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Winter Maintenance Improvements: Phase I

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16. Abstract

The main goal of the project was to evaluate mechanical, electronic and optical means of improving the visibility of the snowplow operator as well as the snowplow vehicle to other motorists on the road. After a survey of various technologies the research team implemented and tested the following methods of visibility improvement. (1) Radar-based collision warning system to give visual and audio warnings of vehicles detected in the path of the snowplow vehicle that the snowplow operator might not see due to poor visibility conditions. (2) Vehicle mounted airfoil that modifies the pressure zone behind the snowplow vehicle to reduce the amount of swirling snow particles building up on the rear lights and surface of the snowplow vehicle. (3) Air blower system that may help decrease density of the falling snow in front of the snowplow vehicle in order to improve the operator's field of vision. (4) Investigating different types of warning lights as well as their configuration and determining which combinations were the most visible by other motorists during snowplowing operations. (5) Tail light puffer system that channels air from the snowplow vehicle's compressor to the rear tail lights in order to clear away built up snow.

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WINTER MAINTENANCE IMPROVEMENTS: PHASE I

FINAL REPORT

Submitted to

Nevada Department of Transportation (NDOT)
1263 South Stewart Street
Carson City, NV 89712

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ABSTRACT

The main goal of the project was to evaluate mechanical, electronic and optical means of improving the visibility of the snowplow operator as well as the snowplow vehicle to other motorists on the road. After a survey of various technologies the research team implemented and tested the following methods of visibility improvement. (1) Radar-based collision warning system to give visual and audio warnings of vehicles detected in the path of the snowplow vehicle that the snowplow operator might not see due to poor visibility conditions. (2) Vehicle mounted airfoil that modifies the pressure zone behind the snowplow vehicle to reduce the amount of swirling snow particles building up on the rear lights and surface of the snowplow vehicle. (3) Air blower system that may help decrease density of the falling snow in front of the snowplow vehicle in order to improve the operator's field of vision. (4) Investigating different types of warning lights as well as their configuration and determining which combinations were the most visible by other motorists during snowplowing operations. (5) Tail light puffer system that channels air from the snowplow vehicle's compressor to the rear tail lights in order to clear away built up snow.

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EXECUTIVE SUMMARY

The overall goal of this research project was to reduce the number of accidents associated with snowplowing operations in northern Nevada as well as improving its efficiency. Upon looking at data from previous accidents it was determined that the reduced visibility during snowy weather was the biggest factor in causing collisions. The research team studied various published work and conducted a survey of Northern United States Department of Transportations related to the area of snowplowing and decided upon a number of technologies that can be useful for the NDOT fleet.

The technologies considered were 1) Global Positioning System (GPS), 2) magnetic road sensors, 3) different light types and arrangements, 4) air blower systems, 5) taillight puffer systems, 6) airfoils, and 7) radar-based collision warning systems. The principles of operation of the various technologies were investigated for their feasibility for use at this stage of the project and it was decided to pursue technologies 4-7 during this phase.

The effect of airfoil on the snow accumulation on the truck sander rear face and snow cloud was studied computationally. Model selected based on this study was installed on three different trucks serving three different areas, Month Rose highway, Carson valley, Elko. Although the tests could be considered limited due to lack of snow, the results showed that airfoil can keep the warning and other lights of the truck clear of snow with the exception of lower right lights. Velocity and pressure measurement at different locations of truck rear face was performed. The comparison of these measurements with the computational predictions proved that model developed captures main features of the flow behind the truck. These results will be used to improve the model for future studies. High speed blower system is considered for decreasing the density of falling snow in front of the truck to improve driver's visibility. Computational studies and preliminary laboratory tests seem to show promise to improve driver's visibility. Air puffer system has been installed and its effectiveness is tested. Preliminary results indicate that available pressure may not enough to keep the all of the taillights clear of snow as a stand alone system. Selected radar system has been installed and tested in the field. Results proved that it is not likely to be effective for the snow plow application. Finally a transparent splash barrier was designed and partially fabricated to prevent snow reflected from road side bank from reaching the wind shield. The feasibility study of the air blower system, other possible radar systems, installation and field testing splash guard, further testing and optimization of airfoil system, use of air puffer either for limited number of lights or in combination with airfoil will be accomplished during the second phase.

1.0 INTRODUCTION

1.1 Project Overview

The project was aimed at improving the current fleet of snowplows within the NDOT in order to decrease the number of accidents associated with and to increase the efficiency of the snow plowing operations. Sample accident data was analyzed in an attempt to determine the root causes for the accidents. Visibility was identified as the main concern. Various mechanical and electronic modifications were then investigated to determine their potential effectiveness and feasibility for implementation.

1.2 Accident Survey

NDOT provided accident data of their vehicles for the two previous years. The data was processed so that only accidents involving snowplows and their causes were included. Table 1.1 describes the accidents, the responsible party and the cause.

Table 1.1. Accident Data

COMMENTS	Who	Cause
Plowing snow, pulled to the right, plow fell into dirt, bent & broke frame.	Driver	Driving off road
NDOT truck turned down Icy street in VC hitting a car.	Driver	Driver/Visibility
NDOT plow stuck in snow, while attempting to pull it out damage occur.	Driver	Vehicle stuck in snow
Plowing snow, other vehicle att. To pass hitting the plow.	OV	Motorist/Visibility
Plowing snow, stopped to help stranded motorist, hit in the rear.	OV	Motorist/Visibility
NDOT vehicle plowing snow, plow fell into bride joint causing accident	Driver	Plow hitting unseen obstruction on road level
While plowing, turned corner, hit sidewalk with plow	Driver	Driver/Visibility
NDOT driver clipped the mirror of a parked car with the snow plow	Driver	Driver/Visibility
Driver injured from impact; no seat belt.	Driver	Driver/Visibility
Plowing snow, hit manhole cover that was covered in snow.	Driver	Plow hitting unseen obstruction on road level
Snowing, late at night, hit a snow drift that was bigger than he thought	Driver	Driver/Visibility
Snowing, late at night, rear ended by a Semi.	OV	Motorist/Visibility
Snowing, Driver failed to check plow bit, wore down into mold board	Driver	Maintenance
Snowing, driver failed to see 2nd set of railroad tracks, and hit track.	Driver	Plow hitting unseen obstruction on road level
Snowing, 10 wheeler with wing plow, wing fell into bridge joint.	Driver	Plow hitting unseen obstruction on road level
Snowing, pushing snow at sand pile, drove off road, tipped over in sand.	Driver	Driving off road
Snowing, pushing off to the side, slid off the side of the road and rolled.	Driver	Driving off road
Snowing, Driver failed to check plow bit, wore down into mold board	Driver	Maintenance
Snowing, Driver failed to lift wing plow striking cattle guard.	Driver	Plow hitting unseen obstruction on road level
Snowing, other vehicle, wrong side of road, hit NDOT head on.	OV	Motorist/Visibility
NDOt vehicle plowing snow, bolt came loose, wing plow came loose causing dmg	Driver	Maintenance
While plowing, wing plow fell into bridge joint causing major damage	Driver	Plow hitting unseen obstruction on road level

Although it is a fairly small sample size, it was observed that the prevalent cause of the accidents was the inability of the snowplow operator to see obstacles or the boundaries of the road. It is also noted that the motorists have difficulty seeing the snowplow vehicle itself, resulting in collisions. As a result of these analyses discussions with the NDOT research project panel it is decided to concentrate on the visibility issues and means of assisting the motoring public to see the snowplow and the snowplow operator to avoid obstacles as well as stay on the road.

1.3 Snow plowing and visibility survey

The research team conducted a survey by phone and via email of 24 Northern state Department of Transportations (DOTs) to gather information on the equipments, applications or lighting configurations used on trucks to improve visibility during snowplowing. Results indicate that most states use light-emitting diodes (LED) for rear lighting and conspicuity signaling. Most of the safety/warning LED lights used are amber, white and blue in color. Many of the DOTs agree that the LEDs are worth the extra investment they require, but feel that it should not be the only type of light for rear lighting rather be incorporated with incandescent lights. Using rotating beacons or strobes mounted on top of the truck was standard in most states but the mounting location is still important due to glare issues. Halogen lights were the most commonly used as headlights due to their availability on the market and acceptable heat discharge characteristics. A few states use fog lights in addition to the halogen lights and claim they increase visibility. Methods suggested to prevent glare are painting the back of the plow and the hood flat black, lowering the truck lights or keeping front lights away from the hood as much as possible. There were only a few states that employed the collusion avoidance system/GPS, and some were conducting research on the topic. Using wing plows was very prevalent and was supported because of their ability to clean multiple lanes in one pass. Underbelly plows are found to be very effective on scrapping the pavement. To reduce snow built up at the windshield many states had tried heating technique, such as heated mirrors, etc., but most of these heating techniques were said to be inefficient in the long run. Snow deflectors were also used to increase the visibility. Finally, survey results revealed that mounting airfoil on the top of the sander can effectively reduce snow build ups on rear lights. Summary results are given in Fig. 1.1 and details of this survey are described in Appendix A.

