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AERODYNAMICS LABORATORY

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Abstract

Through its ecoTECHNOLOGY for Vehicles II (eTV II) program, Transport Canada has commissioned a study to investigate the potential safety implications of using boat-tails to reduce fuel consumption and greenhouse-gas emissions from heavy-duty vehicles (HDVs) on Canadian roads. A concern has been raised regarding the possibility for ice and snow to accumulate and shed from the cavity of a boat-tail, posing a potential safety hazard for other road users. This report describes a search of relevant work to the topic of snow and ice accumulation and shedding, and identifies several approaches to evaluating this problem.

There has been no significant work previously done to investigate the potential for ice and snow accumulation and shedding from the cavity of a boat-tail. Several approaches, including on-road observations, conventional or climatic wind tunnels, and computational methods, are identified as ways to evaluate the potential problem for boat-tail-equipped HDVs. A proposed plan for the second and third years of the project is provided, which includes on-road observations to identify the severity of the problem, and greater-detailed investigations towards the experimental and computational approaches available for evaluating and mitigating the problem. If a potential problem is still perceived after year two, a decision on the most appropriate way forward will be made in year-three.

Table of Contents

List of Figures

Nomenclature

Acronyms:

CFD	computational fluid dynamics
eTV	ecoTECHNOLOGY for Vehicles
GHG	greenhouse gas
HDV	heavy duty vehicle
NRC	National Research Council
TC	Transport Canada
UOIT	University of Ontario Institute of Technology

1. Introduction

1.1 Background

Transport Canada, through its ecoTECHNOLOGY for Vehicles (eTV) program, undertakes testing and evaluation of current and emerging vehicle technologies. The program will help inform various stake-holders that are engaged in the development of regulations, codes, standards, and products for the next generation of advanced light and heavy-duty vehicles.

The addition of a boat-tail to the base of a heavy-duty vehicle (HDV) has been shown to generate a reduction in vehicle drag (5% improvement), resulting in a corresponding reduction in fuel consumption per vehicle (order of 3000 L/year). The term boat-tail refers to a kit of extension panels or fairings that are mounted to the rear of a trailer. The fuel savings is accomplished through streamlining of the rear of the vehicle, thus guiding the flow inwards towards the centre of the vehicle wake. This increases the average pressure on the aft end of the vehicle, providing a smaller pressure difference in the direction of motion, and hence a lower drag force.

Transport Canada, through its eTV II program, is interested in investigating safety implications of using boat-tail-equipped HDVs on Canadian roads. In a report prepared for Transport Canada in 2010 (Patten *et al.*, 2010), and further emphasized in a report for Transport Canada's eTV II program in 2012 (Patten *et al.*, 2012), NRC identified that the use of boat-tails affects the flow-field behind a tractor trailer in a significant-enough manner that it warrants investigation into safety issues surrounding the implications to other road users. As such, in 2012 NRC proposed a project to study the safety implications associated with the potential accumulation of ice and snow for a boat-tail-equipped HDV. In the first year of the project, a review of possible methods to investigate this issue has been performed and is described herein.

1.2 Project Objectives and Outcomes

The primary objective of the project is to evaluate safety implications associated with the aerodynamic improvements from boat-tails, in particular the effects of changes in the turbulent-wake characteristics on the possibility of ice and snow accumulating within the boat-tail, and subsequently shedding from the vehicle in the presence of following vehicles. The goal is to identify whether the use of boat-tails would pose greater safety concerns for vehicles travelling in the wake of a boat-tail-equipped HDV.

This project will support the following two eTV II program outcomes:

- Support the development of advanced vehicle technology safety outcomes: test results will provide Transport Canada (TC) with recommendations regarding safety implications of using boat-tails on Canadian roads.
- Support for the development of non-regulatory codes and standards: test results provide quantitative guidance so that industry can optimize product development for Canadian conditions.

1.3 Aerodynamics of HDVs Equipped with Boat-Tails

The aerodynamic performance of an HDV is primarily concerned with the wind forces that resist the forward motion of the vehicle, called vehicle drag. These wind forces come from a variety of sources, but can be categorized as one of two basic drag mechanisms:

- Pressure drag is the component of drag that acts in the direction of motion as a result of the pressure forces acting on the body.
- Friction drag is the component of drag that acts parallel to a surface as a result of shear and viscous effects in the flow adjacent to the body surface.

