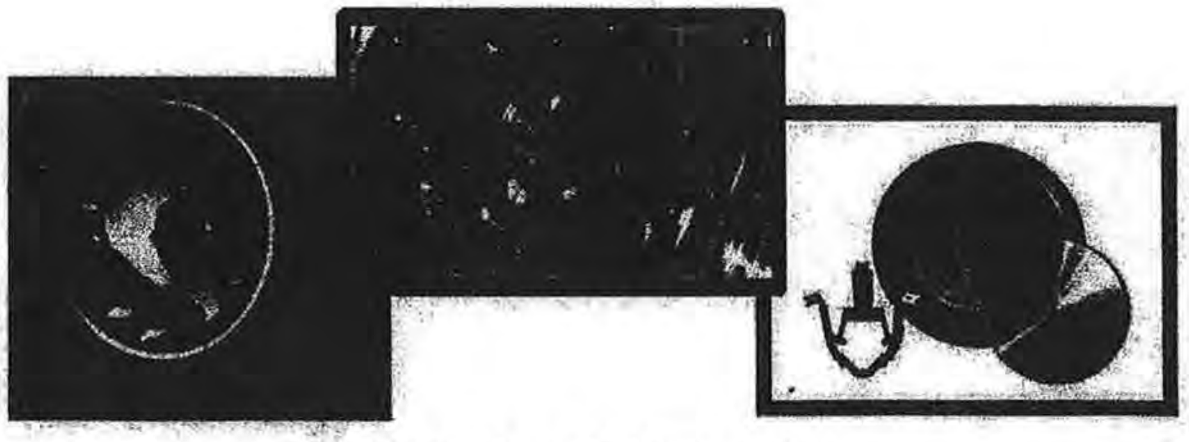

Figure 43 – Examples of wheel cover mounting

(Left to right: Deflektor, Real Wheels, ATDynamics)

5.1.2.4 Wheel Cover Use in North America

The availability of wheel covers is rather limited. While the truck tarp model is available for purchase online by the general public, the other three models (steel, aluminum and polycarbonate/aluminum) can only be purchased through specific dealers or carriers. The discontinued model, scheduled for re-release, is the only wheel cover offered as part of an aero package, with side skirts, tail fairings, and front fairings (pictured in Figure 3).

Wheel covers are being used on select fleets within North America. In early 2010, Schneider National announced the installation of the truck tarp model on their entire 12 000 tractor fleet (Figure 6). The other three models have been installed on numerous tests fleets, including a few in Canada. There were no Canadian wheel cover OEMs identified in this review.

Table 15 – Wheel Cover Availability

	OEM	Model	Availability
1	Deflektor	Deflektor 101	Online – general public
2	Real Wheels	Aero Stainless	Dealers and carriers only
		Aero Aluminum	
		Aero Clear	
		Air valve kit	
3	ATDynamics	WheelShield	Discontinued

5.2 Survey

NRC-CSTT received feedback from 10 different Canadian trailer manufacturers. Most of the questions were fully answered. The results of the survey were as follows:

5.2.1 *Questions 1 and 2 were non-technical;*

5.2.2 *Question 3: What type of products do you produce?*

The manufacturers claimed to currently produce tankers, flat beds, flat decks, lowbeds, semi-dumps, chip B train, van, side dump, end dump, forestry, bulk and off-road. It is clear that the respondents had a wide array of product lines, however, only one respondent indicated 'van' trailer, which is the most common type of trailer fitted with aerodynamic devices.

5.2.3 *Question 4: How many units did you manufacture in 2010?*

The responses varied from 30 to 1 500 units.

5.2.4 *Question 5: Do you offer disc brakes on your trailers?*

100% of the respondents indicated that they did offer disc brakes on at least one of their trailer models.

5.2.5 *Question 6: Do you also offer drums on your trailers?*

100% of the respondents indicated that they did offer drum brakes on at least one of their trailer models.

5.2.6 *Question 8: Have you ever delivered a trailer with disc brakes?*

100% of the respondents indicated that not only did they offer disc brakes on their trailers, but they had delivered at least one trailer with disc brakes.

5.2.7 *Question 9: If yes to Q8, what percentage of trailers left the factory in 2010 with disc brakes?*

The responses varied from less than 1% to over 25% of trailers in 2010 that left the factory with disc brakes.

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5.2.8 *Question 10: Why did the customers choose disc brakes over drum brakes?*

The respondents indicated that better braking performance and ease of maintenance were the primary reasons for customers choosing disc brakes over drums.

5.2.9 *Question 11: If no to Q8, why?*

There were no answers to this question since every manufacturer had at least one disc brake customer.

5.2.10 *Question 12: Do you offer aerodynamic packages on your trailers?*

Only 30% of the respondents said they did offer at least one model of trailer with aerodynamic devices.

5.2.11 *Question 13: If yes to Q12, what type of devices are offered?*

The three manufacturers who answered 'yes' to question 12 indicated that cones and enclosed sides were offered on their trailers.

5.2.12 *Question 14: If no to Q12, why not?*

70% of the respondents indicated they did not offer any aerodynamic packages at all. The rationale included: hard to fit on tankers, no interest from industry and not applicable to their product line.

5.2.13 *Question 15: Have you ever delivered a trailer with an aerodynamic package?*

Only 30% of the respondents said they had delivered at least one trailer with aerodynamic devices.

5.2.14 *Question 16: If yes to Q15, how many trailers left the plant with at least one aerodynamic device?*

One respondent indicated that no trailers left the facility in 2010 with aerodynamic devices whereas a second respondent indicated 25% did so.

5.2.15 *Question 17: If no to Q15, why not?*

The majority of respondents indicated that there was no demand from their customers to install aerodynamic packages on their trailers. One manufacturer responded that aerodynamic packages are 'too costly, too heavy and too complicated".

5.2.16 *Question 18: Do you educate your customers on the benefits of aerodynamic packages?*

Nine manufacturers out of 10 do not educate their customers on the benefits of aerodynamic packages.

5.2.17 *Question 19: Why do customers not want aerodynamic packages?*

There were many answers to this question. The principal reasons why the manufacturers don't provide aerodynamic packages were:

- Cost;
- Unaware of benefits;
- Creates logistics and movement issues around the yard; and
- Lack of product offering;

5.3 Impact Testing

The results of the impact tests were as follows:

5.3.1 *Test #1: Skirt #1 at a Support*

The bicycle struck the side skirt at the expected location directly at a support (Figure 46); the side skirt was pushed backwards (Figure 47) and the weight was ejected and the bicycle rebounded backwards into the test fixture. The force of the impact drove many of the diagonal braces permanently backwards along the frame rails, forcing the skirt to hinge upwards and remain permanently pushed in Figure 44. Additionally, the aluminum panel sustained significant permanent crushing damage that would be difficult to repair and would likely affect the performance of the side skirt. Four of the six diagonal braces moved (Figure 45) due to the impact, as follows, with brace #1 being closest to the front of the trailer:

Brace #1: Moved by 24 cm (9.5 in);
Brace #2: Moved by 28 cm (11.0 in);
Brace #3: Moved by 24 cm (9.5 in);
Brace #4: Moved by 9 cm (3.5 in);
Brace #5: Did not move; and
Brace #6: Did not move;

[redacted]

Figure 44 – View of permanent damage as a result of strike well ahead of slider rail

Figure 45 – Movement of diagonal support brace, skirt #1

Figure 46 – T1 at initial point of impact

Figure 47 – T1 at maximum deflection

5.3.2 *Test #2: Skirt #1 between Supports*

The bicycle struck the side skirt at the expected location directly between two supports; the weight was ejected and the bicycle rebounded backwards into the test fixture. The force of the impact drove many of the diagonal braces permanently backwards along the frame rails thus allowing the skirt to hinge upwards and remain permanently pushed in. Additionally, the aluminum panel sustained significant permanent crushing damage that would be difficult to repair. The moment of impact and the moment of greatest deflection are shown in Figure 48 and Figure 49. Three of the six diagonal braces moved due to the impact, as follows, with brace #1 being closest to the front of the trailer:

Brace #1: Did not move;
Brace #2: Moved by 1.5 cm (0.6 in);
Brace #3: Did not move;
Brace #4: Moved by 18 cm (7 in);
Brace #5: Moved by 1.5 cm (0.6 in); and
Brace #6: Did not move;

Figure 48 – T2 at Initial point of Impact

Figure 49 – T2 at maximum deflection

5.3.3 *Test #3: Skirt #2 at a Support*

The bicycle struck the side skirt at the expected location directly at a support; the weight ejected and the bicycle rebounded backwards into the test fixture. The side skirt absorbed all of the impact energy, deflected by 17 cm and then rebounded to its original position and attitude. Post test inspection revealed no visible damage on the outside of the skirt (Figure 53) and a slight kink in the vertical support member as a result of being bent upwards, as show in Figure 52.