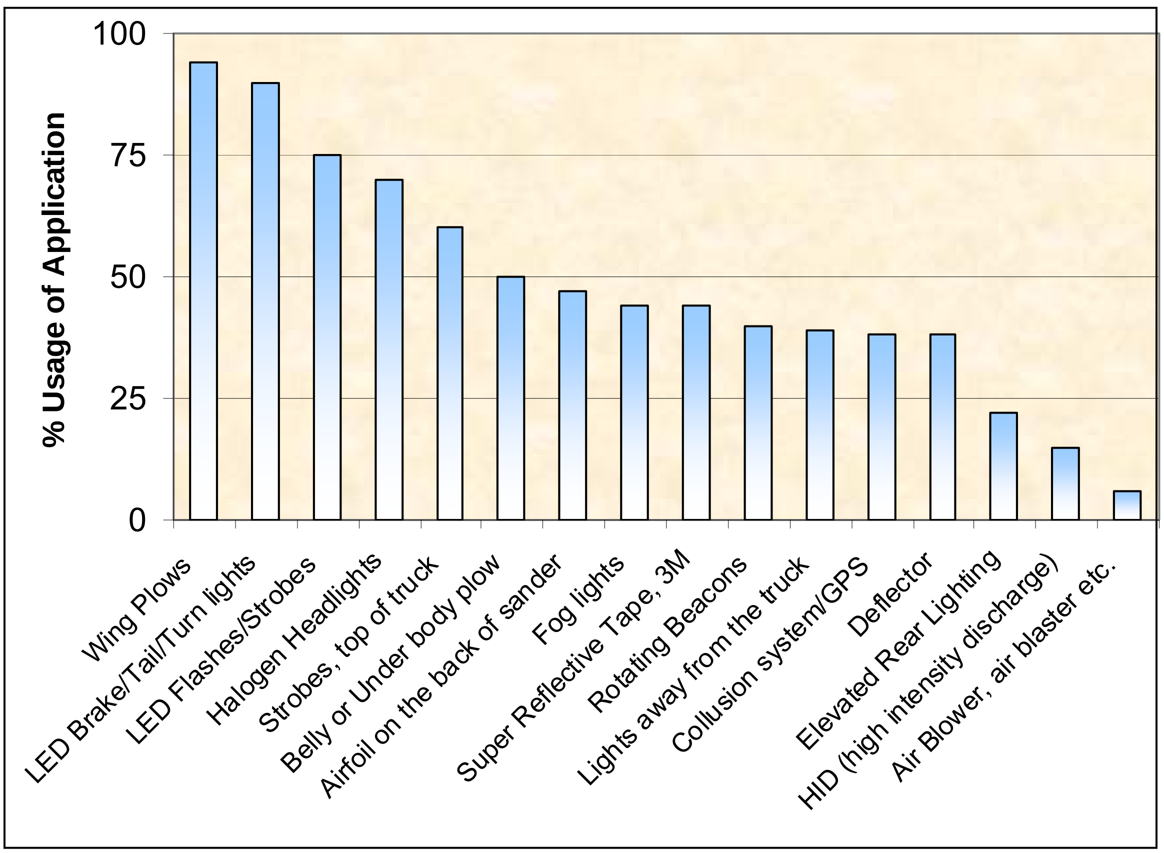


Fig. 1.1 Summary Survey Results

2.0 LITERATURE SURVEY

In addition to identifying problem areas that should be concentrated on, the research team also reviewed similar projects from different parts of the country to identify any previous work that could be implemented to improve the NDOT fleet. Summary of this literature survey is given below. The following chapters describe the selected technologies and in detail and provide conclusions of the research conducted.

To address the issue of road departure, the University of Minnesota conducted research on the use of high-precision Global Positioning System (GPS) to detect lane position on a roadway. This was done by placing markers on an already surveyed site and driving the snowplow truck over these markers. A camera was attached to the vehicle so that they could tell at what instant the truck was over a particular marker and then compare that to the reading from the GPS receiver. Technology can be developed into a high-accuracy system that could alert the driver when the truck is about to go off the road (Bajikar, et al., 1998). Further development would consist of creating a high bandwidth display inside the truck that could display real-time position data. This technology would also require accurately surveyed roadway data that could be used in sync with the GPS technology to minimize the error.

The California Department of Transportation and the University of California Davis have worked on a project involving a radar-based collision warning system and a magnet-based road position detection system for snowplow vehicles. The collision warning system involves the installation of a commercially available product that is normally meant for semi trucks. This system will give audio and visual warnings of objects in the collision path of the host vehicle. The main advantage of this system is its use in adverse weather conditions where the visibility is low. The magnet-based road position detection system involves drilling into the roadway and embedding dipole magnets at intervals of 1.2 meters. The snowplow truck is then fitted with an array of magnetometers that will read the strength of the magnets and from these readings will determine the relative position of the snowplow truck on the road. Combined with a display this system should be capable of giving warnings when the vehicle is about to go off the road (Yen, et al, 1999).

According to our survey several state agencies cited the snow blowing over the top of the moldboards as a major problem for visibility of snowplow drivers. Once the plow-over debris (splash) starts depositing on the windshield, obstruction and the change in the effective flatness and refractive properties of the glass will degrade the visibility severely. On the other side, snow entrained in the wake of the snowplow (snow cloud) appears as the most pronounced visibility problem during snowplowing operations which 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 because of 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. Several rides are taken to the Mount Rose Area with the Nevada DOT Snow Trucks in order to observe the visibility problems. It is found out that the severest but rather a common scenario arises when snow cloud builds up snow 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 (Fig 1.2).

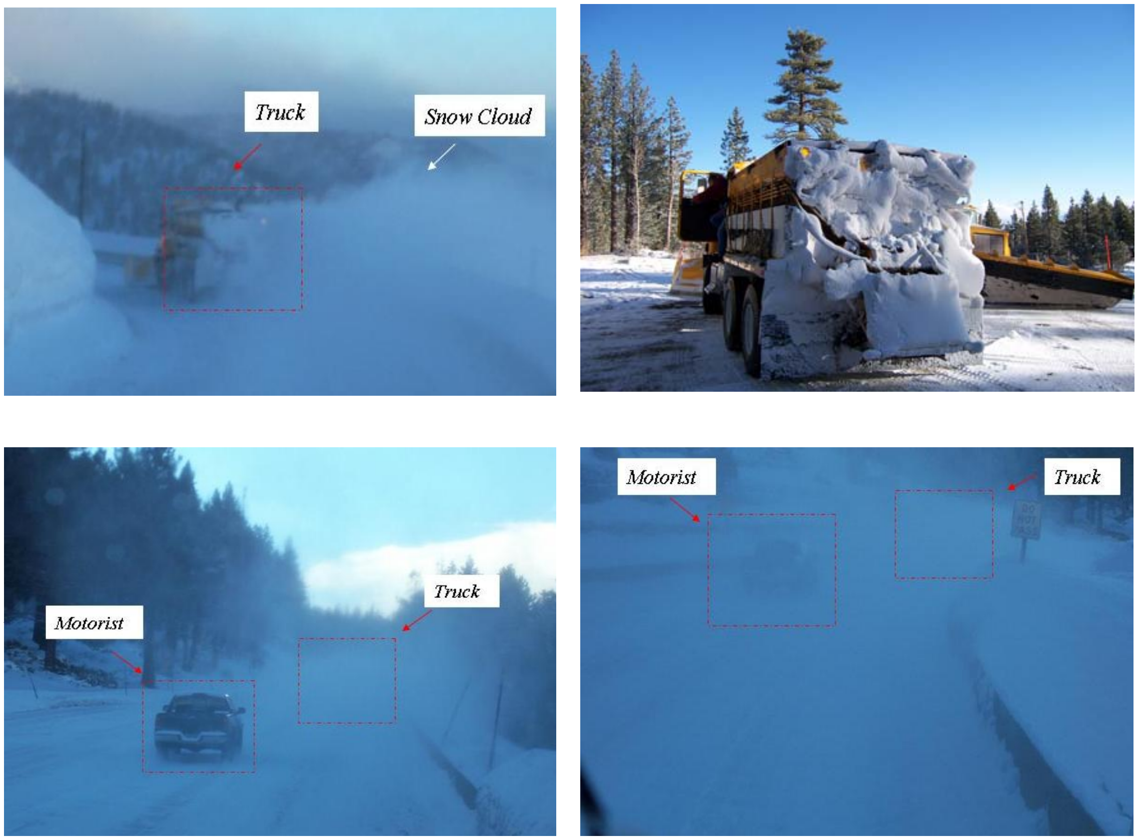


Figure 1.2 Covered Lights and Visibility Impairment behind the Truck (Mount Rose Highway, Washoe County, NV, March 2006)

Addressing two of the major visibility problems identified (i.e. splash and snow cloud), the mechanical methods are employed for improving the visibility of snowplow drivers and following public. The vanes and deflectors attached to the top of the moldboard appear as practices to decrease snow blowing over top of the plow (Rea and Thompson, 2000). The final report of Clear Roads (2006) shows that hood mounted wind deflectors and plow flaps are common practices to reduce snow blown to windshield in high driving speeds. A research project conducted Nakhla (2001) studied the behavior of snow particles around plow trucks during operating conditions. Detailed review of the literature identified snow build up on the rear of the snowplow truck as a common problem due to the characteristics of the air flowing around the vehicle. Further investigation showed that several other Departments of Transportations around the country had implemented airfoils on the rear of their snowplow trucks to alter this airflow and decrease the amount of snow accumulation on rear surface of the truck during snow plowing operations. This results in the better visibility of tail and warning lights that alert motoring public at enough distance and avoid rear end collusions. Our research team identified commercially available airfoils and modeled the selected truck with and without these add on devices by using a leading computational fluid dynamics (CFD) software. The resulting model is used to analyze and compare effectiveness of different airfoils in altering the air flow and pressure around and the rear of the snowplow truck in order to decrease snow buildup. In addition to the tailgate deflector, another type of airfoil mounted on the sides of the truck are also acknowledged in order to reduce suspended debris (Nakhla, 2001). Moreover, packing flaps at the discharge end of front plows are reported as a possible mean of reducing the size of snow cloud around and behind the plow. Finally, when wing plows are used, junction flap that closes the gap between the front plow's discharge end and the intake end of the wing plow will also reduce the size of the snow cloud.

Several papers dealing with the characteristics of airflow out of nozzle jets were studied in order to apply the concept to a vehicle mounted air blower. Previous works included the study of flow decay and different types of jets such as free, wall, and impinging (Nottage, 1951). Also different geometries of nozzles were investigated to study the effect on outflow characteristics (Colucci and Viskanta, 1996). Using the results of these and other published work research team designed an air blower apparatus that would be best suited for a snowplowing vehicle.

A study quantifying driver response to different types of lights provided the basis for the survey that the UNR research team used to query other Departments of Transportation that also had snowplow vehicles in their fleet (Bullough et al., 2001). After determining the best types of lights and lighting arrangements from the results of the study, the survey then asked the other states if they were using anything similar and what kind of success they were having.