As identified in a report for Transport Canada's eTV II program in 2012 (Patten *et al.*, 2012), for heavy vehicles such as tractor-trailer combinations and buses, pressure drag is the dominant component due to the large surfaces perpendicular to the main flow direction and due to the large wake resulting from the bluntness of the back end of such vehicles. Friction drag occurs along the external surfaces of heavy vehicles, particularly along the sides and top of buses and trailers, however, its contribution to overall drag is generally small (10%).

Tapering the back end of a long vehicle, as is the purpose of boat-tails, will increase its base pressure by providing pressure recovery of the surrounding flow before it leaves the sharp back edges and forms a wake. This increased base pressure lowers the overall pressure difference from front-to-back of a tractor-trailer combination, thus decreasing the pressure drag.

The aerodynamic performance of various boat-tail configurations was examined in a report commissioned by Transport Canada for the eTV program in 2010 (Patten *et al.*, 2010). The results of the study showed that the range of boat-tail configurations tested in the study (various lengths, taper angles, side-panel shapes, and bottom-panels) can reduce tractor-trailer aerodynamic drag between 7.6% and 11.8% at 105 km/h road speed. This performance corresponds to an estimated reduction in fuel consumption between 4.7% and 7.3% or an estimated annual savings of between 2,457 and 3,797 litres for each tractor pulling a boat-tail-equipped van semi-trailer. This also results in CO_2 emissions being reduced between 6,707 and 10,366 kg per vehicle. The results of this study also showed that a marginal increase in aerodynamic performance is obtained when increasing boat-tail length beyond 0.6 m (2 ft). Recent work performed in the US (Salari and Ortega, 2010) has also demonstrated that a boat-tail with a length of 0.6 to 0.9 m (24 to 32 in) is optimal for drag reduction purposes and typical length restrictions.

Of particular interest to the current study is the effect of the boat-tails on the structure of the turbulent wake downstream of an HDV equipped with a boat-tail. The 2010 study (Patten *et al.*, 2010) also demonstrated through computational fluid dynamics (CFD) simulations that boat-tails cause a significant change in the shape of the vehicle wake. Figure 1.1, reproduced from Patten *et al.* (2010) represents the magnitude of turbulence in the flow-field surrounding an HDV with and without a boat-tail along the vehicle centreline. It is evident from Figure 1.1 that the boat-tail guides the wake of the vehicle closer to the ground and apparently reduces the magnitude of turbulent fluctuations in the wake. In a companion report to this (McAuliffe, 2013), describing an experimental study on the dynamic wind-loads experienced