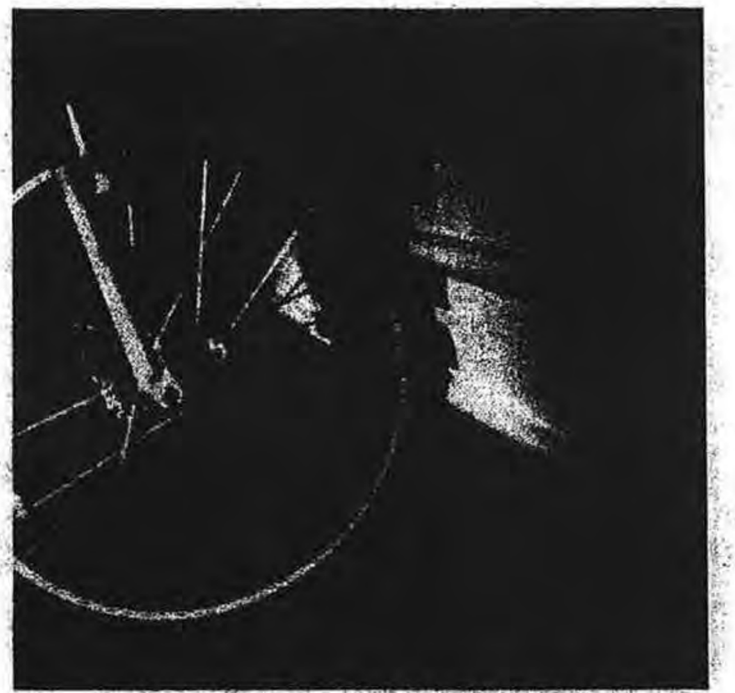

Figure 50 – T3 at initial point of impact

Figure 51 – T3 at maximum deflection

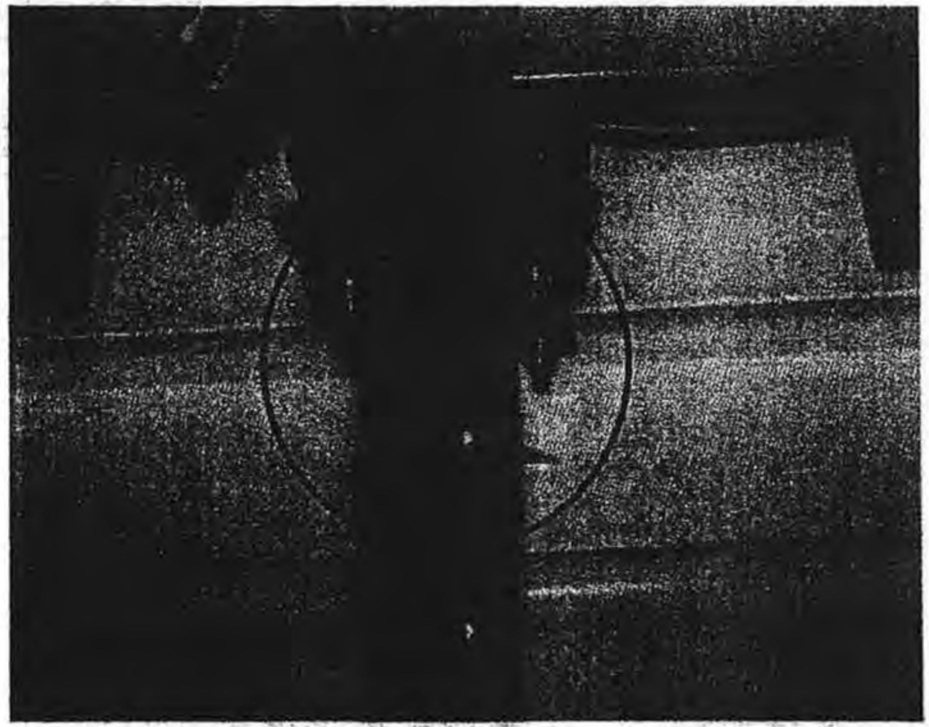

Figure 52 – Post test slight damage to vertical support

Figure 53 – Post test photo of skirt #2, showing no visible damage (paper removed)

5.3.4 ***Test #4: Skirt #2 between Supports***

The kinked vertical support was replaced with a new member.

The trailer was moved ahead by approximately 2.1 m (7 ft) in order to line up the impact ramp between two panel supports.

The bicycle struck the side skirt at the expected location between two supports; the weight ejected and the bicycle rebounded backwards into the test fixture. The side skirt absorbed all of the impact energy, deflected elastically by 26 cm and then rebounded to its original position and attitude.

Like test #3, post test examination did not reveal any damage to the skirt on the outside, or on the inside.

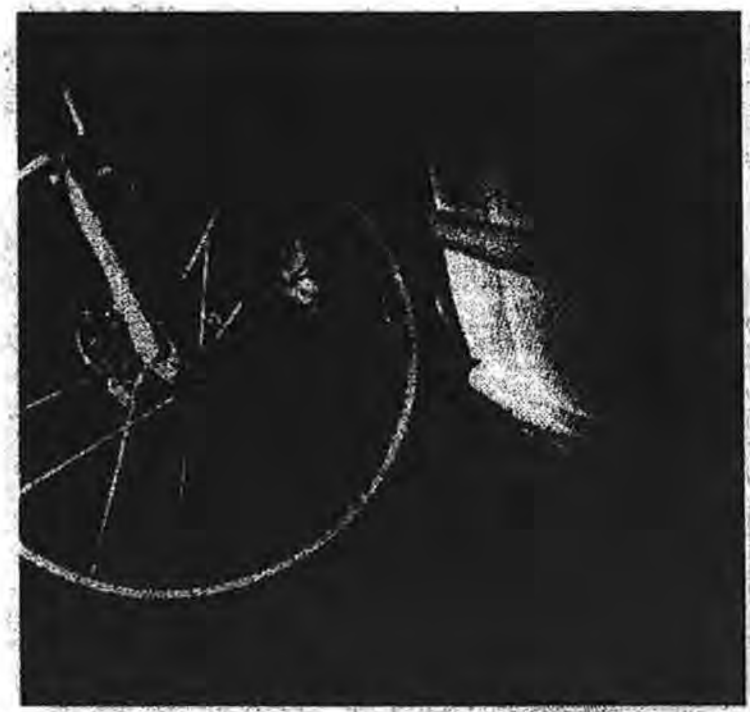

Figure 54 – T4 at initial point of impact

Figure 55 – T4 at maximum deflection

5.3.5 *Test #5: Skirt #3, at a support*

The bicycle struck the side skirt at the expected location directly at a support; the weight ejected and the bicycle rebounded backwards into the test fixture. The side skirt absorbed all of the impact energy, deflected by 33 cm and then rebounded to its original position and attitude. Post test inspection revealed no visible damage on the outside of the skirt (Figure 58), however, one of the fiberglass support rods compressed beyond its elastic region and returned to its rest position sliced in two, as shown in Figure 59.

Figure 56 – T5 at initial point of impact

Figure 57 – T5 at maximum deflection

Figure 58 – Post test photo of skirt #3, showing no visible damage (paper removed)

Figure 59 – Backside of skirt #3 showing damaged support rod

5.3.6 *Test #6: Skirt #3, between supports*

The bicycle struck the side skirt at the expected location directly between the two rear most supports; Although the test appeared to be as expected, reviewing the high speed video camera feed allowed the test team to determine that the handle bars of the bicycle may have contacted the protective plywood, thus reducing the impact speed and force. The maximum transient displacement was determined to be 23 cm. The test team noted the condition of the skirt and took photos but agreed a re-test in that same location was warranted.

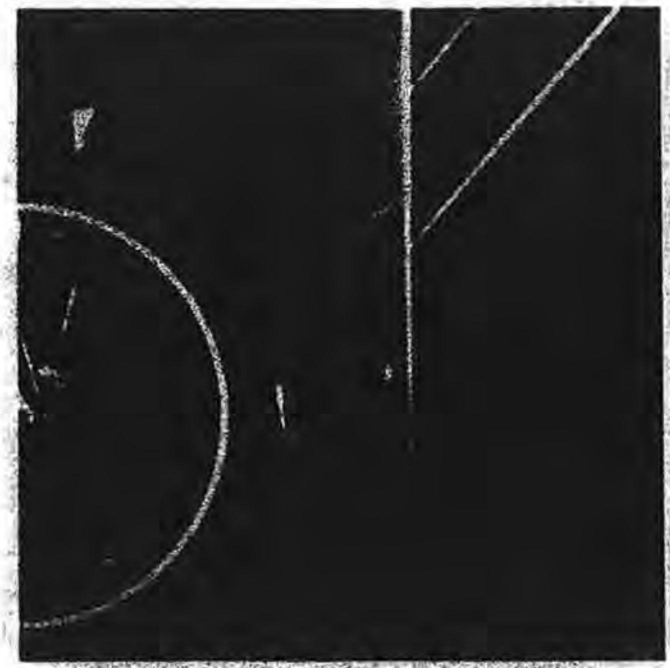

Figure 60 – T6 at initial point of impact

85

Figure 61 – T6 midway through impact (note bend in supports)

Figure 62 – T6 at maximum deflection (note wave action of skirt)

5.3.7 *Test #7: Skirt #3, between supports*

Test #7 was a repeat of test #6. The bicycle struck the side skirt at the expected location directly between two supports; the ballast weight was ejected and the bicycle rebounded backwards and became lodged into the test fixture. The side skirt absorbed all of the impact energy, deflected by 37 cm and then rebounded to its original position and attitude. Post test inspection revealed no visible damage on the outside of the skirt, however, the rear most fiberglass support rod compressed beyond its elastic region and returned to its rest position sliced in two, as shown in Figure 66.