3.0 RESEARCH STUDY

3.1 Global Positioning System (GPS)

GPS technology uses receivers to acquire signals from geosynchronous satellites and then triangulates the signals to identify its position on the Earth. There are 24 total satellites in orbit and each one transmits what is called a pseudo-random code (PRC) with each satellite having its own unique PRC. The first phase of triangulating location involves the determination of how far away a satellite is from the GPS receiver. GPS receivers have a copy of each satellite's PRC stored within. Thus calculating the distance from a satellite is done by determining the time delay between the signals called phase shift. The time delay is multiplied by the speed of the PRC signal (speed of light) to determine how far away the satellite is. Using this distance as a radius, an imaginary sphere is created around the satellite. Fundamentally, this process is repeated two more times so that there are a total of 3 satellites with their distances from the receiver known; and consequently 3 spheres created by the satellites. These 3 spheres intersect at two points, one of which is the location of the receiver on earth. The other point is thrown out because it is either in outer space or it is moving at an unreasonable speed.

Ideally this process would give accurate location data, but there are many sources of error that would cause the system to be unreliable. First, interference from the atmosphere, buildings and other objects could slow down the signal from the satellite. Since the signal is traveling so fast, a small error in time causes large errors in distance. There are additional timing errors arising from the fact that when GPS receivers compare the PRC codes, their internal clock is not as accurate as the atomic timing from the satellites.

There are several processes to combat these sources of error. In addition to the PRC, satellites also transmit almanac data, which is information about the satellites' current location in space, which is constantly updated by the Department of Defense. The satellites will also transmit error correction data based on solar effects and the gravitational pull of the moon. Furthermore, current GPS receivers use 4 or more satellites to triangulate its position to reduce error. This is because if only 3 satellites are used there is always a point of intersection of the Earth regardless of timing errors. Using 4 or more satellites will ensure that only one point of intersection will exist if the timing is accurate. Since the aforementioned errors will throw off the timing, the GPS receivers will adjust the timing of the codes and make the necessary corrections so that all the satellites line up at a single point.

However, even with all these correction methods there is still a large enough error to make the system too inaccurate for practical use. This led to the development of Differential GPS technology (DGPS). With DGPS there are base stations spread out over a certain area, each having its own GPS receiver. The base stations compare its known location with the location it determines using traditional GPS methods. The error in distance between the two locations identifies the timing error and the base station then transmits the error correction data to the surrounding mobile GPS receivers. The working principle behind DGPS is that receivers in the same locality will generally experience the same timing error.

Currently, GPS can still be used as a valuable tool for fleet management and give the NDOT the ability to monitor all the trucks out in the field in real time. This will allow the identification of delays and stoppages as well as areas for possible improvements in route efficiency. It was decided that GPS technology would not be integrated with the snowplow vehicles for this project.

3.2. Magnetic Sensing

The California Department of Transportation (Caltrans) and the University of California Davis (UCD) conducted experiments with a magnetism-based system to prevent road departure of snowplow trucks. The two main components of the system are the magnetometers installed on the snowplows and the magnets embedded in the road at intervals of 1.2 meters in the center of the lane. Figure 3.1 shows the magnetometer setup UCD and Caltrans used.

Figure3.1 Magnetometer array underneath snowplow truck (Yen et al., 1999)

An array of 7 magnetometers installed on the bottom of the snowplow detect the field strength of the magnets embedded in the road. The working principle is that the two magnetometers with the strongest magnetic field strength reading between them is where the embedded magnet is located (Fig. 3.2). Thus this gives the location of the snowplow with respect to the center of the lane. The accuracy of the system is currently 1.5 centimeters with a 1.0 centimeter standard deviation (Donecker, 2003).

The experiments conducted by UCD and Caltrans showed that the system can reliably detect lane position with high accuracy and can be a useful asset to snowplow operators. An additional benefit of the system is that the magnets can be inverted to reverse their polarity. The alternating polarity of the magnetic fields can be used as a binary code to provide certain information such as upcoming construction, road curvature, etc. A prototype system has been tested on a stretch of I-80 in California and has proved to be successful.

However, there remain several issues that need to be resolved with the system. A sudden change in vehicle velocity can affect the readings of the magnetometers, as can ferrous components in the vehicle and roadway structures. There is also the issue of electromagnetic interference from all of the vehicles components as well as natural inference from the Earth itself.

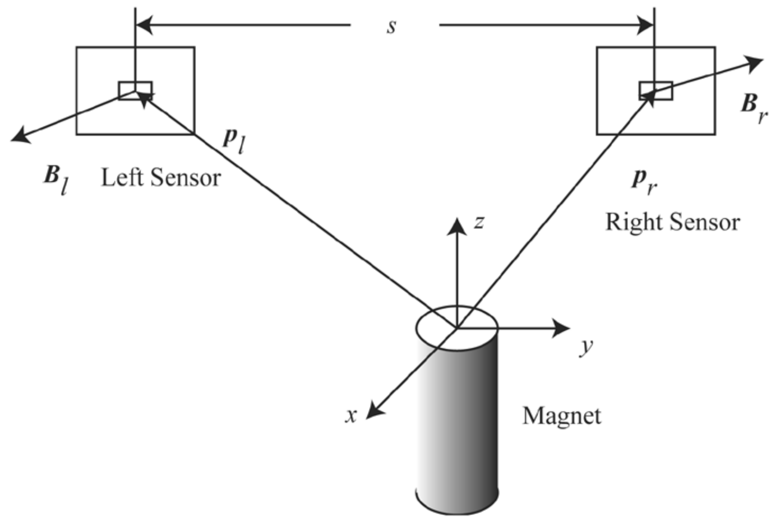


Figure 3.2 Magnetic Sensor Diagram (Donecker, 2003)

The high cost of implementing this system, which is estimated at $10,000/mile makes it prohibitive for the purposes of this project. Although the system can prove to be very valuable in the future to snowplow operators, the initial cost of the system is the main obstacle in its implementation. While it is possible to reduce its cost by spacing the magnets further apart, the side effect would be degradation in performance and accuracy of the system.

3.3 Radar-based Collision Warning System

A commercially available radar warning system (VORAD) was purchased from Eaton and installed onto one of the NDOT snowplows. The system uses Doppler radar to detect any obstacles in the critical path of the host vehicle and gives audio as well as visual warnings up to a distance of 350 ft. The warnings vary in color and sound intensity based on distance and closing speed (Fig. 3.3). However, the system requires that the radar transceiver be placed as close to ground level as possible. Since this is not feasible for snowplow trucks, alternative locations were selected and tested to determine effectiveness. This approach has been used by both the California and Arizona Departments of Transportation with some success (Yen et al., 1999).

The system has an internal gyroscope to help identify the vehicles in the snowplows critical path while driving on a curve (Fig. 3.4). The most important feature of the radar system is, according to the manufacturer, capable of working in adverse weather conditions such as rain and snow. Ideally this would enable snowplow operators to have ample warning of impending collisions with obstacles they cannot see during low-visibility conditions.

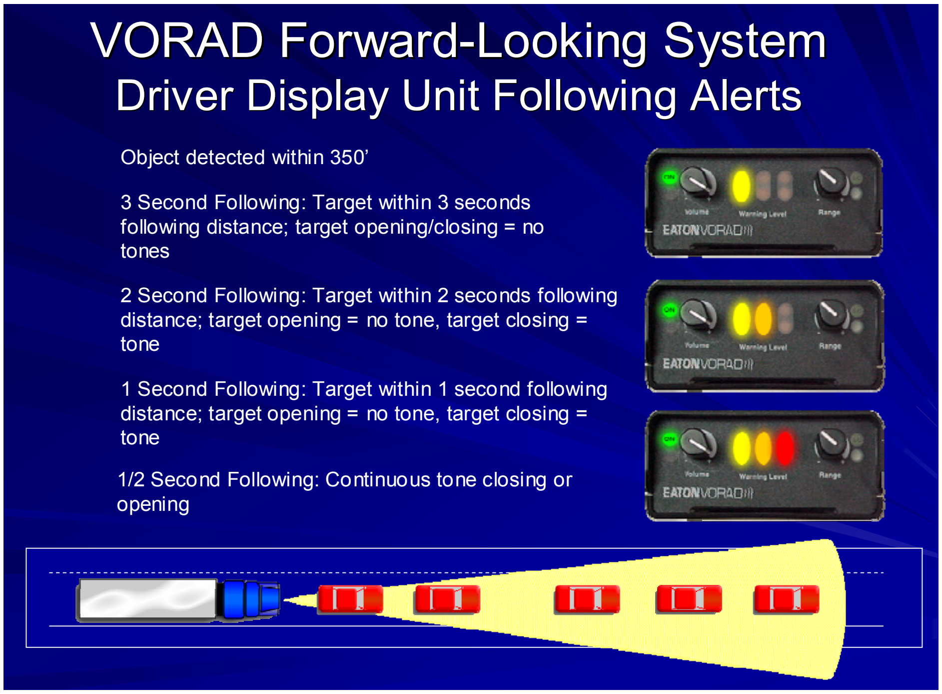


Figure 3.3. Warning scheme of radar system (Eaton Vorad Corporation).

Figure 3.4 Internal gyroscope capability (Eaton Vorad Corporation).

With the installation of the system, the hope was that the snowplow operators could better avoid collisions with vehicles and other objects on the road that they couldn't see with just their naked eye. However, during test runs we encountered numerous issues with the detection capabilities of the system. Figures 3.5 and 3.6 show the placements of the transceiver tested during the runs. The transceiver was first installed at the top of the cab and angled slightly downward based on calculations to achieve a similar field of view as a normal installation, which is close to ground level and parallel with the surface of the road.

Figure 3.5 First placement of transceiver.

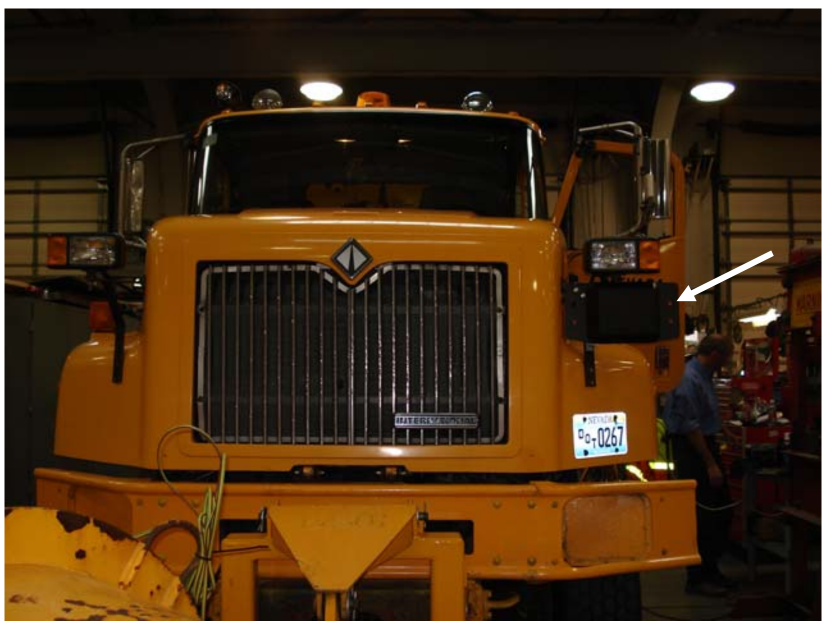


Figure 3.6 Second placement of transceiver.