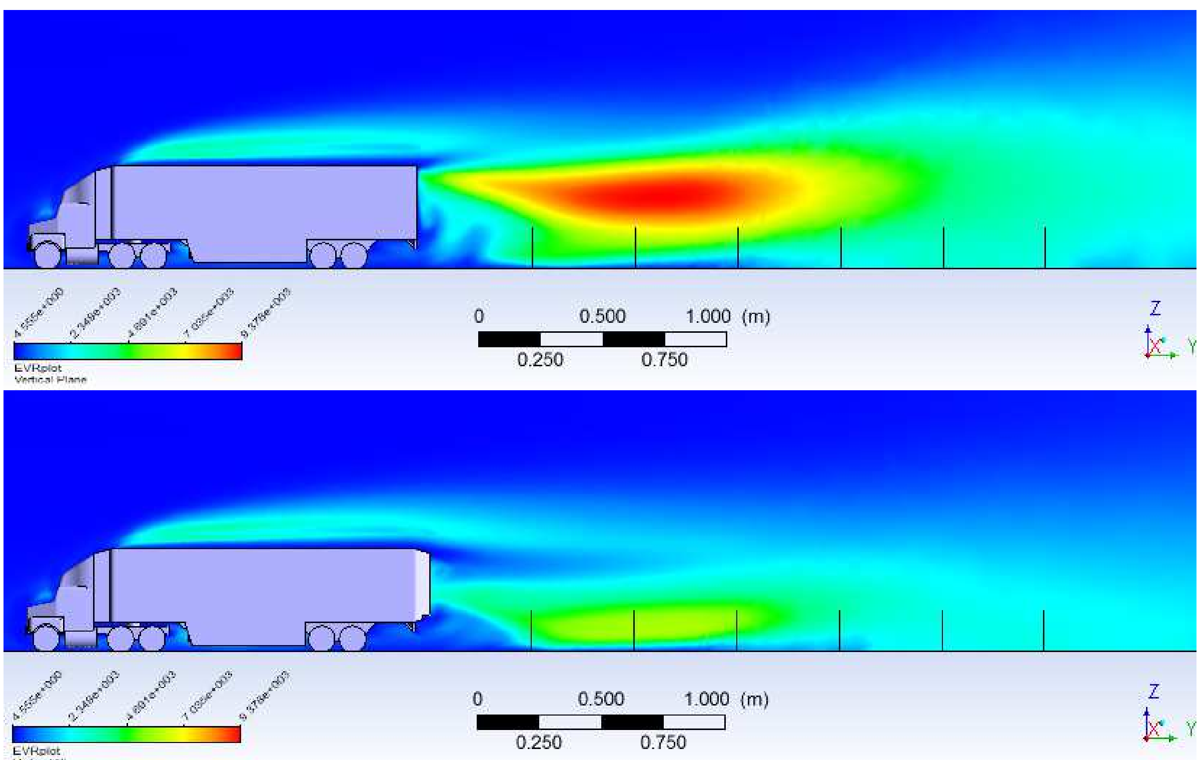

Figure 1.1: CFD results for the effect of a boat-tail on the wake turbulence of an HDV reproduced from Patten *et al.*, 2010 (colours are representative of turbulence levels: blue-low, red-high)

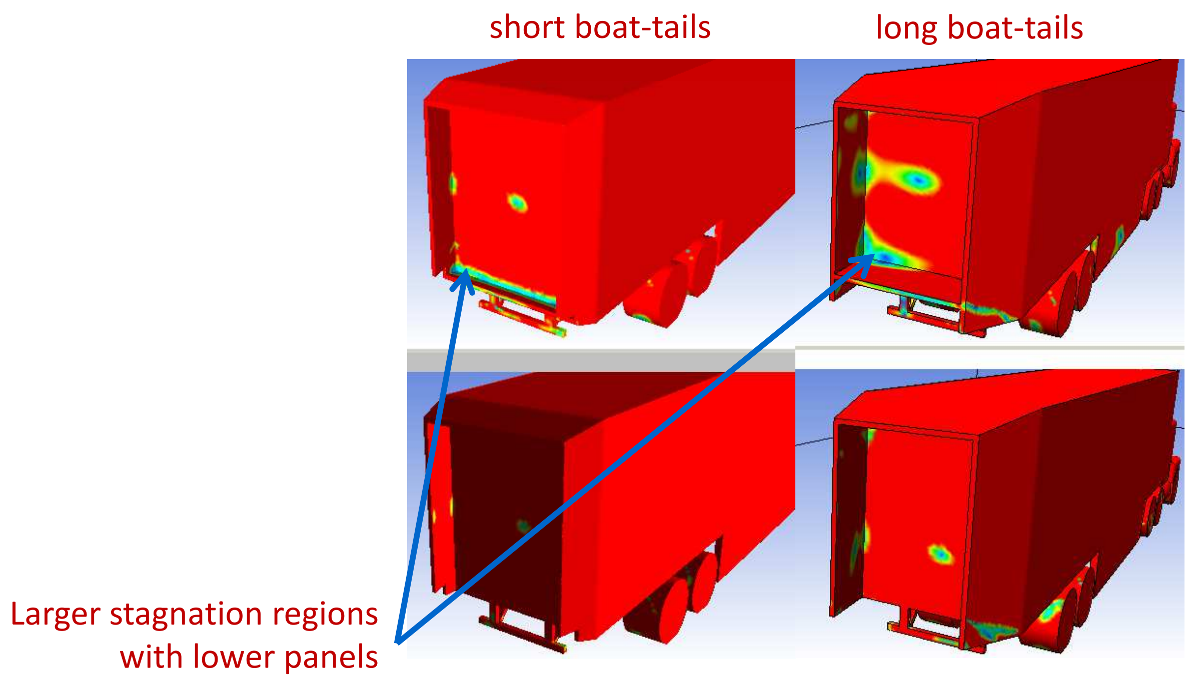

Figure 1.2: CFD results for the effect of a boat-tail on the stagnation zones on the base of an HDV, reproduced from Patten *et al.*, 2010 (non-red colours representative of regions with low-speed winds adjacent to surface)

by vehicles following in the wake of a boat-tail-equipped HDV, it was identified that higher wind fluctuations are found near the ground when a boat-tail is added to the base of the HDV.