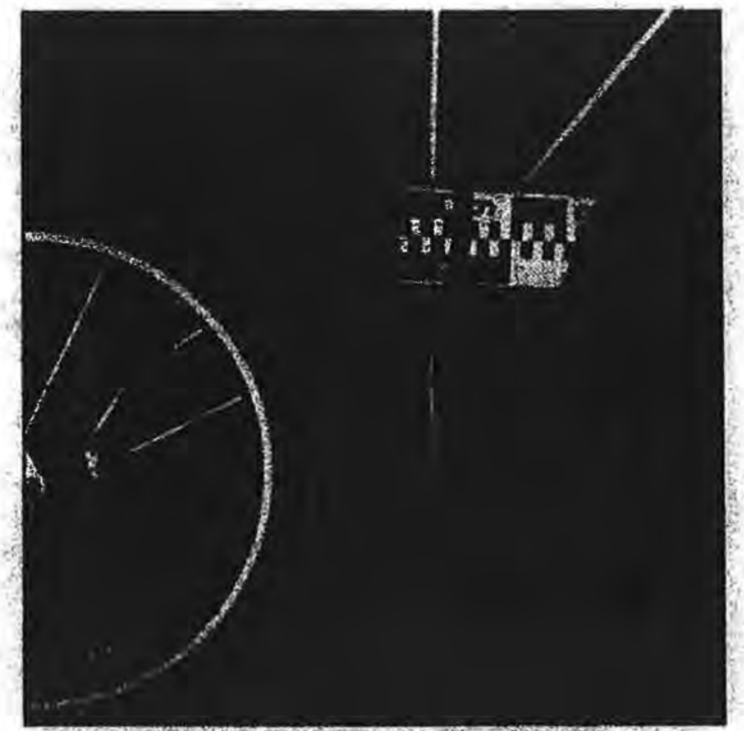

Figure 63 – T7 at initial point of impact

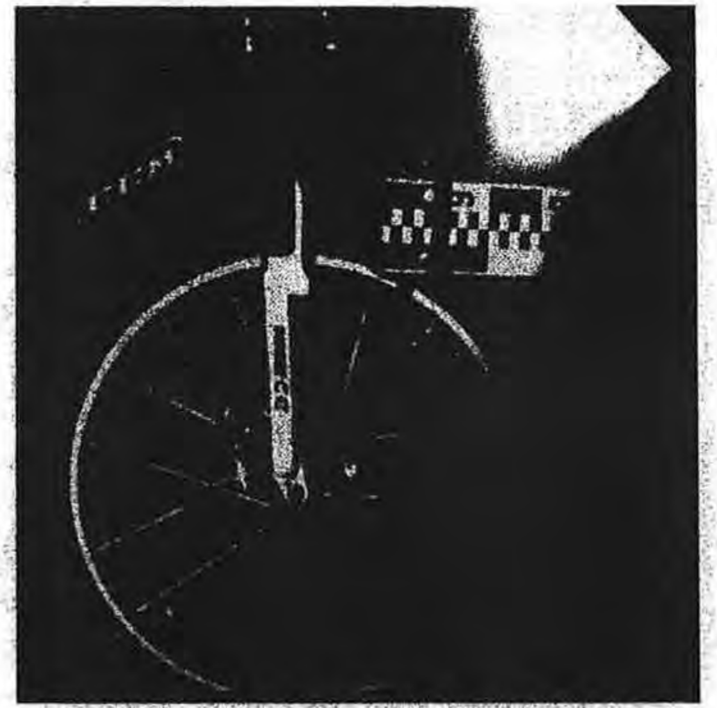

Figure 64 – T7 at maximum deflection

Figure 65 – Side skirt #3, post test showing no visible damage (impact zone arrowed)

Figure 66 – Backside of skirt #3 showing damaged support rod

5.3.8 *Test #8: Skirt #1, Rear Panel, Between Supports*

Test #8 was setup between the two rear-most supports on the aluminum side skirt, test article #1. Since most of the panels used for tests #1 and #2 were destroyed, new panels were installed for tests #8 and #9. The bicycle struck the side skirt (Figure 67) at the expected location directly between two supports; the ballast weight was ejected and the bicycle rebounded backwards (Figure 68) and became lodged into the test fixture. The two rear-most diagonal braces slid along the cross members until striking the bogie slider rail (Figure 72), preventing them from further motion. The aluminum panel was permanently bent inwards at the point of impact. The maximum displacement of the side skirt was 13 cm.

Figure 67 – T8 at initial point of impact

Figure 68 – T8 at maximum deflection

5.3.9 *Test #9: Skirt #1, Rear Panel, Between Supports*

Although not initially outlined in the test plan, time remained to attempt one more impact test therefore a repeat of test 8 was performed to confirm repeatability of the testing. A new rear section of side skirt was installed on the test trailer. Test #9 was setup between the two rear-most supports on the aluminum side skirt (as per test #8), test article #1. The bicycle struck the side skirt (Figure 69) at the expected location directly between two supports; the ballast weight was ejected and the bicycle rebounded backwards (Figure 70) and became lodged into the test fixture. The two rear-most diagonal braces slid along the cross members until striking the bogie slider rail (Figure 72), preventing them from further motion. The aluminum panel was permanently bent inwards at the point of impact. The maximum displacement of the side skirt was 13 cm.

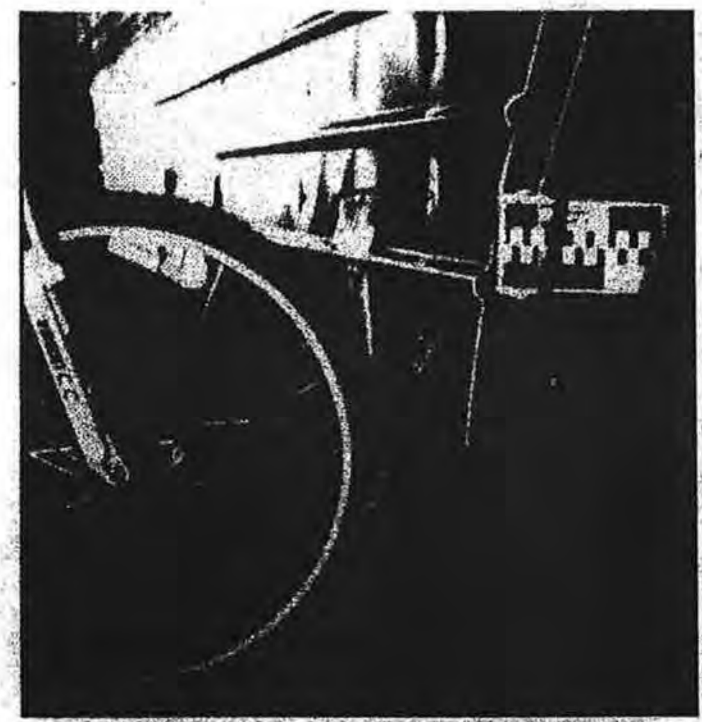

Figure 69 – T9 at initial point of impact

Figure 70 – Test T9 showing bending of front forks, skirt #1

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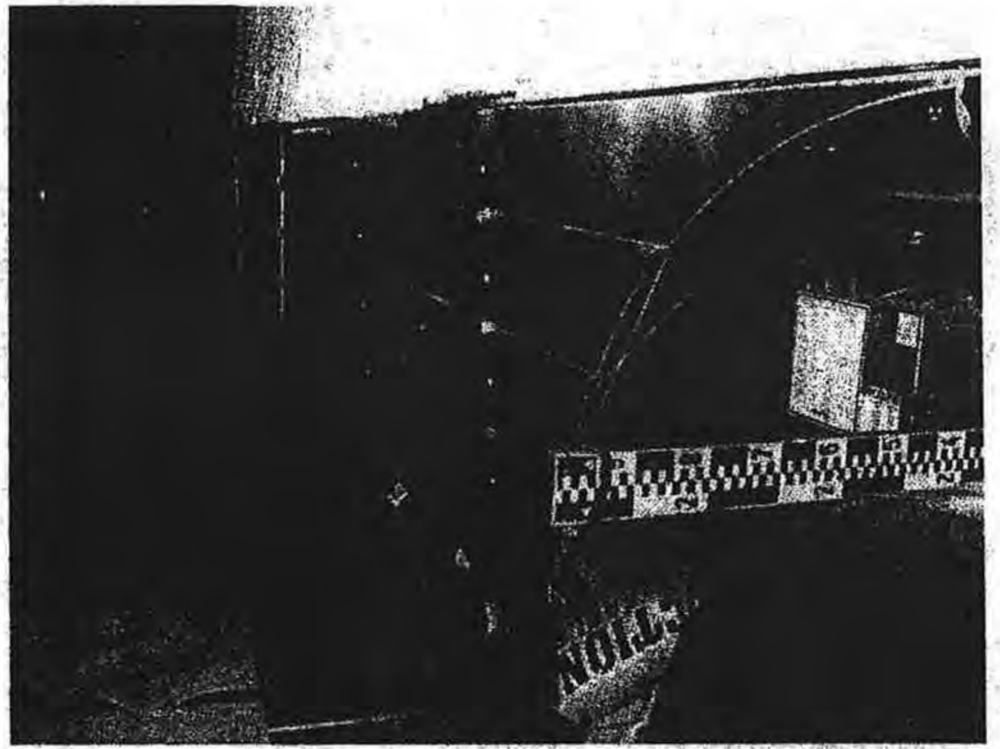

Figure 71 – Side skirt #1, showing permanent damage after impact between supports