The first problem with the system was that it was not properly giving warnings of impending collisions. Tests were conducted by driving up to various objects (vehicles, buildings, etc.) and stopping just before hitting them. The warning system inside the cab would give various visual and audio alarms, but these were not consistent with the types of alarms that were supposed to be given according to distance and closing speed. Consultation with the Arizona DOT, who had also used this system, resulted in the advice of moving it by the driver side headlight.

In the new position the results were not different. We then contacted the who assisted us by sending us a diagnostic tool and a software update for the system. Based on the advise by manufacturer the software was updated and the diagnostic tool is used to conduct a scan and found no faults.

Further discussions with Arizona DOT indicated that although they had some success with their system, they too had issues and the driver feedback wasn't very positive. In light of this as well as the fact that the system wasn't working properly even though there were no identifiable faults, it was decided to remove the system from the truck and pursue other options. One of such options, millimeter-wave radar system that can allow imaging under conditions that cannot be seen with naked eye, was not considered further due to its high cost of adaptation to snow plow operation. Future work in the next phase of the project will include investigation of similar technologies.

3. 4 Taillight Puffer System

The system is a commercially available product that include nozzles and a control unit that channels the available high pressure air toward the taillights of the snowplow truck to help prevent snow accumulation on them. The source of air comes from the snowplow truck's air compressor and is plumbed to the rear towards the taillights via nozzles (Figure 3.7).

Figure 3.7 Air nozzles on the taillights

The control unit that allows the adjustment of the duration of the air bursts and the time interval between them is located Inside the cab of the vehicle (Figure 3.8).

During normal snowplowing operations it is inevitable for snow to build up on the rear lights of the snowplow truck. Obscuring these lights will result in other motorists not being able to recognize the snowplow truck in time to avoid an accident. Therefore keeping the lights clear will help ensure that motorists can see the truck during adverse weather conditions.

Figure 3.8 Air puffer control unit

Field tests have shown that although the system does partially work under light snow conditions, the air flow is not enough to clear heavy and and/or wet snow. As a solution the nozzle pointing toward the reverse (white) taillight may be blocked so that all the air will be concentrated on the red taillight (Fig. 3.7). This is because the reverse light is hardly used during snowplow operations and it is much more important for motorists to be able to see the red running taillights. As a practical matter the red taillights are also easier to see in the snow. After the adjustments are made further tests will be conducted to evaluate the system's effectiveness. Also, this system can be used in combination with other technologies, such as the airfoil discussed in the next section, to increase their effectiveness.

3.5 Airfoil – Computational Analysis, Field Testing, and Implementation

3.5.1. Computational Studies

A preliminary analysis of a generic truck model was performed using FLUENT computational fluid dynamics software (Fluent Inc, Lebanon, NH) for a plowing speed of 35mph plus 10mph wind speed. The model is adapted from the one used in literature in order to verify the computational methodology used (Nakhla, 2001). A typical result of flow trajectory around a generic truck traveling at 35 mph is shown in Figure 3.9.

The general model predictions results agreed well with the published results (Nakhla, 2001). They indicate recirculation zone as the main cause of the snow build up in rear section of the truck. To help with this issue mounting an airfoil on upper rear section of the truck is being considered. Briefly, a concave airfoil works like a natural fan when mounted above the sander body. It directs the high speed air flowing over the truck towards the recirculation zone behind the sander. This will not only scrape the snow particles sticking to the surfaces but also increases the local pressure which cause the recirculation zone to shift further downstream. Therefore, when designed properly airfoil prevents the snow build on up the back of sander and especially over the warning lights. To explore the efficiency of different airfoil designs and the mounting location, a 2D CFD model of NDOT Class-15 Truck with Henke-4806 One-way Plow is developed (Fig. 3.10).

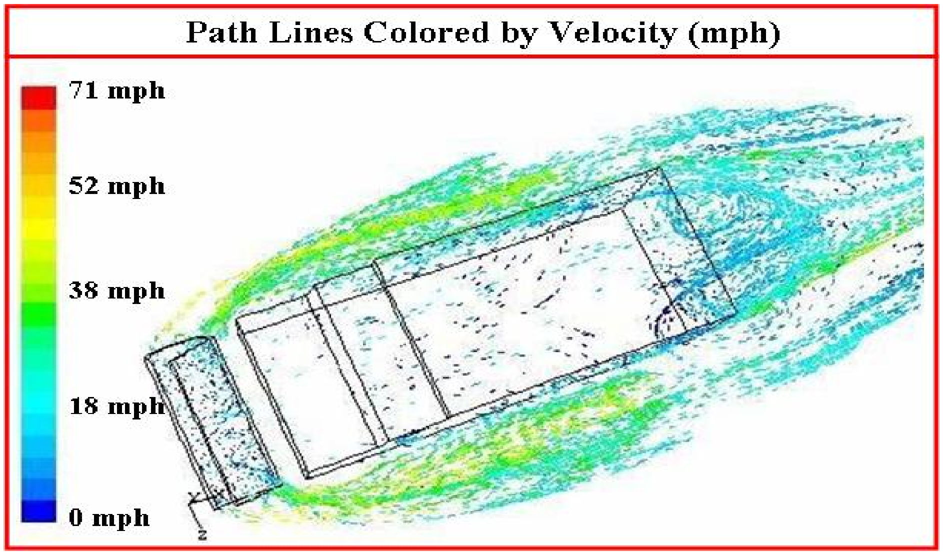


Figure 3.9 3D CFD simulation of air flow around a generic snow plow truck traveling at 35mph

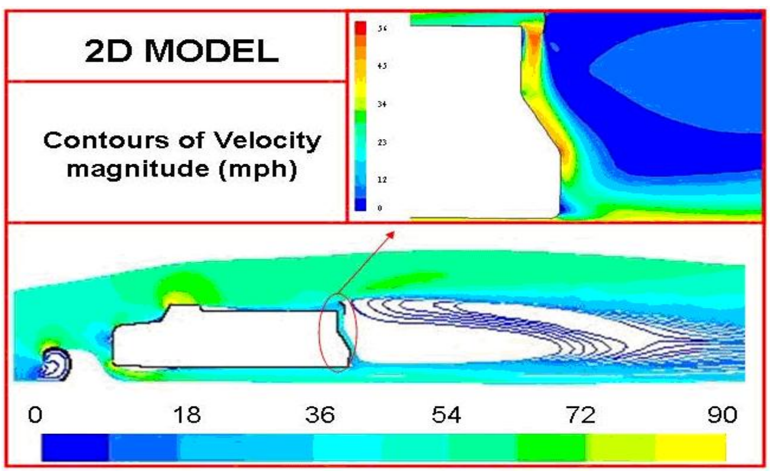


Figure 3.10. CFD simulation of air flow around a Class 15 truck.

The next step involves modeling the airfoils that are intended to be mounted on the vehicle. Two commercially available airfoils, one made by Henderson and one made by Monroe, are selected for comparison of their effect on the pressure, velocity and circulation zones behind the truck. In addition to the airfoil design it is known that both distance and elevation of the airfoil relative to the rear surface of the sander substantially affect the downstream flow characteristics. Hence, the foils were modeled in different positions and orientations with respect to the rear of the vehicle (Fig. 3.11). A double airfoil of Monroe type is also considered. The potential effectiveness of each airfoil and the configuration is evaluated based on four factors namely; 1) The total gage and total pressure enhancement on the rear surface, 2) The average wall shear stress on the same surface, 3) The size of the separation bubble and 4) The average turbulence intensity values observed at the downstream wake region. The first two parameters quantify the effectiveness of airfoils for reducing the snow accumulation on the back surface of the truck. The last two parameters measure the effect of airfoils on the size and strength of the snow cloud behind the truck.

In order to investigate this optimization problem adequately, three zones are identified on the sander surface (Zones A, B, C in Fig. 3.12) for each of the flow parameters investigated individually. Pressure enhancements and wall shear stresses are calculated separately on each zone for the evaluation of two airfoils (Henderson Manufacturing, IO and Monroe Truck-Equipment, WI) in different configurations.

