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Computational modeling of wake flow to improve visibility during high speed snow plowing

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ABSTRACT

The snow particles entrained in the wake of the maintenance trucks and the subsequent snow accumulation on the rear warning lights appear as the most pronounced visibility problems during high speed snowplowing (HSSP). Development of reliable and cost-effective methods have been demanded by State Department of Transportations to address the visibility hazards that impair safety of the operator and following traffic. An experimentally validated three dimensional computational fluid dynamics (CFD) model was developed to study the performance of a convex shaped tailgate airfoil to reduce visibility problems during HSSP. Possibility of snow coverage at the rear side of the truck is assessed by evaluating pressure and shear stress distributions. The airfoil selected based on the numerical study is installed to the tailgate of the truck and tested in the field. The full scale field tests validated the accuracy of the CFD model and confirmed the improved rear-side visibility by the tailgate airfoil.

1. Introduction

Degradation of visibility from blowing or suspended snow, reflected headlight glare and obscured windows cause serious hazards for snowplow operators and following motorists. The annual statistics given by Federal Highway Administration and Transportation Research Program indicate that nearly 24 percent of weather-related vehicle crashes occur on snowy, slushy or icy roads and over 15 percent happen during snowfall for which the reduction in visibility can certainly be taken as a major cause (Federal Highway Administration (FHWA), 2014; Larson and Shi, 2007). In particular, due to the accumulation of snow debris on the rear side of the snowplow, numerous accidents involving snowplows have been reported by several Department of Transformation (DOT) agencies (Akin et al., 2014; Nookala, 2001; Stutzel, 1995). Troedsson et al. reported that 58% of the collisions with the rear end of snowplows caused by falling or blowing snow (Troedsson, 1995). Nakhla et al. listed the major contributors of those accidents as (i) obstruction of vision by airborne debris, which causes inability to gauge speed and distance; and (ii) accumulation of debris on windows, reflective signage, head lights and rear lights (Nakhla, 2001). An overview of the DOT snow-ice removal/control efforts and the annual cost/economical impact of winter maintenance operations in United States have been summarized by Strong et al. (2010) and Dur (2007). Despite recent advances in the use of roadside sensor technologies for road condition monitoring (Kutila et al., 2009; Reihm et al., 2012; Ruiz-Llata et al., 2014), automated vehicle location (Ye et al., 2012), automated de-ice spraying (Thompson and Thompson, 2014; Ye et al., 2013) and de-icing products (Shi et al., 2013, 2014) the root cause of visibility hazards during snowplow operations remain unaddressed. Current knowledge on visibility hazards and management relies mostly on studies performed a decade ago as detailed below.

Visibility problem during snow plowing operations can be listed as three main hazards; glare, splash and snow cloud (Rea and Thompson, 2000). Once the plow-over debris, i.e. splash, starts depositing on the windshield, obstruction and the change of glass refractive index will degrade the visibility severely (Thomas et al., 2006). The snow entrained in the wake of the snowplow, i.e. snow cloud, appears as the most pronounced visibility problem during snowplowing operations and allows no clear sight for the following motorists. Fine airborne snow particles are very susceptible to airflow around the truck and generate a dynamic whiteout surrounding the truck. This results in poor visual performance due to the reduced contrast and faded images. Snow debris around and behind the snowplow brings difficulty in judging lane position and following distance for the drivers (Fig. 1). Very serious but rather a common scenario arises when snow builds up on the rear face of the truck covering the rear lights. This further brings the difficulty for other vehicles to realize the snowplow is on the road as depicted on Fig. 1.

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Majority of the numerical and experimental studies to aid visibility during HSSP concentrated on front-side hazards, whereas rear-side snow cloud problem has received limited attention (Eskridge, 1982; Garcia Nieto et al., 2010; Ishimoto, 1995; Ishimoto et al., 1992). Earlier studies showed that fine snow particles can be entrained in a wake that extends several vehicle lengths downstream (Eskridge, 1982). To suppress the blowing snow and prevent road icing different types of snow fences were studied through numerical models (Garcia Nieto et al., 2010) and field testing (McCarthy and Keith, 2008; Tabler, 2003). Wind tunnel experiments (Pell, 1994; Thompson and Nakhla, 2002a) and two dimensional (2D) computational fluid dynamics (CFD) simulations (Thompson and Nakhla, 2002b) demonstrated the efficacy of the plow mounted front deflectors for decreasing the size of the recirculation regions to improve the front-side visibility. Combined wind tunnel tests and field experiments (Pell, 1994) identified persistent recirculation regions between the plow and the truck, on windshield of the truck, over the bed of the truck and in the vehicle wake. Nakhla (2001), Thompson and Nakhla (2002a), (2002b) conducted the most comprehensive study up-to-date incorporating two dimensional (2D) CFD modeling, wind tunnel experiments, and full scale field tests to evaluate the performance of multiple mechanical devices for reducing the suspended debris and improving visibility during snowplowing. They concluded that the visible area behind high-speed snowplows outfitted with overplow deflector, packing flap, junction flap and hopper vanes can be 50% larger than conventional plows for the following motorists. This improvement was linked to reduction of debris in the downstream snow cloud. The major limitation of these 2D CFD models was the inability to represent the complete characteristic of the flow domain due to the asymmetry of the one-way front plow. Furthermore, 2D formulation lacks the ability to capture the highly 3D turbulence phenomenon inside the wake flow accurately. Several department agencies including Montana, Idaho and Wyoming have reported the use of tailgate airfoils or deflectors that are attached to the back of the trailer as a promising method to improve the rear-side visibility (Dur, 2007). A tailgate deflector can be interpreted as a naturally driven fan when mounted above the trailer body. It directs the high speed air flowing over the truck towards the recirculation zone behind the truck. The aerodynamic shear of the high momentum air flow prevents the adhesion of snow debris on the rear surfaces. Moreover, the enhanced dynamic pressure in the close proximity of the resulting jet flow weakens the wake flow recirculation, essentially reduces the diffusion of snow particles towards the truck. Therefore, when designed properly airfoil attached to the top of the trailer may clear and further prevent the snow build up on the back of trailer and especially over the warning lights. Unlike other types of deflector vanes and flaps (Nakhla, 2001; Rea and Thompson, 2000) systematic evaluation of the tailgate airfoil devices received limited attention.