The intent of the current study is to examine whether the changes to the flow field in the wake of a boat-tail-equipped HDV may modify the manner in which ice and snow accumulates and shed from such vehicles. There is the potential for ice and snow to accumulate in a different manner than what is observed for standard configurations, a result of the modified flow-field and altered trailing-edge geometry, which then may shed from the vehicle in a manner adverse to vehicles following in the wake. This was identified in the 2010 report to Transport Canada (Patten *et al.*, 2010), in which stagnation regions (areas with low-speed winds) were identified within the boat-tail cavity on an HDV. Figure 1.2, which represents results from the same CFD simulations described above, shows such areas of low-speed winds for two boat-tail lengths with and without lower panels present. These results show stronger stagnation regions when the lower panels are present. These are potential sites for precipitation accumulation, which may introduce safety concerns for other road users. The simulations that provided these results were performed using steady-flow computations, meaning that the effect of wind fluctuations in the wake are imposed through models which evaluate their influence on the mean wind patterns. Unsteady-flow computations that resolve the fluctuating nature of the winds may provide further insight to the potential for ice and snow accumulation. A steady-flow stagnation region could be the result of high unsteady wind patterns that change directions periodically and average, over time, to a net low-speed flow region. Under these circumstances, there may be a lower potential for precipitation accumulation than what is inferred from Figure 1.2. Boat-tails have not been used extensively in Canada, especially under adverse winter conditions, and there is insufficient relevant work currently available to quantify these effects.

1.4 Report Outline

This report contain three main sections:

- Section 2 provides an overview of literature relevant to the problem of ice and snow accumulation and shedding for HDVs, as well as identifying other applications for which such problems have been addressed.
- Section 3 describes the manner in which the problem can be observed and evaluated.
- Section 4 provides an overview of the approach proposed by NRC for identifying the magnitude of the potential issue, and the recommended approach towards mitigation.

2. Literature Survey

2.1 HDV Snow and Ice Issues

A literature survey was conducted to identify any previous work performed in the evaluation of ice and/or snow accumulation for HDVs. Only two sources of relevant information were identified.

The most relevant existing publication is a 2008 report by the American Transportation Research Institute (Trego and Brewster, 2008). However, the focus of this publication is primarily on snow and ice accumulation on vehicle tops and the possibility of dislodging during truck motion. The publication contains reviews of existing literature, snow/ice removal products, and regulatory actions related to snow and ice safety issues. It also documents current industry practices and identifies potential solutions for mitigating the safety risks of snow and ice falling from trucks and tractor trailers, none of which are intended for the rear of the vehicle. Proposed solutions include redesigning the trailer shape to impede the accumulation of ice and snow while driving. However, the report states that there were no engineering efforts underway to mitigate such problems through trailer redesign.

One other source of information was found pertaining directly to the eTV II effort to examine the ice and snow accumulation issue for boat-tails. During the recent meeting of the *Task Force on Vehicle Weights and Dimensions Policy* in Montreal on January 2, 2013, a boat-tail manufacturer (*ATDynamics*) presented on the benefits of boat-tails (Grossman, 2013) and noted that feedback from approximately 500 boat-tail-equipped HDV units with at least one year of northern-winter use claimed no adverse accumulation effects with their product. They identified that there was reduced ice and snow on the doors, that the panels released snow before unsafe weight could accumulate and that only minor snow accumulation was observed on the lower panel when parked. No comment was provided on the nature of the winter environments; since such devices are not common in Canada, it can be presumed that the claims were from Northern US states which may not receive the same magnitude of winter snow and ice conditions as regions in Canada. The minutes from the meeting did not identify any discussion associated with the presentation (Pearson, 2013).

2.2 Snow and Ice Research

Although snow and ice issues have not been studied to a great extent with regards to HDVs, other fields of study have addressed similar problems.

Aircraft icing is a major concern due to the potential build-up of ice on lifting surfaces. If sufficient accumulation occurs on wings and stabilizers, the shape of the airfoils can be changed sufficiently that a loss of lift can occur, resulting in the inability of the aircraft to maintain flight (Kind *et al.*, 1998). Experimental and computational efforts have evolved over decades of research to evaluate properly such problems and develop anti-icing solutions (Oleskiw and Penna, 1999, and Szilder and McIlwain, 2011).