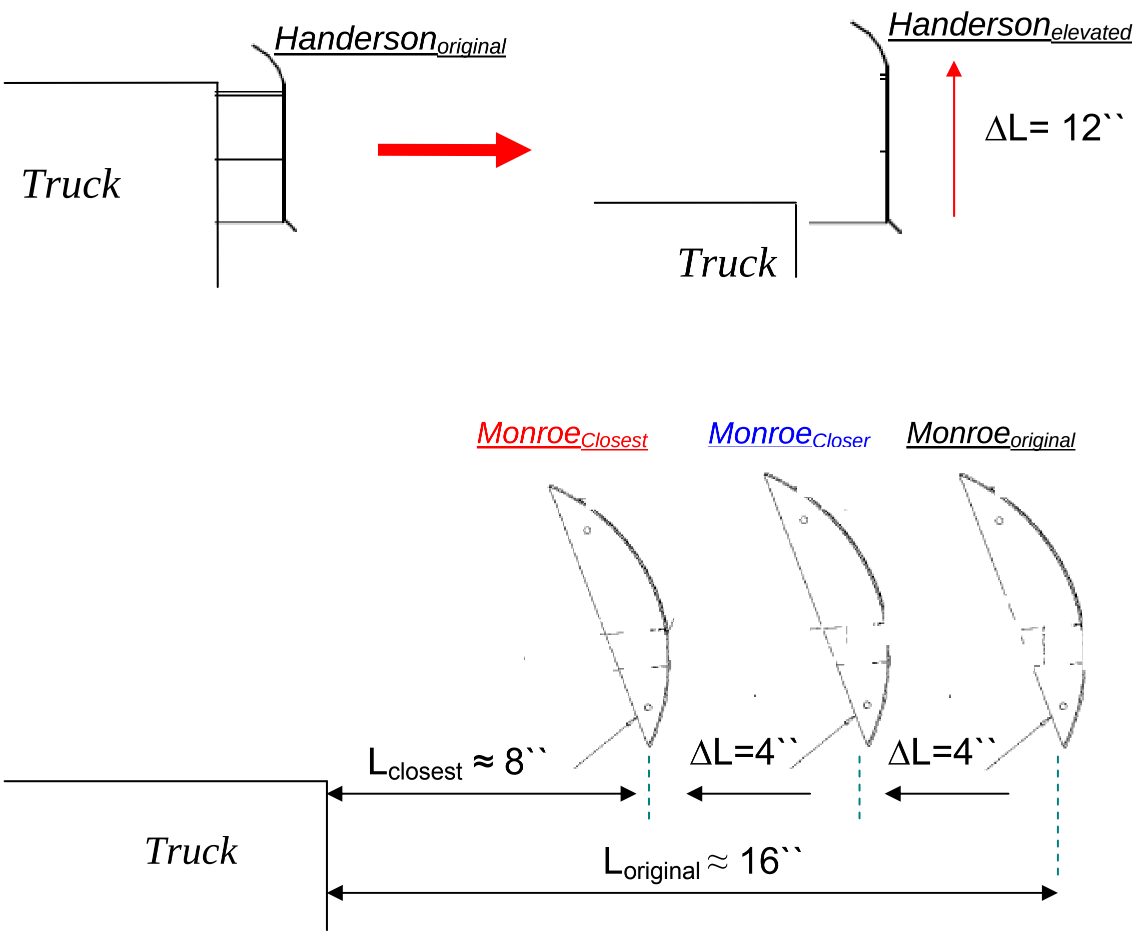
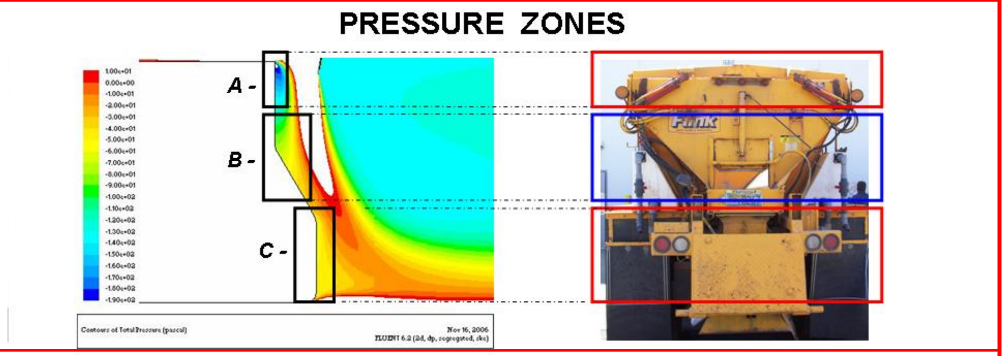


Figure 3.11 Additional Configurations Investigated; (upper) Elevated Henderson Airfoil – Mounted to the Same level with Monroe Airfoil, (lower) *MonroeCloser and MonroeClosest* - Reducing the Gap between the Truck and Airfoil

Figure 3.12 shows the comparisons between the two airfoils in terms of improvements in pressure corresponding to specific zones.



	% IMPROVEMENT ON TOTAL PRESSURE					
MODELS / ZONES	Monroe	Handerson	Handerson Elevated	Monroe Closer	Monroe Closeset	Double Airfoil
ZONE A	- 70 %	30%	-115%	-65%	-45%	60%
ZONE B	40%	20%	40%	140%	170%	115%
ZONE C	50%	20%	20%	125%	76%	60%

Figure 3.12 Pressure improvement comparison

As a conclusion of the two dimensional analysis, the proper location of the airfoil should be based on the target location where the maximum shear and maximum base pressure that results in the minimum snow accumulation. Based on the 2 dimensional pressure (Fig. 3.12) and wall shear stress predictions (not shown), Monroe model has a higher potential over Henderson Model on reducing the snow accumulation and further prevent the inward diffusion of snow particles due to pressure gradient. In addition, the Double Airfoil configuration can be suggested to boost the overall performance although causing larger recirculation zone. The comparison of the recirculation lengths and heights of the models favors the Henderson Airfoil over other models which is shown to be capable of reducing snow could size even slightly smaller than that of the base configuration. The lower turbulence values also provide evidence that the snow entrainment inside wake zone might be less compared to other models. Among the Monroe Models, based on recirculation size and turbulence characteristics, the least adverse effect on the snow cloud appears when the airfoil is moved 4` closer from the original configuration.

Considering the limitations of the 2D model (lack of ability to resolve the highly three dimensional turbulence behind the truck) and goal of monitoring the flow over the critical locations on the truck (such as snow accumulation on the taillights) the need for the three dimensional modeling becomes prevalent. Three dimensional modeling techniques are employed on both the base configuration (without any airfoil mounted) and the Monroe Airfoil configuration in order to gain more insight about the effect of sander mounted airfoil on the wake flow dynamics. Monroe Airfoil is selected based on its superior performance over Henderson Airfoil in clearing the truck rear surface off snow based on 2-D results. The details of the model are given in Appendix B.

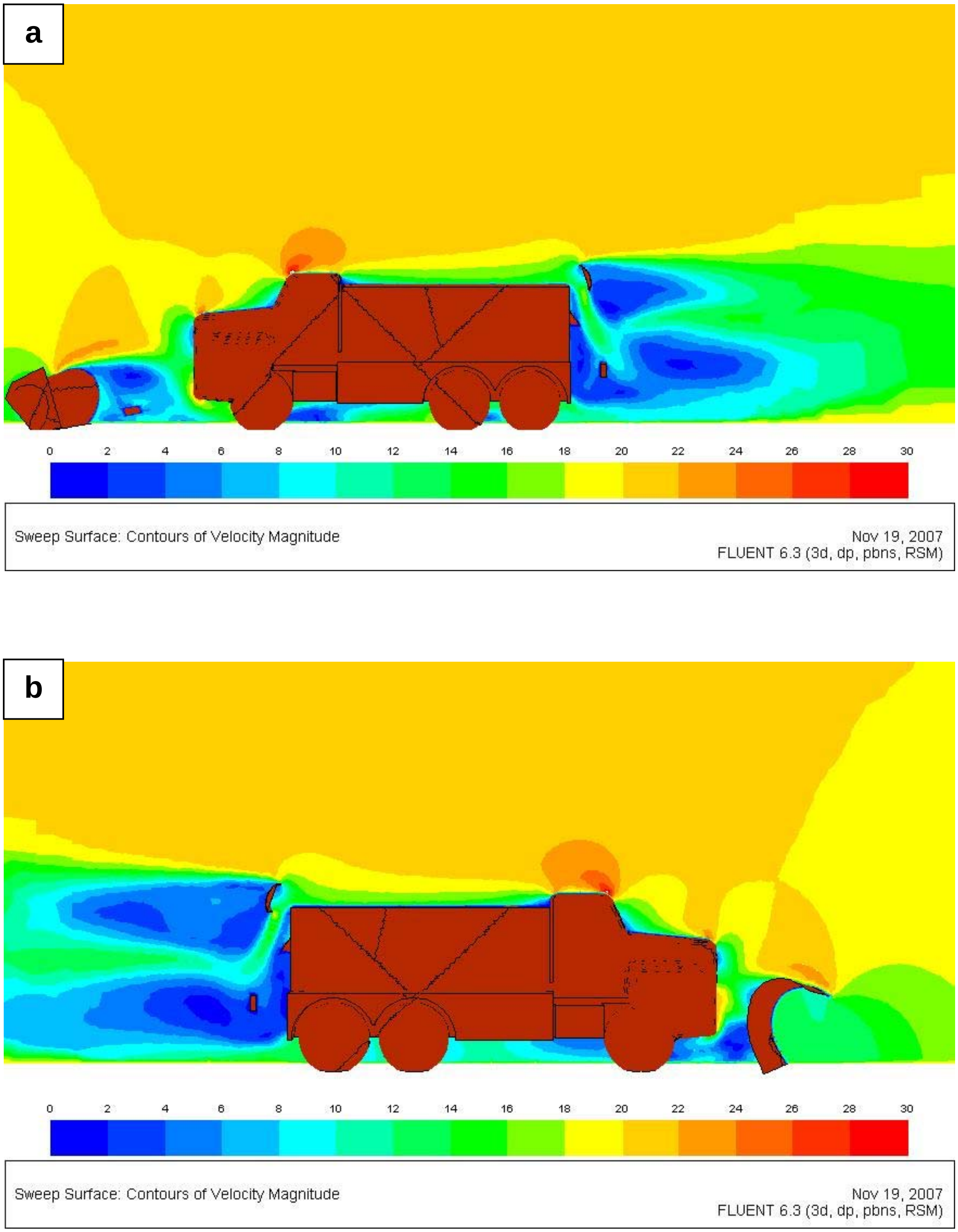


Figure 3.13 Contour Plots Colored with Velocity on (a) Right Side Plane (z= 0.65) (b) Left Side Plan (z= - 0.65m) Showing Flow Asymmetry and Reduced Effectiveness of the Airfoil to Divert High Speed Air over the Left Taillights

The three dimensional model provided a better insight on the flow path inside the recirculation bubble and also detailed resolution of the flow variables behind the truck. Figure 3.13 shows that the flow asymmetry on the right hand side of the truck diverts the airfoil jet flow towards horizontal direction earlier compared to the left hand side of the spreader. Hence, the effectiveness of the airfoil to direct the high speed air in vertical direction over the taillights is reduced on the right hand side of the truck. Figure 3.14 gives the comparison of the static, dynamic, total (i.e. static + dynamic) pressure and wall shear stress on four different locations (upper flasher lights and lower taillight on the right and the left side of the sander) on the backside of the truck for base and airfoil configurations. The results show that the wall shear stresses on the truck surface increases considerably over the truck surface which scrapes the rear side snow away. The static pressure also increases over the taillights so that the snow particles have fewer tendencies to diffuse towards the taillights with the airfoil configuration. However, due to the boundary layer detachment from the top trailing edge of the truck the static pressure decreases considerably around the upper flasher lights.