Based on earlier agency reports and surveys (Dur, 2007; Rea and Thompson, 2000; Strong et al., 2010; Thomas et al., 2006), efforts addressing the visibility degradation during HSSP are insufficient and visibility problem of snowplow driver and the following public has been unresolved. Moreover, there is a prevailing need for establishing a reliable and cost-effective method to evaluate the effectiveness of the winter maintenance equipments, which have so far been based mostly on the field experience of individual department agencies with limited scientific background. Derived particularly from the need for safer snowplowing operations, the primary objective of current study is to prevent the snow built up on the rear lights and decrease size of the snow cloud. To properly address this issue 3D CFD modeling is employed. Reynolds-Averaged Navier-Stokes (RANS) equations along with a turbulence model are solved to resolve the wake flow behind maintenance truck with and without airfoil. Based on the low density powder-like snow and high drag coefficient, snow particles are assumed to follow aerodynamic forces and their effect on the flow pattern is neglected. To validate the accuracy of the CFD simulations and confirm the effectiveness of the tailgate airfoil full scale field tests are performed on an instrumented maintenance truck during HSSP.

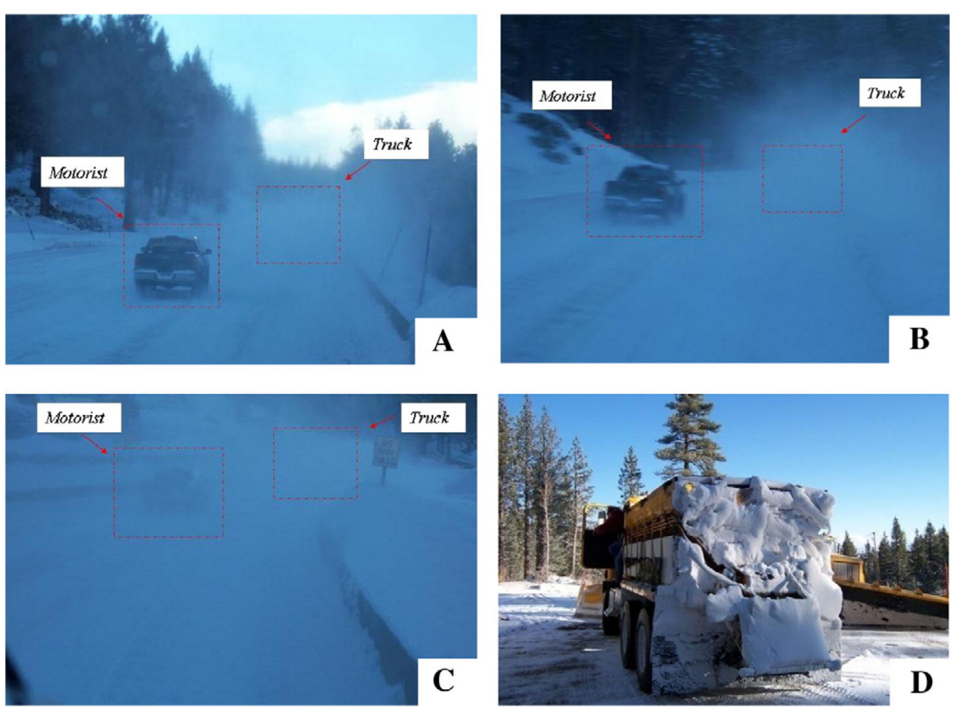

Fig. 1. Visibility impairment inside the snow cloud depicted by pictures taken inside a vehicle behind the snowplow truck and following motorists driving on Mt. Rose Highway, March 2006). Truck disappears due to snow cloud and built up snow on its base (Panel A), motorist switches to the left lane in order to avoid the visual whiteout (Panel B), both truck and motorist are faded out inside the snow cloud (Panel C), snow covered lights behind the truck during a regular plowing shift (Panel D).