Cables for bridges, as well as power-conductor cables, are susceptible to ice build-up and this can lead to significant weight being accumulated on such structures. Experimental and numerical techniques have been useful in studying the phenomenon of ice build up and the resulting modifications to the cables shape (Poots and Skelton, 1995, and Koss *et al.*, 2012). Not only is the added weight of concern for the strength of the supporting structures, the accumulated ice on cables can change the aerodynamic properties and cause vibrations.

Snow build up and snow loads are often a concern for civil engineers, and examining snow drift patterns on and surrounding a building is common practice using experimental and computational means. Sometimes real snow is used in climatic wind tunnels (Okaze *et al.*, 2012), but simulated snow has been used for conventional wind-tunnel tests as well (lsyumov and Mikitiuk, 1990) where bran flakes have been used and provide a good representation of the motion of snow in the wind.

Several years ago, work began at NRC to develop a snow-storm simulator for snow-ingestion studies for ground-vehicles in the NRC 9 m $\times$ 9 m Wind Tunnel. Although the project was prematurely ended and no formal documentation exists describing the work, it was intended to provide dry snow conditions to examine accumulation in the air intakes of road vehicles. Snow ingestion issues are a major concern for commercial-vehicle development. Air intake systems can become blocked if snow and/or ice can buildup in the intake passages. Takamura and Saito (2008) describe a numerical model to simulate snow ingestion for a compact car. Of most interest from their study is the measurement of snow observed on Canadian roads. To develop mathematical models of snow behaviour, they first measured the concentration and sizes of snow particles kicked-up by a forward vehicle on a Canadian road in winter conditions. They measured snow particles with diameters on the order of 0.1 to 0.4 mm. This work may form the basis for understanding the snow conditions in which HDVs operate on Canadian roads.

3. Evaluation Methods

3.1 Possible Approaches

The current project pertains to the possible accumulation and shedding of ice and snow from HDVs equipped with boat-tails. Three primary approaches have been identified that can be useful in identifying whether a problem exists, and if so how it can be mitigated. The three evaluation methods are:

1. On-road observation;
2. Experimental testing; and
3. Computational simulation.

These three approaches are described in the following.

3.2 On-Road Observations

It is currently unknown whether ice and or snow will accumulate in the cavity of a boat tail. As such, a first step towards evaluating the potential problem would be to perform on-road observations. Several options are available for performing such observations.

One approach would be to travel Canadian highways with still and video cameras to observe HDVs with boat-tails on the road and look for snow and ice accumulation in the boat-tail cavities. With a low-level of market penetration for boat-tails in Canada, this may prove difficult to obtain sufficient observations to make any conclusions.

A second approach would be to partner with a transportation company that either uses boat-tails or would like to use boat-tails. Drivers could be given cameras to document any snow or ice accumulation when at rest stops. Conversely, if sets of tandem vehicles could be arranged on a regular basis, the following vehicle could have a video camera setup in the cab to capture any accumulation and shedding from the forward vehicle. Boat-tails could be supplied if a transportation company interested in helping with the work does not currently have such devices.

Observations through an entire winter may provide sufficient evidence of whether the accumulation and shedding of ice and snow is problematic for HDVs with boat-tails.

3.3 Experimental

As described in Section 2.2, experimental investigations for ice and snow are common practice for aircraft and large structures. Most often, wind tunnels are the primary tool for such investigations.

NRC has a history of studying aircraft icing and - to a lesser extent - snow issues using wind tunnels. The NRC 3 m × 6 m Propulsion and Icing Wind Tunnel is an open-circuit wind tunnel that, when operating in winter conditions, provides a naturaly cold airstream through the test section. A spray system is available for use in the wind tunnel to introduce supercooled water droplets into the cold airstream to study ice accumulation for various aeronautical applications. Figure 3.1 shows an upwind view in the test section with the spray-bar system in operation. The test section is not large enough for a full-sized HDV, however, a smaller-scale HDV model (20-30% scale) could be tested in cold weather conditions with the spray-bar system to examine ice accumulation and shedding associated with a boat-tail. At such scales, the physics of the water/ice particles and the manner in which they travel through the air is not significantly different from what would be experienced at full-sized vehicle conditions (Kind *et al.*, 1998), that an adequate simulation of the droplet motion will be achieved.