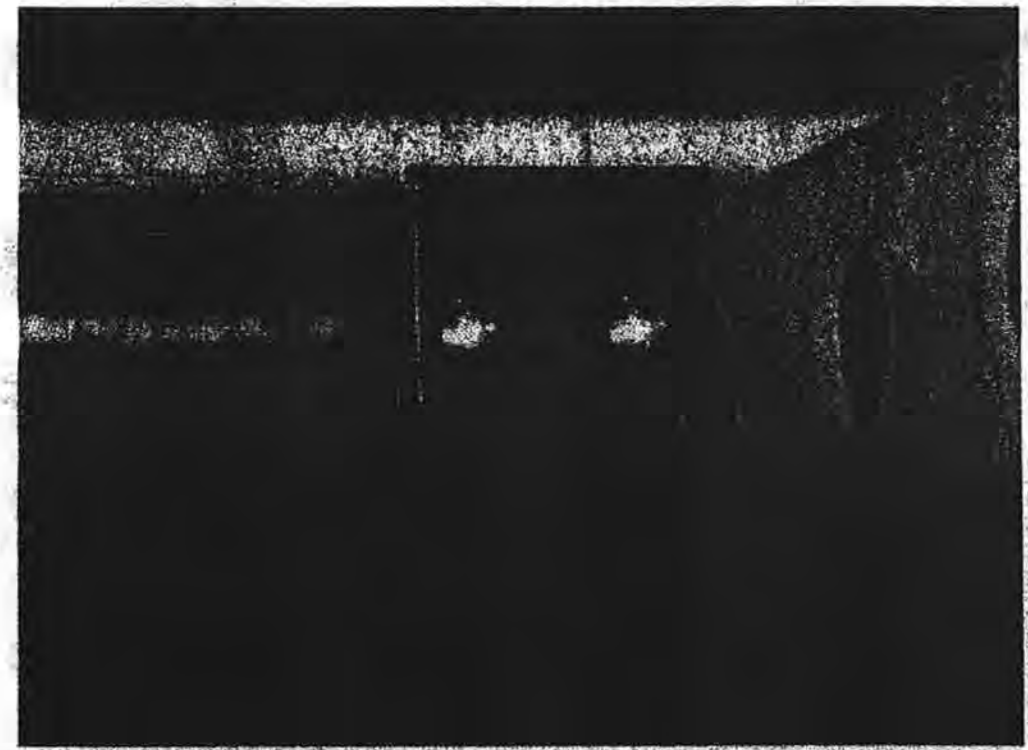

Figure 72 – Diagonal brace jammed against slider rail as a result of impacts #8 and #9, skirt #1

The results of impact tests #1 through #9 have been summarized in Table 16:

Table 16 – Impact Testing Results

[illegible]	[illegible]	[illegible]	[illegible] (km/h)	Location	At Support (Y/N)	Maximum Deflection (cm)	Maximum Permanent Displacement (cm)
1	Aluminum	1	23.43	Front panel	Yes	40	40
2	Aluminum	1	22.41	Mid panel	No	30	30
3	Plastic	2	21.59	Halfway	Yes	17	0
4	Plastic	2	22.58	Halfway	No	26	0
5	Plastic	3	23.78	Mid panel	Yes	33	< 5
6	Plastic	3	19.36	Rear panel	No	23	< 5
7	Plastic	3	20.42	Rear panel	No	37	< 5
8	Aluminum	1	21.26	Rear panel	No	13	13
9	Aluminum	1	22.20	Rear panel	No	13	13

5.4 Effect of Side Skirts and Wheel Covers on Brake Cooling

Drum Brakes

The total heat transfer from the brake drums to the surrounding air was calculated for Cases 1 through 3 and is shown in Table 17. The values have been normalized against the heat transfer from the forward drum of the baseline trailer case, Case 1, to demonstrate the relative impact of the side skirts and wheel covers. As previously discussed, the absolute value of the heat transfer is not reported for the purpose of this comparative study. In this table, larger negative numbers represent lower levels of heat transfer (or decreased cooling) from the drum surfaces relative to the heat transferred from the forward drum. The last column in this table presents the percent change in heat transfer at the rearward drum, relative to the rearward drum heat transfer from the baseline trailer case, Case 1.

Table 17 – Relative effects on drum brake cooling (zero yaw)

		Heat Transfer delta from Baseline (%)		
Case	Description	Forward	Rearward	Rearward % Change
1	Drum brakes on baseline trailer	Baseline	-7	-
2	Drum brakes on trailer with side skirts and wheel covers	-20	-31	-25
3	Drum brakes on trailer with wheel covers only (no side skirts)	-8	-25	-20

As seen in the table, the level of cooling is reduced by 20% and 25% at the front and rear drums, respectively, with the addition of both side skirts and wheel covers. Wheel covers alone (without side skirts) result in 8% and 20% reduced cooling at the front and rear drums, respectively. The results indicate that, for this vehicle system, cooling of the forward and rearward brake drums is affected by both the side skirts and wheel covers, with the wheel covers having a greater impact on cooling of the rearward drums compared to the forward drums.

The cooling effects can be visualized through examination of the flow field. It is clear from Figure 73, which shows contours of speed[1] on a horizontal plane through center of the trailer wheels, that there is less airflow carried to the trailer wheel stations (indicated by an arrow in the figure) due to the presence of the side skirts, which serve to redirect and streamline the undercarriage flow in order to reduce aerodynamic drag.

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[1] In this figure, the colour scale indicates the magnitude of the velocity (speed). Blue zones represent lower speeds while red zones represent higher speeds.

Figure 73 – Velocity contours on horizontal plane through center of trailer wheels, Case 1 (top) and Case 2 (bottom)

The addition of the wheel covers also reduces the airflow to the drum surfaces, as evidenced by Figure 74, which shows velocity vectors on a horizontal plane through the centerline of the passenger side trailer wheels for Cases 1 and 3. In the baseline configuration, there is significantly more airflow pulled through the openings in the wheel hubs and around the drum surfaces compared to the wheel with covers. The brake drums in this figure are coloured by contours of the heat flux from the drum surfaces to the surrounding air. Red zones indicate higher cooling and blue zones represent lower cooling. In this image, the differences in heat transfer between the baseline and wheel cover configurations are visualized by comparing the relative sizes of the non-blue zones on the drum surfaces.

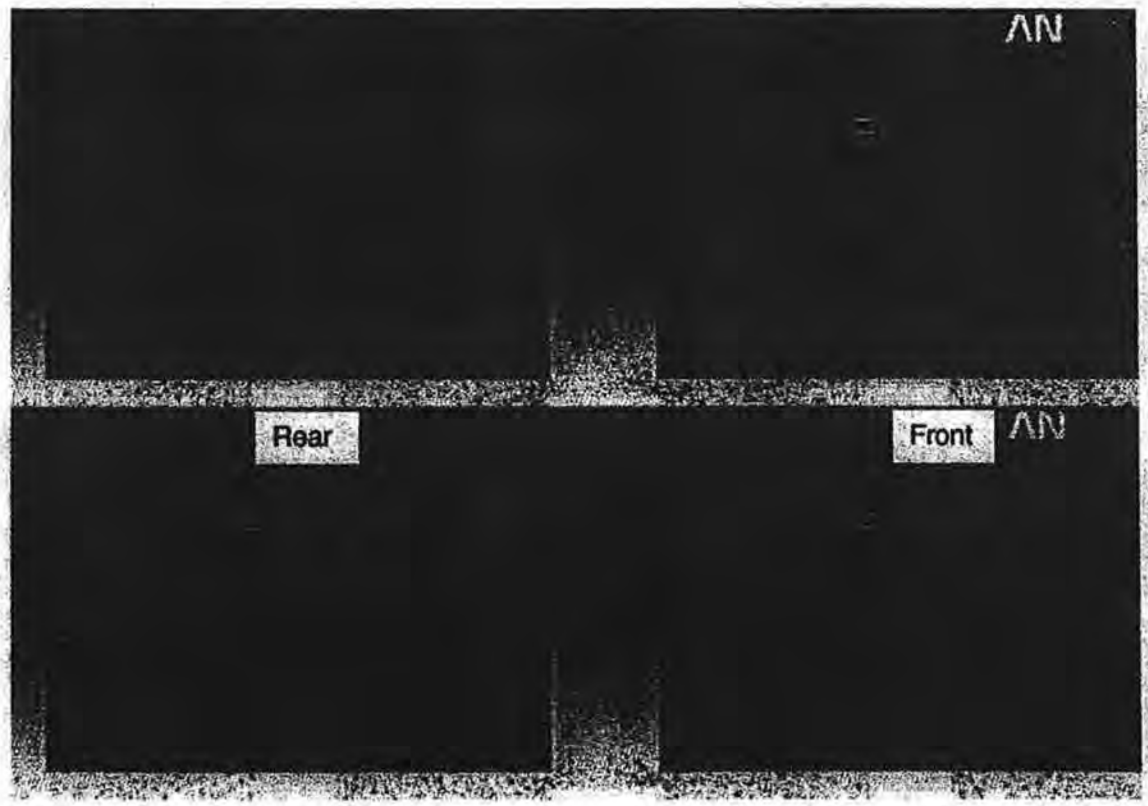

Figure 74 – Air flow on horizontal plane through center of trailer wheels, Case 1 (top) and Case 3 (bottom). Brake drums coloured by wall heat flux.