Other important parameters regarding the snow accumulation and visibility of the truck include turbulence level and size of the recirculation zone behind the truck. The average turbulent fluctuations on the flow field behind the truck is compared for the models (Table 3.1) It is found that the high turbulent intensity value for the Airfoil Model is 6.23% higher than the Base Model. Moreover, the instantaneous velocity fluctuations are higher on the right hand side of the truck compared to the left. Results summarized on Table 3.1 show also a brief comparison with the two dimensional solution highlighting the over predicted turbulence intensity.

It is also shown that the recirculation zone size and the turbulence characteristics are adversely affected by the installation of the Monroe Airfoil Table. Hence, although reducing the snow accumulation over the rear side of the truck, Monroe Airfoil may enhance snow cloud formation.

The size of the recirculation bubble is estimated using the pathlines plotted on the three orthogonal planes. The results show that the length of the recirculation vortices vary on the midplane, left and right side planes coinciding with the sander spinner, the left and right taillights respectively. Longest recirculation length is observed on the midplane for both models. The length of the separation bubble behind the Monroe Model is found around 15% longer than that of the Base Model. Table 3.2 summarizes the recirculation lengths of the models comparing them with the experimental finding of Duell et al. (1999) and Large Eddy Simulation results of Krajnovic et al. (2003) for a generic bus-like body based on Ahmed's body. The height of the separation bubble also changes considerably (i.e. around 30%) from 0.88 x H_{truck} to 1.13 x H_{truck} based on the relocation of vertical horseshoe vortices behind the airfoil geometry. The width of the horseshoe vertices on the horizontal plane is found very close to the width of the truck for both models. In conclusion, the size of the separation bubble is found to be increased around 19% after the airfoil is mounted to the back of the sander.

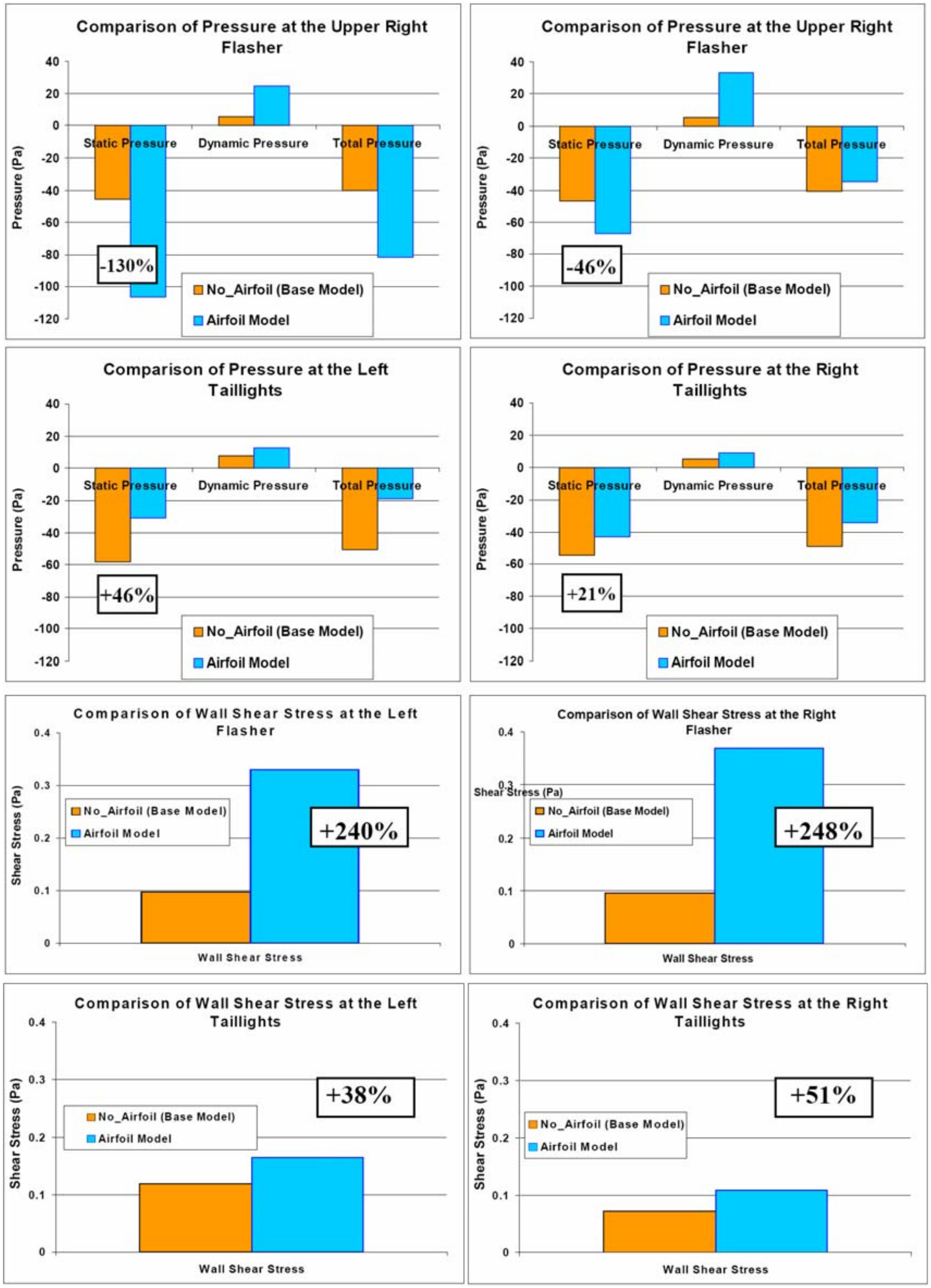


Figure 3.14 Comparisons of Static-Dynamic-Total Pressure and Wall Shear Stress for Base (Orange) and Airfoil Model (Blue) on the Left&Right Flashers&Taillights -*Percentages inside White Boxes Indicate the Change of the Parameter after Installing the Airfoil*

Table 3.1 Summary of Average High Turbulent Intensity Results around the Truck Calculated using the 10% < AHTI < Wake Flow Maximum

CONFIGURATION	Average High Turbulent Intensity (%)	Percent Increase (%) Compared to Base Conf.
NO AIRFOIL	12.34	*BASE CONFIGURATION*
MONROE_3D_MODEL	13.148	6.23
MONROE_2D MODEL	14.79	8.70 *(compared to 2D Model)*

Table 3.2 Summary of Recirculation Lengths (X_r) Found for the Base Configuration and Airfoil Configuration and Comparison with the Finding Cited from the Literature

Contribution	Xr (m)	Xr/Htruck
Base Model_RSM	3.7	1.24
Airfoil Model_RSM	4.24	1.43
Duel and George (1999) *EXP*	-	1.1
Krajnovic and Davidson (2003) *LES*	-	1.18

3.5.2 Implementation and test results

In order to provide information of the flow field behind the snowplow truck and validate the reliability of the computational solutions velocity inside the wake of the snowplow truck is measured. The measurements are performed on several locations for both the original truck configuration and the truck with Monroe Airfoil mounted on top of its sander (Fig. 3.15). Due to the unique nature of the application the in-house experimental apparatus is calibrated in laboratory environment (Appendix C) in order to validate the reliability of the velocity measurements (Fig. 3.16). In addition, environmental variables such as vibration of the truck structure; the magnitude and direction of the wind speed are also measured. Probe holders designed have high structural rigidity to withstand such vibration but still avoid imposing significant flow obstruction. In order to match with the boundary conditions imposed in the computational model the test are conducted on a straight road with minimum traffic density and geographical change. The west-east oriented portion of the Mt. Rose Highway which has approximately one mile length is chosen (Fig 3.17). The days of the experiments (i.e. November 2nd, 5th and 6th, 2007) scheduled based on the whether forecast where the wind speed is low. The daily wind speed reports indicate that the maximum wind speed was no more than 1 m/s during the experiments (weather.ktla.com) very similar to the wind speed measurements explained below. The tests are conducted while the truck is traveling with 45mph (20m/s) on the particular section of Mt. Rose Highway between two stations as indicated in Figure 3.17.

Overall, three dimensional computational models predict the velocity values inside the wake of the truck within the specified accuracy range based on formulation errors, accuracy error of the measurement transducers and errors associated to the mounting location and design of the measurement apparatus.

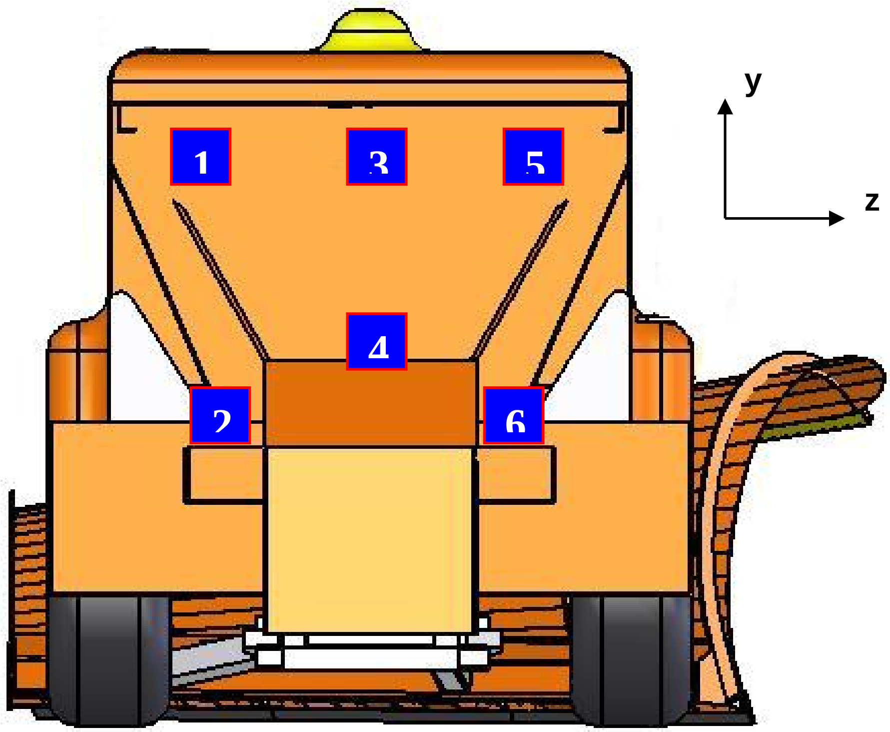


Figure 3.15 Measurement Points Located on the Backside of the Sander

Based on the 2-D results the determination was made to install the Monroe model and conduct field tests with an NDOT fleet snowplow early January 2007. One airfoil was installed to test if actual performance matches the theoretical modeling. Figure 3.18 show photos of the rear of a snowplow truck that was operating on Mt. Rose on January 2007. The photos were taken after the vehicle completed a snowplowing run and indicate the difference that the installed airfoil made.