Figure 3.1: Upwind view of spray-bar system in the NRC 3 m × 6 m Propulsion and Icing Wind Tunnel

The NRC 3 m $\times$ 6 m Propulsion and Icing Wind Tunnel has also been used to examine snow accumulation on a wing. Oleskiw and Penna (1999) describe a study of anti-icing fluids for which a snow simulation was performed. In those tests, an in-house snow machine was developed using the same type of technology as the current spray-bar system. The spray nozzles were installed in the settling chamber, which allow the water droplets to crystalize and clump prior to entering the test section. Figure 3.2 shows an example of the snow accumulation in the test section section during these tests. The snow-particles in the test section for these tests were on the order of 0.1 mm, which is similar to the range observed by Takamura and Saito (2008) in their snow measurements on Canadian roads.

The main drawback to the examination of ice and snow issues in the NRC 3 m $\times$ 6 m Propulsion and Icing Wind Tunnel is the inability to control the air temperature. The air is drawn into the wind tunnel from outside, and therefore the temperature is dependent on the atmospheric conditions and such tests can only be conducted during the winter.

Another experimental option for examining ice and snow accumulation and shedding issues for HDVs is the use of a climatic wind tunnel. Climatic wind tunnels, such as the one at the University of Ontario Institute of Technology (UOIT) in Oshawa, Ontario, are designed for variable wind speeds and air temperatures, and generally have ice and snow-making abilities (UOIT, 2011). The UOIT facility was partly funded by General Motors and was specifically

Figure 3.2: Snow simulation in the NRC 3 m $\times$ 6 m Propulsion and Icing Wind Tunnel

designed for ground vehicles. The UOIT facility can control the air temperature down to -40°C, has a turntable to vary the wind direction relative to the vehicle, has a spray system for rain and freezing-rain simulation, and has a snow-gun system for generating either overhead snow or blizzard conditions. Other climatic wind-tunnel facilities are found in the United States and Europe with similar capabilities.

3.4 Computational

Computational techniques are available for simulating the accumulation of ice on bodies. Such techniques have been applied to aeronautical and civil-engineering problems. NRC has proprietary computer-simulation capabilities that have been applied to the problem of ice build-up on wings and helicopter surfaces using a morphogenetic ice-accretion approach (Szilder and Lozowski, 2002). The NRC capabilities have been shown to simulate correctly the build-up of different types of ice formations on aeronautical surfaces. These types of techniques typically have three steps towards generating a full simulation of ice accretion:

1. Simulate the flow field surrounding the body using a computational fluid dynamics (CFD) method;
2. Calculate particle trajectories through the flow-field based on the appropriate characteristics (size, mass, aerodynamic properties) of the precipitation of interest; and
3. Calculate the build-up of the ice using models that represent the appropriate spreading and freezing of the precipitation once it makes contact with the surface.

Although such techniques are typically used to simulate ice accretion, the mathematical models that describe the physics of the accumulation and freezing processes can be adapted to other types of precipitation. A better understanding of the physics associated with the stickiness and clumping of snow may provide a realistic simulation environment based on the current NRC capabilities. NRC experience with helicopter ice-accretion shows the potential for evaluating such problem in a highly-unsteady flow-field such as what is found in the wake of an HDV.

4. Conclusions and Recommendations

4.1 Conclusions

In an effort to evaluate the potential safety hazards of snow and ice accumulating and shedding from the cavities of boat-tails, a preliminary study has been undertaken to examine what, if anything, has been done to address such issues and how such an evaluation can be done.

No relevant work to the issue of snow and ice accumulation and shedding from the back of an HDV was found. A boat-tail manufacturer has claimed there are no such issues, but the lack of boat-tail use in Canada precludes such conclusions from being adopted for Canadian-winter conditions. Snow and ice accumulation has been the focus of work related to aircraft, buildings and bridges, power-conductor cables, and engine ingestion for ground-vehicles.

Three approaches have been identified for examining the problem of snow and ice for boat-tail-equipped HDVs:

1. On-road observations during a Canadian winter;
2. Experimental testing using a conventional or climatic wind tunnel with appropriate precipitation simulation; and
3. Computational simulation using ice and snow accretion models.