Disc Brakes

The flow field in and around the disc brake system is highly complex and three-dimensional, as shown in Figure 75 and Figure 76. The convective cooling effectiveness of ventilated brake discs is based largely on their ability to pump high volumes of air from the inner radius, through the vaned passages (where there is a significant surface area for heat transfer) to the outer radius of the disc.

Figure 75 – Velocity vectors on horizontal plane through front trailer wheel station. Disc brake vane surfaces coloured by heat flux.

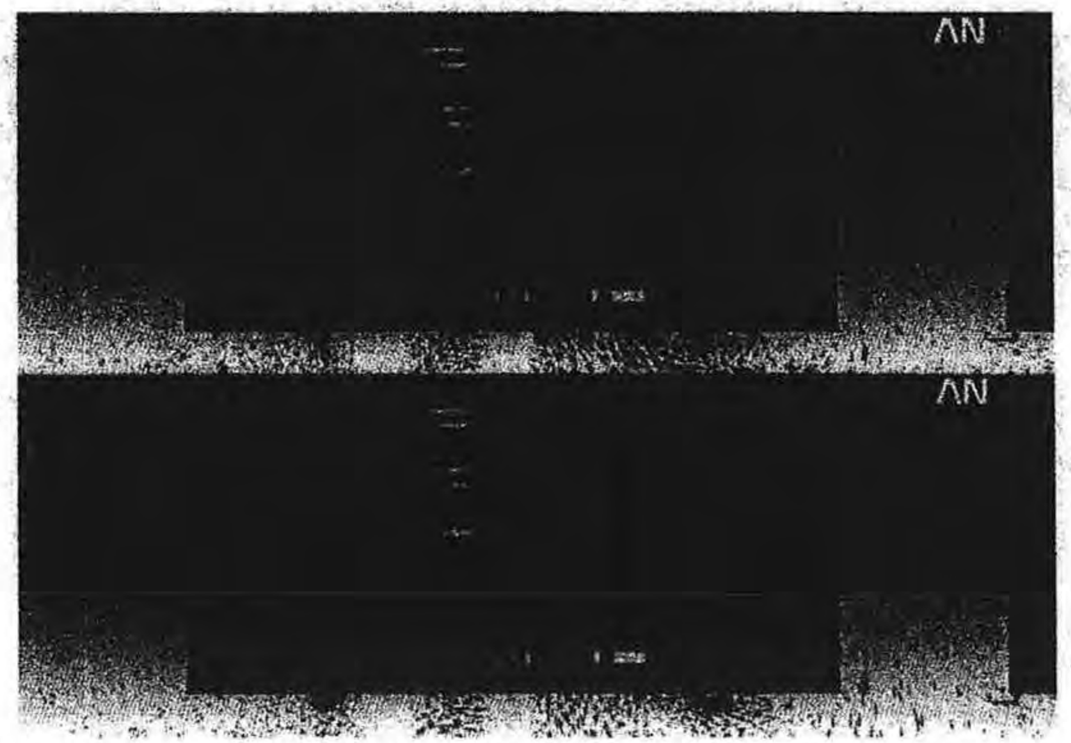

Figure 76 – Velocity vectors on horizontal plane through rear trailer wheel station, Case 4 (top) and Case 5 (bottom).

The total heat transfer from the brake discs to the surrounding air was calculated for Cases 4 through 7 and is shown in Table 18. The values have been normalized against the heat transfer from the forward disc of the baseline trailer case, Case 4, to demonstrate the relative impact of the side skirts and wheel covers. The last column in this table presents the percent change in heat transfer at the rearward disc, relative to the rearward disc heat transfer from the baseline trailer case, Case 4.

Table 18 – Relative effects on disc brake cooling (zero yaw)

		Heat Transfer delta from Baseline [%]		
Case	Description	Forward	Rearward	Rearward % Change
4	**Disk brakes on baseline trailer**	Baseline	-17	-
5	Disk brakes on trailer with side skirts and wheel covers	-12	-27	-12
6	Disk brakes on trailer with wheel covers only (no side skirts)	-2	-18	-1
7	Disk brakes on trailer with side skirts only (no wheel covers)	-12	-24	-8

As shown in the table, the level of cooling is reduced by 12% on both the forward and rearward discs through the addition of both side skirts and wheel covers. Unlike the drum brake configuration, the presence of the wheel covers has much less effect on the cooling of the discs (1-2% reduced cooling with wheel covers only – Case 6) compared to the presence of the side skirts. This is observed because the openings in the wheel rims are relatively small compared to the large mass of air that is pumped through the vaned passages of the ventilated discs. In other words, the openings in the wheel hubs do not provide significant amounts of cooling air, so the presence of wheel covers has little effect on the overall cooling of the discs. It is also of note that the presence of the aerodynamic drag reducing devices impacts the cooling of the disc brakes nearly equally at the forward and rearward wheel stations. The results of the computer simulations show trends that indicate that brake cooling could be reduced at highway speeds, however, on-road testing using vehicles with instrumented brakes would be required to quantify brake temperatures with, and without, the aerodynamic devices.

The effect of cross winds (yaw) on disc brake cooling was also considered. Figure 77 shows the definitions of positive and negative yaw used in this report. Simulations were first conducted on the baseline trailer configuration (without side skirts or wheel covers), the results of which are shown in Table 19. Note that all reported values in this table are of the convective heat transfer from the discs at the passenger side wheel stations. Further, the values have been normalized relative to the heat transfer from the forward discs from the baseline, non-yaw condition, Case 4. Finally, the last column in this table presents the percent change in heat transfer at the rearward disc, relative to the rearward disc heat transfer from the baseline, non-yaw condition, Case 4.

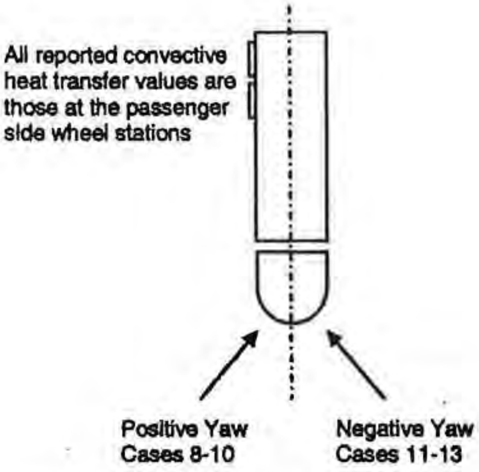

Figure 77 – Definitions of positive and negative yaw (cross wind)

Table 19 – Effect of 10-degree yaw (cross wind) on baseline configuration

		Heat Transfer delta from Baseline [%]		
Case	Description	Forward	Rearward	Rearward % Change
4	Disk brakes on baseline trailer	Baseline	-17	-
8	Disk brakes on baseline trailer, with positive yaw side wind	58	17	41
11	Disk brakes on baseline trailer, with negative yaw side wind	24	31	58

As seen in the table, a 10-degree cross wind significantly increases the convective heat transfer (i.e., improves cooling) from the forward and rearward passenger side brakes. A positive yaw side wind (Case 8) corresponds to a larger relative increase in heat transfer from the forward disc brakes compared to the rearward disc brakes, and the opposite trend is seen in the case of a negative yaw side wind.

Also of note is that the level of cooling provided by the forward disc is significantly greater than that of the rearward disc for the positive yaw wind case. The reason for this difference can be seen by examining the mechanism through which heat is transferred from the various regions of the brake disc. Convective cooling from ventilated brake discs occurs primarily through heat transfer between the inner and outer friction surfaces and the interior vaned passages. As shown in Table 20, there is a significantly larger portion of cooling provided by the vaned passages (i.e., by a large mass flow of air pumped through the interior of the disc) for Case 8[2]. Figure 78 shows velocity vectors through a plane cutting through the center of the forward and rearward discs for Case 8. As can be seen by the low angle of attack on the leading edge of the disc vanes, the disc is operating at a very high efficiency point, resulting in very good heat transfer compared to the rear disc, where a significant angle of incidence can be seen at the leading edges of the vanes, resulting in a separated flow that creates low velocity recirculation

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[2] The relative contributions to convective cooling for the disc brakes examined in this study is also consistent with the findings of [21] for automotive disc brakes.

zones and therefore poorer heat transfer. Figure 79 shows the higher heat flux at the surfaces of the vaned passages in the forward versus rearward discs.