From the pictures it is quite evident that the airfoil makes a dramatic improvement in reducing the snow buildup on the rear of the truck. It is the recommendation of the research team that NDOT continue to use the airfoils and look into the possibility of installing one on the entire fleet of snowplows. Future research will include the effectiveness of the double airfoil model and whether or not that is an option worth pursuing.

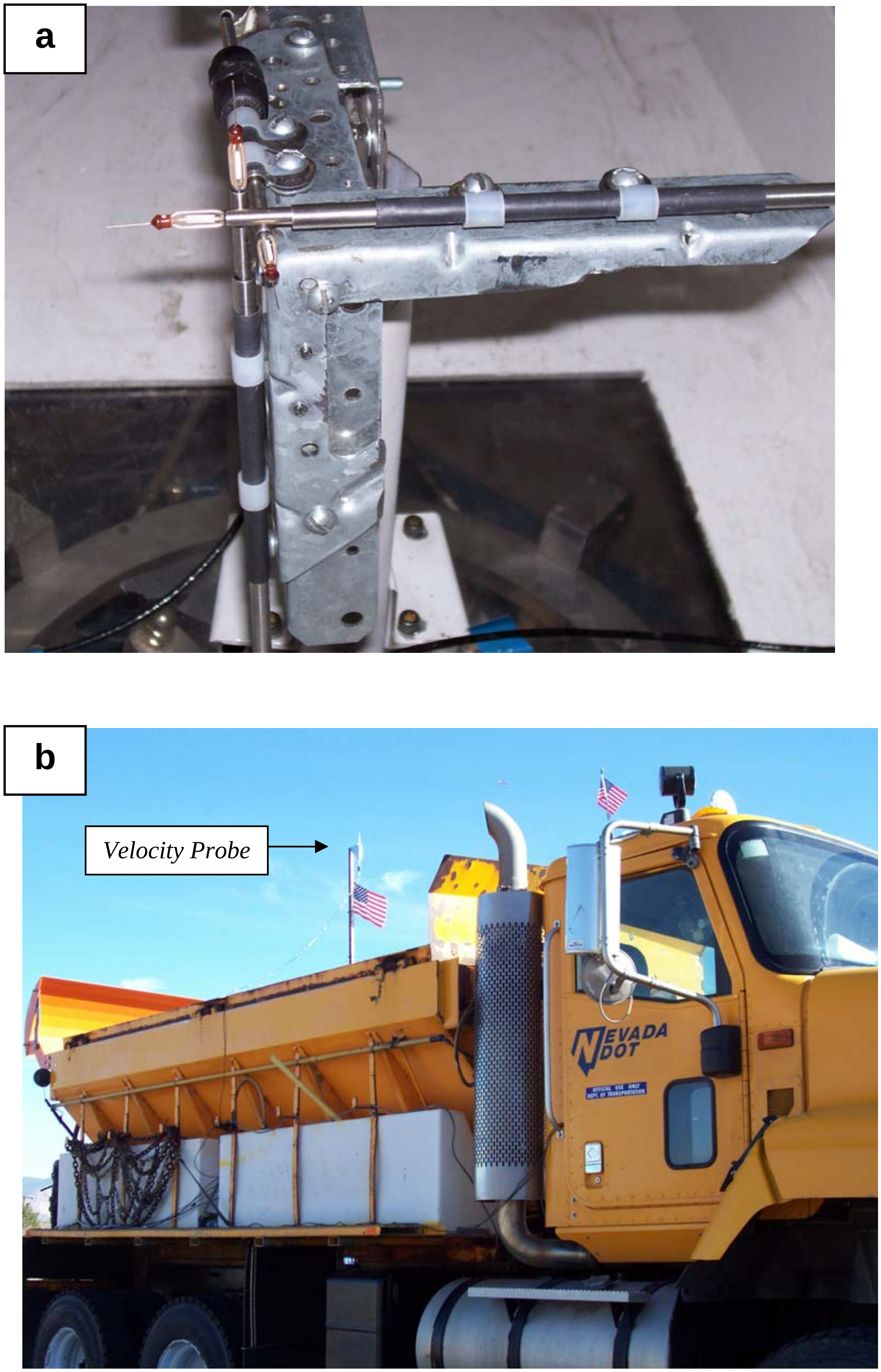


Figure 3.16 (a) Wind Tunnel Testing of Velocity Probes (b) Field Testing; Wind Speed and Direction Assessment - Two Flags and a Velocity Probe

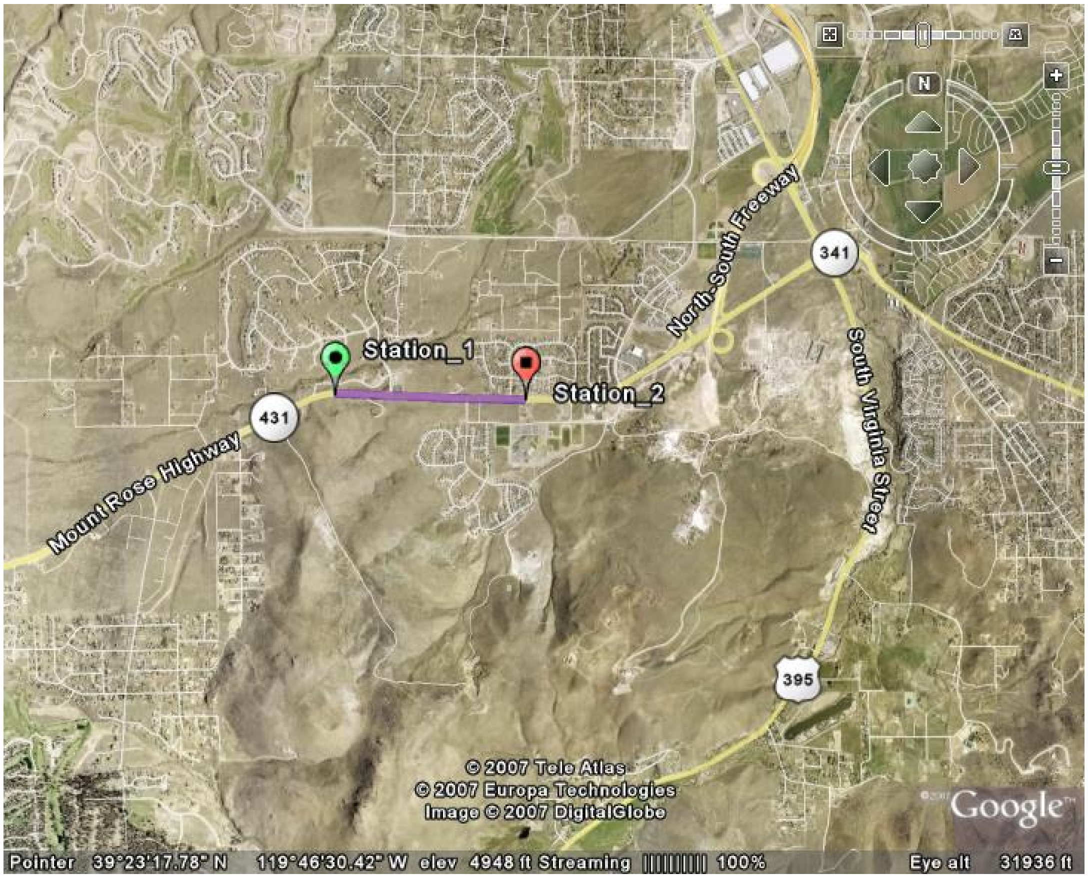
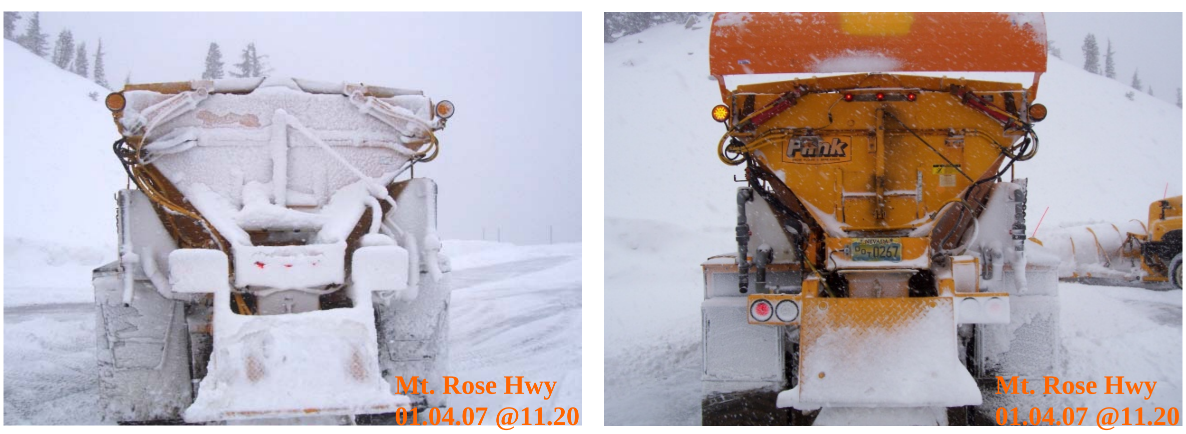


Figure 3.17 Field test route on the Mt. Rose Highway



(a) Without airfoil (b) With airfoil

Figure 3.18 Airfoil test run comparison, January 2007

3.6 Air Blower System

Research team considered the idea of high speed air to decrease the density of falling heavy snow to improve the truck driver's visibility. A test setup built uses commercially available centrifugal blower (20 HP) and inverter as major building blocks (Fig. 3.19). A flexible connector, directing the outflow via a venturi meter to the an air nozzle, facilitates the reciprocating motion of the nozzle. Figure 3.20 is a schematic graph presenting each part. Different shaped nozzles are made with respect to compare, and optimize the effectiveness and dynamic characteristics of the outflow air.