Of these approaches, each has their benefits and drawbacks and likely a combination of two or all three will provide an answer to the problem of snow and ice accumulation and shedding for boat-tail-equipped HDVs.

4.2 Recommendations

Based on the review of previous work and the approaches identified for evaluating the problem of ice and snow accumulation, NRC is proposing a multi-directional approach to evaluate the potential safety hazard of snow and ice accumulation and shedding from the cavity of a boat-tail-equipped HDV. The proposed project plan is shown in Figure 4.1 and described in the following.

The proposed second-year of work for the project involves better identifying the potential hazard of snow and ice accumulation and shedding for boat-tail-equipped HDVs, and further evaluating the experimental and computational approaches to the problem with an emphasis on identifying which of the two options will provide the most realistic simulation of the

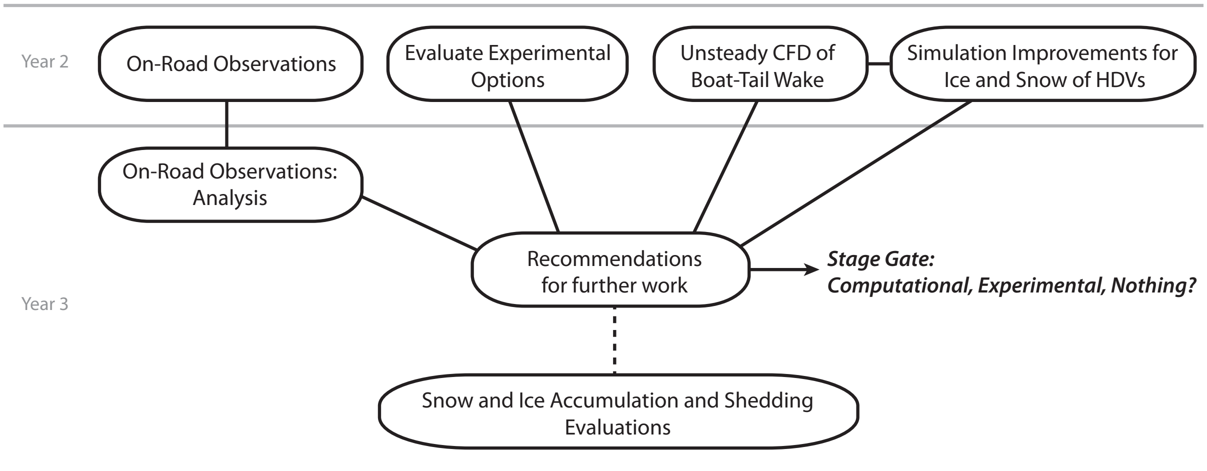

Figure 4.1: NRC proposed project plan

problem. The tasks proposed for the second year of the project are:

1. Initiate a campaign to identify the potential problem of snow and ice accumulation through on-road observations. Partnering with a transportation company would provide the greatest opportunity for such observations.
2. Further investigate the two potential experimental options, those being testing in a conventional wind tunnel, such as at the NRC, or testing in a climatic wind tunnel. An important part of the investigation will be examining the ice- and snow-making techniques available for the two options and identifying whether they are sufficient to represent the conditions encountered by HDVs in Canadian winters.
3. Previous CFD work by NRC has shown stagnation, or low-wind-speed, zones in the cavity of a boat-tail-equipped HDV where snow or ice may be deposited. The steady-flow assumptions in those analyses do not provide evidence about the magnitude of the wind fluctuation in such time-averaged stagnation zones. Unsteady CFD simulations can provide a description of the flow-field within the cavity to identify better the magnitude of any stagnation regions for which build-up can occur over time.
4. The unsteady CFD results described in item 3 can be used to evaluate the potential for computational methods to simulate adequately the accumulation and shedding of ice and snow. Such techniques will require particle trajectories associated with the unsteady winds in the wake of an HDV. Furthermore, the extension of the NRC ice-accretion simulation capabilities to snow-accumulation must be evaluated.

The third year of the project will depend on the outcomes of the second-year tasks. After examining the results of the on-road observations, and better identifying the experimental or computational techniques that can best address the problem, a decision should be made as to the approach for further work. If sufficient on-road observations identify that snow and ice accumulation and shedding is not a safety concern, then no additional work will be done. If a safety concern is still present, a decision will be made as to the most appropriate method for better evaluating and mitigating the problem, whether experimental or computational.

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