Table 20 – Cooling mechanism from front and rear brake discs, Cases 8 and 11 (10 degree yaw)

		HT from front disk [% of total]			HT from rear disk [% of total]		
Case	Description	Outer friction surface	Inner friction surface	Vaned passages	Outer friction surface	Inner friction surface	Vaned passages
8	Disk brakes on baseline trailer, with positive yaw side wind	8%	26%	66%	13%	28%	59%
11	Disk brakes on baseline trailer, with negative yaw side wind	14%	26%	59%	13%	27%	59%

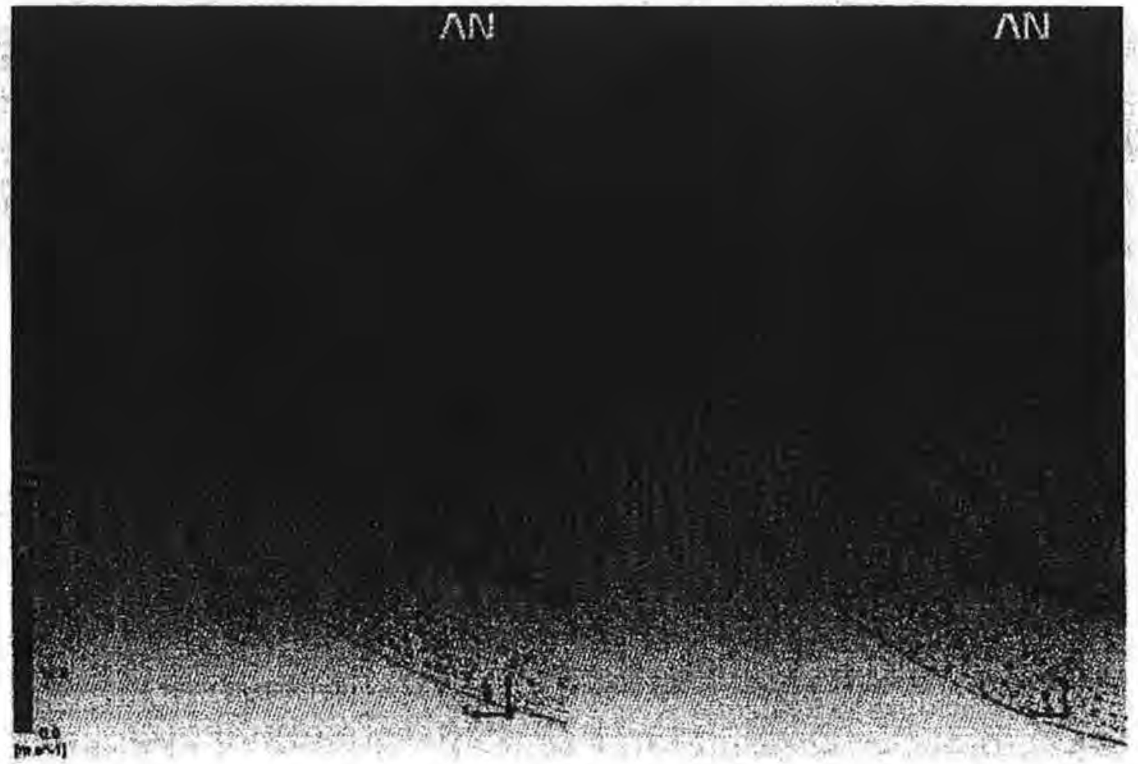

Figure 78 – Velocity vectors in vaned passages of forward (left) and rearward (right) disc brake, Case 8

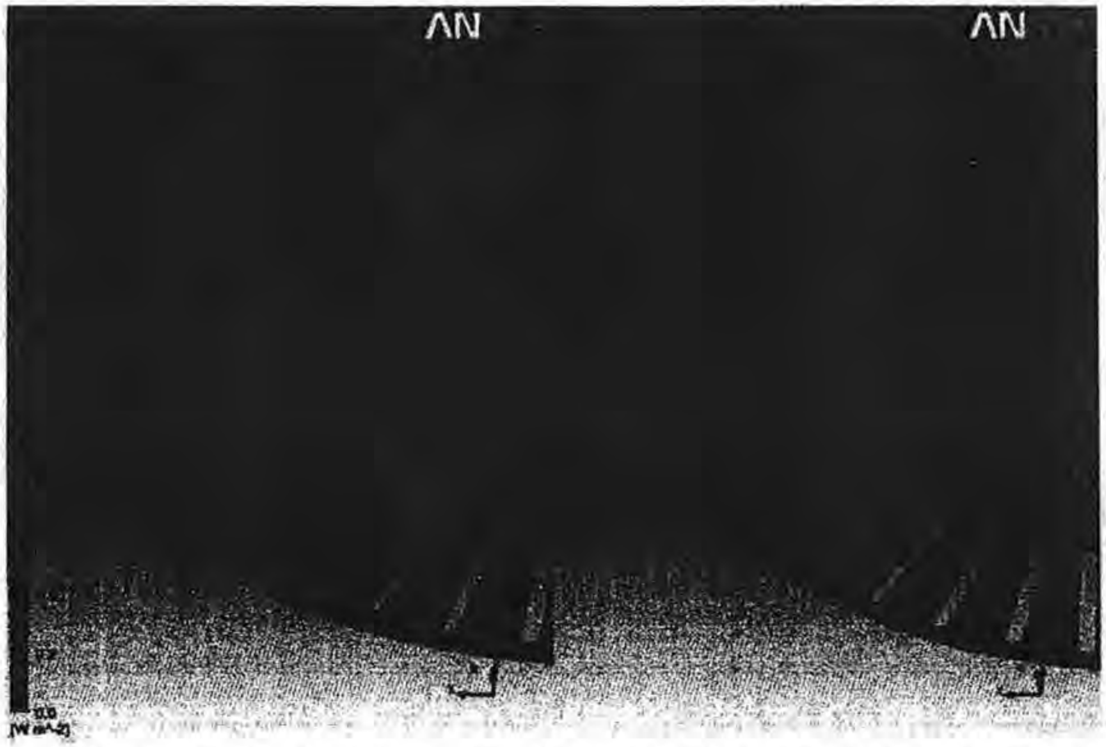

Figure 79 – Wall heat flux (normalized) in vaned passages of forward (left) and rearward (right) disc brake, Case 8

The effect of wind yaw on the cooling of disc brakes on trailers equipped with wheel covers, and with both wheel covers and side skirts, was also examined. The results are presented in Table 21. The values in this table have been normalized relative to the heat transfer from the forward discs from the baseline non-yaw condition, Case 4. The last column in this table presents the heat transfer at the rearward disc for the various cases, relative to the rearward disc heat transfer from the baseline, non-yaw condition, Case 4.

Table 21 – Effect of 10-degree yaw (cross wind) on brake cooling

		Heat Transfer delta from Baseline (%)		
Case	Description	Forward	Rearward	Rearward % Change
4	Disk brakes on baseline trailer, no yaw	Baseline	-17	-
8	Disk brakes on baseline trailer, with positive yaw side wind	58	17	41
11	Disk brakes on baseline trailer, with negative yaw side wind	24	31	58
6	Disk brakes on trailer with wheel covers only (no side skirts), no yaw	-2	-18	-1
10	Disk brakes on trailer with wheel covers only (no side skirts), with positive yaw side wind	57	8	30
13	Disk brakes on trailer with wheel covers only (no side skirts), with negative yaw side wind	21	27	53
5	Disk brakes on trailer with side skirts and wheel covers, no yaw	-12	-27	-12
9	Disk brakes on trailer with side skirt and wheel covers, with positive yaw side wind	39	-4	16
12	Disk brakes on trailer with side skirt and wheel covers, with negative yaw side wind	0	6	27

As with the non-yaw (no cross wind) cases, wheel covers have less impact on disc brake cooling compared to side skirts. A comparison of Cases 8 and 10, for positive yaw side wind, shows that the improvement in brake cooling compared to the non-yaw case is nearly the same at the forward wheel station, 58% for the baseline, positive yaw case versus 57% for the wheel covers only, positive yaw case. The trend is continued at the rear wheel station, however, due to the complex nature of the positive yaw airflow around the vehicle, there is a larger effect on cooling (41% improvement in cooling for the baseline, positive yaw case versus 30% for the wheel covers only, positive yaw case).

When the yaw wind direction is negative (refer to Figure 77), the effect of the wheel covers is again small compared to the effect of side skirts. At the forward wheel station, the presence of wheel covers reduces the total increase in cooling effectiveness to 21% from 24% at the baseline condition (Cases 13 and 11, as measured against the normalized zero yaw case, Case 4). At the rear wheel station, wheel covers reduce the total increase in cooling effectiveness from 58% to 53%, at the baseline condition.

The addition of side skirts has the effect of reducing brake cooling efficiency by approx 10%-11% over the non yaw baseline configuration (Case 5 versus Case 4). It is important however to remember that it is rare for a highway tractor-trailer to continuously operate in a condition of zero yaw (i.e.: no crosswind). By comparing Cases 9 and 12 to Case 4, it is observed that when the presence of a 10 degree yaw component is added, there is no net negative effect of side skirts and wheel covers on brake cooling, with improvements over the baseline cooling at zero yaw ranging between 0% and 39%. Figure 80 and Figure 81 show comparisons of the flow field for Cases 4, 9, and 12.

Figure 80 – Velocity contours on horizontal plane through center of trailer wheels, Case 12 (top) and Case 9 (bottom)

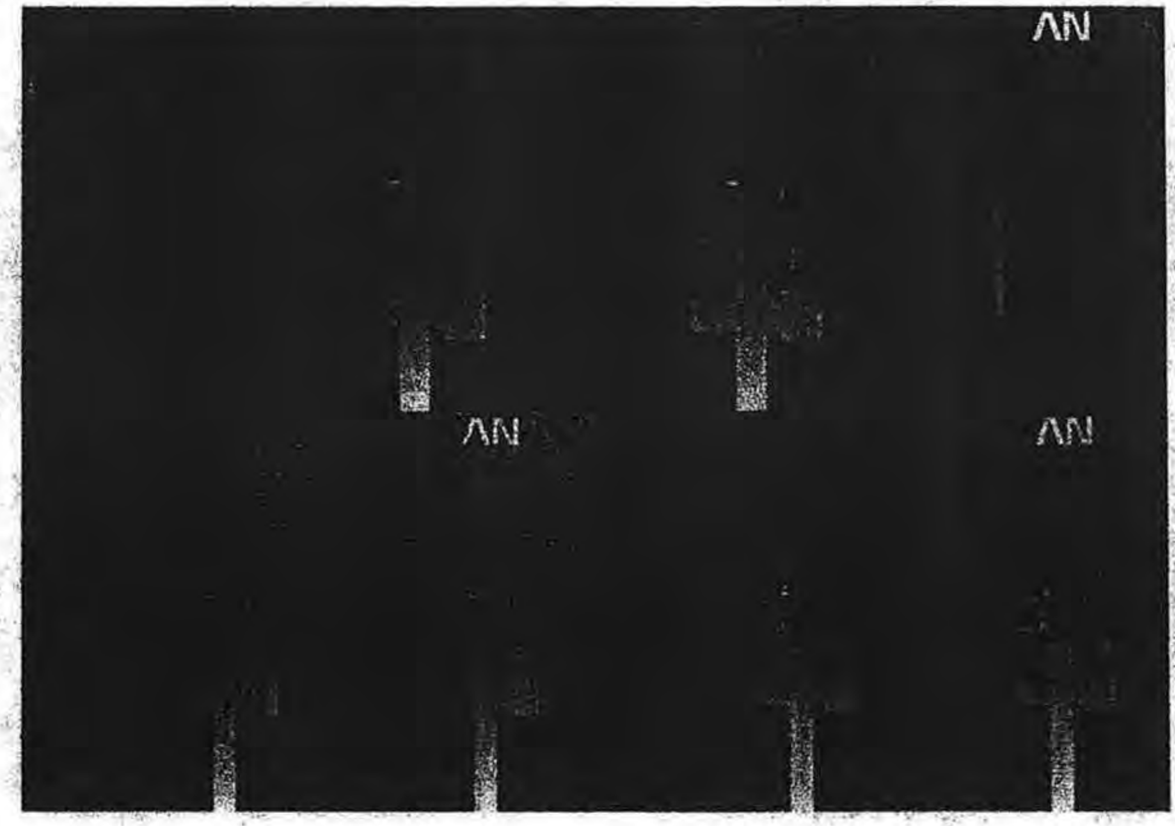

Figure 81 – Velocity contours and vectors on horizontal plane through center of trailer wheels, Case 4 (top), Case 9 (bottom left) and Case 12 (bottom right)

It is important to note that the observations from this analysis are applicable only to the vehicle configuration considered here, and that variations in side skirt, wheel cover and brake system geometry could produce a range of performance results. The convective cooling of the brake systems will also vary as a function of vehicle speed, and this effect has not been considered here.

6 ANALYSIS/INTERPRETATION OF RESULTS

6.1 Survey

From the survey results, it was clear that many customers are now demanding disc brakes on their trailers. The rationale behind this new trend was primarily based the customers' feelings that disc brakes provide ease of maintenance and improved braking performance when compared to drum brakes.

With respect to aerodynamic devices, the results of the survey may have been skewed towards smaller and purpose built trailer manufacturers that do not tend to produce van semi trailers as their main product. Van semi-trailers are by far the most suitable candidate for aerodynamic devices therefore the manufacturers who replied to this survey may be producing trailers that are, by design, difficult to fit with aerodynamic devices. However, a culture appears to exist in the industry that manufacturers produce trailers based on demand by the customer, rather than providing the latest aerodynamic features on the trailer and educating the customers about the benefits and returns on investment of the devices. Question 19 provided some curious information: many respondents indicated there was a lack of product offering, yet the literature review conducted as part of this project provided great insight into the myriad of devices that are now available in the industry in Canada and the USA.

In order to truly understand the use, or non-use, of side skirts, it would be necessary to contact manufacturers whose principal product is van semi-trailers and to understand if they educate their customers or simply follow requests from customers who do their own research.

6.2 Force and Pressure Measurement

It was of interest to determine the strike force of the bicycle against the skirt and the pressure applied to the skirt. The nature of the impacts and the elasticity of the skirts precluded the use of conventional force load cells therefore NRC-CSTT elected to use pressure paper (Figure 82) which not only served as a witness plate for the exact point of impact but also allowed for a rough estimate of the pressure that was applied between the skirt and the bicycle front tire upon impact.

Additionally, the high speed camera was used to determine the deceleration of the loaded bicycle. Since the mass of the bicycle and simulated rider was known, it is possible to calculate the approximate force of impact using $F = m * a$.

Although both methods have error, together they form a good estimate of the force of impact and can be used to compare against the European test method.

Figure 82 – Pressure paper on skirt #1, post test, T1

6.2.1 *Force via Pressure Paper*

Although originally intended to be part of the data collection exercise for the purposes of calculating tire contact pressure, the pressure paper proved to be difficult to read and often showed long skid marks as a result of the tire aggressively rolling against it, rather than impacting it. However, the paper did prove useful as a witness plate to determine the exact location and angle of impact and confirm that an impact was at, or between, a main support beam (See Figure 82).

6.2.2 *Force via Deceleration Time*

The high speed camera proved invaluable for post test evaluation and calculations. Although it is not possible to derive exact values of deceleration from a high speed movie, a range of deceleration times may be produced, which can then be used to calculate the approximate force of impact based on the weight of the impact. Presenting an estimate of force also allows for the uncertainty of the exact timing of the block departure from the bicycle, which made the bicycle much lighter. The average values of time, deceleration, maximum skirt deflection and impact force have been presented in Table 22. As expected, the last two tests resulted in the greatest estimate of force due to the rigid support beams being driven into the solid steel bogie slider rail, effectively cutting that skirt's ability to absorb energy in half (results from tests 1 and 2). Additionally, the results show that skirt #2 can absorb significantly more energy when struck between two supports when compared to directly on the support.

Table 22 – Force and Deceleration Time

Test #	Time from V_i to 0 (sec)	Deceleration (m/s^2)	Maximum Transient Displacement (m)	Mass of bike (kg)	Force of Impact (N)
1	0.144 sec	-49.32	0.40	93.6	4 617
2	0.120 sec	-58.54	0.30	93.6	5 479
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
5	0.168 sec	-52.69	0.33	93.6	4 932
6	0.120 sec	-54.41	0.23	93.6	5 093
7	0.162 sec	-39.54	0.37	93.6	3 701
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

6.2.3 *Momentum*

The total mass of the bicycle just before impact was 93.6 kg. With an average impact speed of 21.9 km/h, the average momentum of the bicycle just before impact was calculated to be:

= 6.08 m/s * 93.6 kg
= 569.20 kg m/s

6.2.4 *Comparison to European Test Method*

Although the devices tested in this phase are not intended to be used as side guards, it is of interest to determine if the tested side skirts could pass the European test for side guards. The background information behind the European method may be found in the NRC-CSTT side guard document [1], however, the basic requirements from Aprosys have been re-iterated here, in italics:

......Section 7.8 Sideguards shall be essentially rigid, securely mounted (they shall not be liable to loosening due to vibration in normal use of the vehicle) and, except as regards the parts listed in paragraph 7.9, made of metal or any other suitable material. The side guard shall be considered suitable if it is capable of withstanding a horizontal static force of 1 kN (224 lbf) applied perpendicularly to any part of its external surface by the centre of a ram the face of which is circular and flat, with a diameter of 220 mm + 10 mm, and if the deflection of the guard under load is then not more than:

- *30 mm over the rearmost 250 mm of the guard, and*
- *150 mm over the remainder of the guard.*

Compliance with this requirement can be verified by calculation.

The European test method is specific regarding force and deflection, however, uses vague terms such as 'essentially rigid'. It is not known if the side skirts tested in this program would pass the European test method as none of them, particularly skirts #2 and #3, can be classified as rigid. All of the skirts deflected significantly more than allowed by the European test method, however, the applied force was significantly higher than those used in the European test method. None of the manufacturer's analysed or contacted during this project claimed to have side skirts that currently pass the European strength test.

7 CONCLUSIONS

Side Skirts

A thorough review of commercially available trailer side skirts was conducted using the EPA SmartWay list of verified technologies as a primary source, along with a combination of telephone interviews and web-based searches. In total, 19 skirt models were reviewed, including six offered by Canadian OEMs.

The main side skirt panel is commonly constructed of aluminum, TPO, or FRP, and the average total increase in tare weight is approximately 270 pounds. Single and multi-panel models are available, with numerous design options, including rigid and flexible systems. The flexible systems bend inward and outward, allowing the trailer to easily pass over obstacles, such as railroad crossings and snow banks, with minimal damage to the skirt. Side skirt installation, which takes about 3.5 person-hours to complete, often involves a no-drill clamping method; however, some designs do require permanent alteration to the trailer. Custom side skirt designs are available for tanker and flatbed trucks, however, most are not SmartWay verified.

The average cost of aerodynamic side skirts is $1 675, with claimed ROIs between four and 24 months, and warranties between one and ten years. Side skirt OEMs estimate fuel savings of between 4.0% and 7.5% per tractor, based on SmartWay-mandated track testing; in a Canadian context, this fuel savings could result in an approximate greenhouse gas emissions reduction between 670 kt and 2 000 kt. In addition to fuel savings, OEMs often offer claims regarding the use of side skirts, including reduced road spray, increased driving stability, and resistance to winter weather conditions. Through the NRCan SmartWay Technology funding program, these side skirt claims (among other fuel savings technology claims) will be evaluated in a Canadian context in order to inform industry professionals of the potential for side skirt use in their operations.

Wheel Covers

A review of commercially available aerodynamic wheel covers was performed by means of web-based searches and telephone interviews with OEMs. Very few fleets in North America appear to be using this technology, and product availability was found to be quite limited; only five wheel cover models were identified, available through three OEMs.

Wheel covers are constructed of steel, aluminum, polycarbonate/aluminum and truck tarp, with an average weight of two to six pounds per cover. The more common design is the bracket and bolt system; however a zipper-tarp tab model is also offered. All models are easy to install and the majority are compatible with standard wheel sizes, and some with wide-based tires. Most covers limit access to wheel hub components, however, some models are available with clear windows for easy visual inspection, quick-release covers, and air valve extensions for easy air pressure checks and re-fills. In addition, OEMs offer customizable covers with company branding for aesthetic appeal.

The average cost of aerodynamic wheels covers is $100 per cover, with claimed ROIs between four and six months. Wheel cover OEMs estimate a fuel savings of 0.25% per wheel. However, this estimate is based on standard fuel consumption track testing (also used for side skirts) for which the margin of error is approximately equal to the potential savings; as a result, in-service test are currently being carried out by test fleets to further evaluate the potential aerodynamic benefits of wheel covers.

Survey

All of the manufacturers who responded to the survey are currently offering disc brakes on their trailers and each manufacturer delivered at least one trailer in 2010 equipped with disc brakes. Disc brakes are a desirable option for many operators and therefore the operators request them on their trailers.

The majority of trailer manufacturers who responded to the survey are not currently offering aerodynamic packages on their trailers, nor are they educating their customers on the benefits of using the devices.

A culture may exist in the trailer industry that manufacturers are reluctant to provide aerodynamic devices on a trailer until a customer specifically asks for them.

Many of the respondents produce purpose-built speciality and tanker trailers that may not lend themselves well to aerodynamic devices compared to van trailers.

Impact testing

A repeatable and realistic test environment was created after many experimental test runs. The behaviour of the skirts during an impact is more clearly understood, and future tests may be fully instrumented to gain more accurate estimates of deceleration and deflection.

The tests produced estimated impact forces between 3 701 N and 9 142 N and decelerations of between 39.5 m/s^2 (~4g) and 97.67 m/s^2 (~10 g).

The test method was developed to demonstrate the strength of the side skirts under one specific type of collision, which may or may not be representative of how bicycles typically collide with heavy vehicles. For instance, under typical conditions, the bicycle and the trailer would each be moving, however, in order to facilitate testing, the trailer remained stationary while the bicycle was impacted into the trailer. Under these conditions, the testing demonstrated that all three side skirts prevented the loaded bicycles from entering under the trailer. Furthermore, the bicycles did not become wedged underneath the skirts. In all tests, the bicycles were ejected rearward along their original path and away from the trailer and became tangled in the test fixture, which would represent an adjacent lane, be it oncoming traffic or a lane travelling in the same direction.

The three side skirts behaved somewhat differently from each other with respect to the amount of deformation, rebound, energy absorption and the amount of permanent skirt damage after the test. The aluminum panel design (#1) sustained the highest amount of permanent damage and deformation as a result of testing and clearly appeared damaged after each of the impact tests. The aluminum design's rigid diagonal tubular steel braces did not, themselves, absorb energy and simply transferred the energy and slid along the rails where permitted. The lack of elasticity in the system caused skirt #1 to remain in its final resting position once the impact was over. As a result of this motion, the distance between the ground and the bottom of the side skirt increased by approximately 7 cm to 10 cm as a result of the impact.

Conversely, the skirt that used individual plastic panels (#2) did not have diagonal members at all, and was able to absorb the energy of the impact elastically, and rebound back to its original location and condition with only minor tell-tale signs of impact. The continuous panel plastic side skirt (#3) did have diagonal braces, however, they were made of flexible fibreglass and were able to bend radically upon impact and absorb the energy, and then rebound to their original position, albeit requiring replacement due to bifurcation. With the exception of tire skid marks, the exteriors of both plastic designs did not show obvious signs of damage once the impacts were concluded. The vertical distance between the two plastic side skirts and the ground did not change as a result of the impact testing.

The point of impact on a side skirt, relative to the longitudinal position of the trailer, results in different effects depending on the type of skirt. Side skirts that use rigid diagonal bracing for support (e.g. tested skirt #1) behave differently if they are struck ahead of the trailer bogie slider rails when compared to impacts adjacent to the slider rails. When impacted near the bogie slider rail, the diagonal braces can only slide a few inches and are then driven into the outside edge of the slider rail. This prevents the side skirt from further movement and the bicycle is ejected rearward and the skirt absorbs less energy. Alternatively, when the bicycle impacts the side skirt ahead of the slider rail, the diagonal braces are free to slide along the cross members for as long as the impact force exceeds the clamping force between the side skirt clamps and the trailer's cross members. The testing revealed that some diagonal braces, torqued to 38 ft lb, can slide as much as 28 cm when struck by a loaded bicycle at approximately 21 km/h. The actual amount of sliding is highly dependent on the torque applied to the clamp bolts and the coefficient of friction between the clamps and the cross members.

Some side skirts do not exhibit external signs of damage after an impact. Therefore, it may be necessary to inspect the backside and securing hardware of side skirts on a yearly basis in order to determine if they have been impacted.

None of the side skirts were damaged to the point where they could become hazardous to other motorists should the trailer continue to be driven on the road after an impact with a bicycle. Side skirts #2 and #3 would only require minimal repairs in order to be returned to service after an impact. However, side skirt #1 would like require partial, or complete, replacement after an impact in order to be returned to service.

None of the side skirt manufacturers make claims regarding passing the European side guard test protocol.

Brake Cooling

The results of this comparative study indicate that heavy vehicle trailer brake convective cooling can be negatively affected by the addition of side skirts and wheel covers under certain operational conditions. It is also apparent that the effect of side skirts on brake cooling is relatively similar for trailers equipped with drum brakes or disc brakes. However, the effect of wheel covers on brake cooling is more pronounced with drum brakes on the dual tire configurations than with disc brakes on the single wide tire configurations examined in this study. With non yaw wind conditions, wheel covers have very little impact on disc brake cooling, for the geometries examined in this study.

The results also indicate that while the presence of side skirts decreases the relative effectiveness of disc brake cooling under 10 degree yaw side wind conditions, the net level of cooling is still equal to, or greater than, the levels achieved without the devices, and in the absence of a side wind. In other words, there was no net negative effect on convective cooling of the front or rear disc brakes due to side skirts when a 10 degree yaw side wind was present, compared to a non-yaw condition. This is a significant observation since there is almost always a yaw wind component during normal trucking operations, and that side skirts are particularly beneficial from an aerodynamic perspective under these conditions. It should be pointed out that this conclusion applies to a yaw configuration of 10 degrees only, which represents a realistic upper bound on wind yaw experienced at normal highway cruising speeds, based on hourly-mean wind statistics for North America [23].

The benefit that side skirts and wheel covers offer in reducing fuel consumption, and in turn GHG and other emissions, for long-haul trailers is well understood. The current study has demonstrated that there can also be a negative effect on brake cooling under certain operational conditions, and this should be taken into consideration through the careful design and implementation of these devices.

The results of the computer simulations show trends that indicate that brake cooling could be reduced at highway speeds, however, on-road testing using vehicles with instrumented brakes would be required to quantify brake temperatures with, and without, the aerodynamic devices.

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8 PROJECT TEAM

The project could not have succeeded without the hard work of the following individuals:

- Stephan D'Aoust (NRC-CSTT) designed the impact ramp and trolley system as well as the simulated load;
- Elton Toma, PhD, (NRC-CSTT) assisted with the design of the simulated load and the dynamics of the impact;
- Jon Preston-Thomas (NRC-CSTT) assisted with the experimental tests and the optimization of the final test procedure;
- Jonathan Martin managed the project for NRC-CSTT
- Yves Macra assisted with the construction of the test rig and the testing;
- Bertram McInnis installed the side skirts and assisted with the physical testing; and
- Tim Breithaupt of NRC-IAR operated the high speed camera and assisted with the testing.

The efforts of these people, and those not mentioned here, are appreciated by the authors.

LIST OF ACRONYMS/ABBREVIATIONS

CAD	Canadian Dollars
CG	Center of Gravity
CO_2^e	Carbon Dioxide Equivalent
CSA	Canadian Standards Association
CSTT	Centre for Surface Transportation Technology
CTEA	Canadian Transportation Equipment Association
Deg	Degree
DOT	Department of Transportation (USA)
EPA	Environmental Protection Agency
Fps	Frames per second
FRP	Fiberglass Reinforced Plastic
kt	Kilo tonne
HC	Hydrocarbons
Kg	Kilogram
Km	Kilometers
L	Litres
lb	Pound
MPa	Mega Pascal
MPG	Miles per Gallon
MPH	Miles per Hour
MTO	Ministry of Transportation of Ontario
NHTSA	National Highway Traffic Safety Administration (USA)
NRC	National Research Council
NRCan	Natural Resources Canada
NREL	National Renewable Energy Lab (USA)
OEM	Original Equipment Manufacturer
ROI	Return on Investment
SAE	Society of Automotive Engineers
TMC	Truck Maintenance Council
TPO	Thermoplastic Olefin
US	United States
USD	United States Dollars
USG	United States Gallons
UV	Ultraviolet
V	Volts
W	Watts

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