Figure 3.19 Air blower apparatus

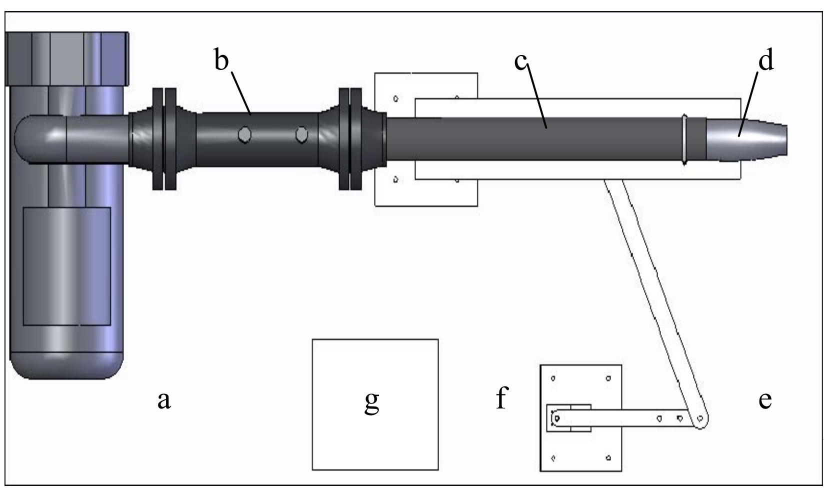


Figure 3.20 Schematic graph of blower system with reciprocating mechanism a. centrifugal blower, b. venture meter, c. air hose, d. nozzle, e. linkage, f. DC motor, g. Toshiba inverter. linkage, f. DC motor, g. Toshiba inverter

The test devices include air speed transducers, pressure sensors, differential pressure transducer, light meters, video camera and data acquisition system. The venturi meter and differential pressure transducer are applied to observe the flow-rate and air speed at the exit. Air speed transducers and pressure sensors are mounted at typical positions in the outflow area, where the critical parameters of air flow are to be measured. The end goal would be to determine if this air blower and nozzle system will be effective in clearing away enough snow in front of the snowplow to improve frontal visibility. The efficiency of the system is calculated in respect with the output air flow-rate, pressure and speed. At the motor speed of 3510 rpm, the efficiency is calculated as 44% ~ 56%. Figure 3.21 schematically shows the entire air test system.

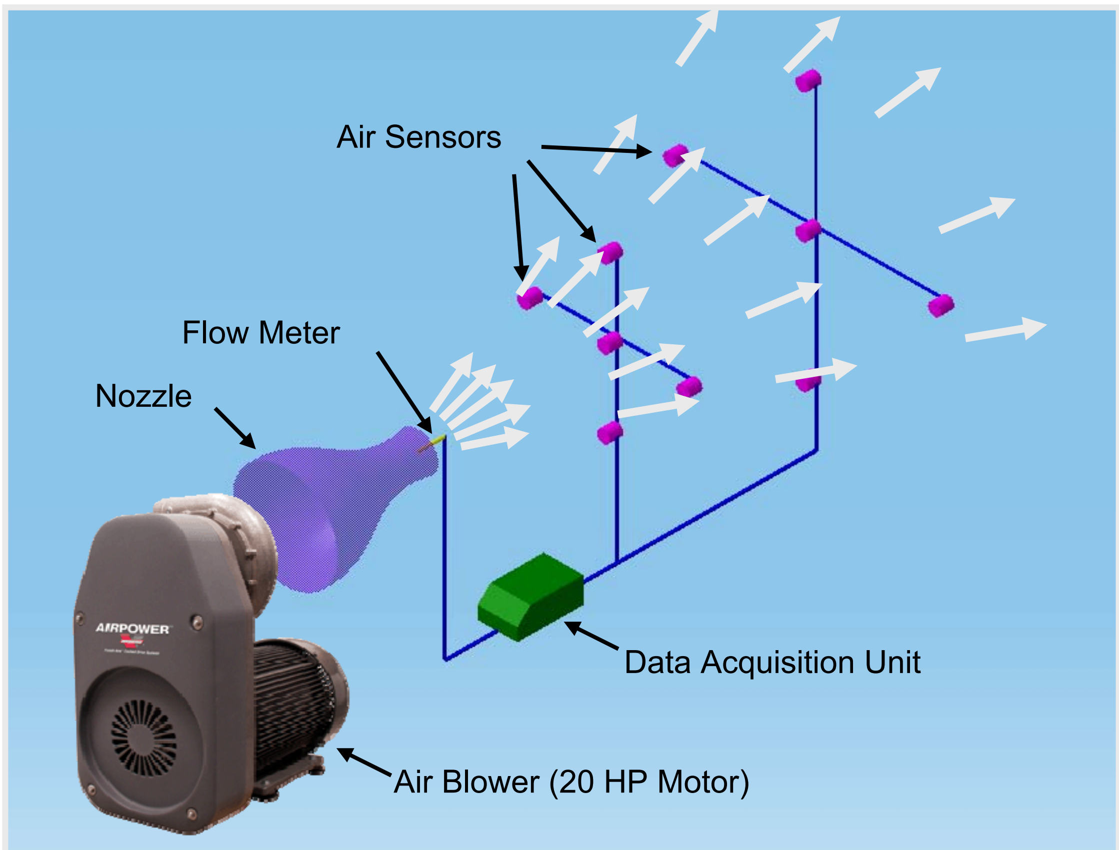


Figure 3.21 Air blower test setup

For the tests, 2 types of nozzles were used to observe the effect of nozzle shape on the improvements of air distribution in respect with speed and pressure. Figure 3.22 schematically shows two aluminum nozzles with the same circumference. Table 3.3 summarizes the flow characteristics of each nozzle.

Figure 3.23 is an experiment data plot, showing exponential decay of the velocity at the jet centerline with distance from the nozzle exit. The initial speed at round and ellipse exit is 130 m/s and 155 m/s, respectively. It decays quickly, though; the speed could still exert sufficient power by the distance of 5 meters. Moreover, the effect of nozzle shape on the speed improvement could be slightly identified on Figure 3.23. Since the ellipse has smaller cross section area, the outflow air possesses higher speed.

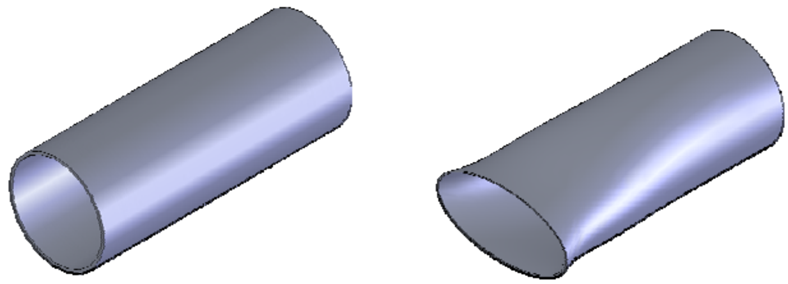


Figure 3.22 Nozzles with different exit crossections; a) Round nozzle with diameter of 3 in., b) Ellipse nozzle with major and minor axis of 3.8×1.9 in.

Table 3.3 Nozzle characteristics

Motor speed (rpm)	3510	
Input Power (HP)	20	
Nozzle Shape	Round	Ellipse
Initial Outflow Speed (m/s)	130	155
Volume Flow-rate (L/s)	583	556

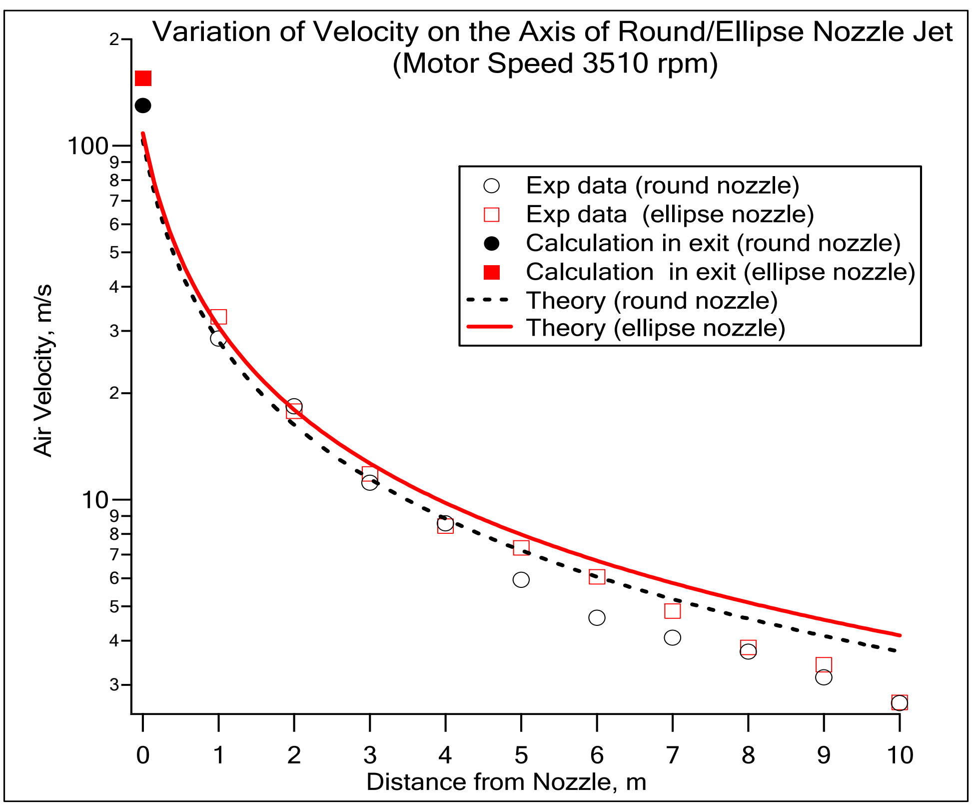


Figure 3.23 Jet velocity vs. distance, experiment and theory

Figure 3.24 indicates relative static pressures to the atmosphere at the air flow axis, in which the effect of nozzle can also be seen.

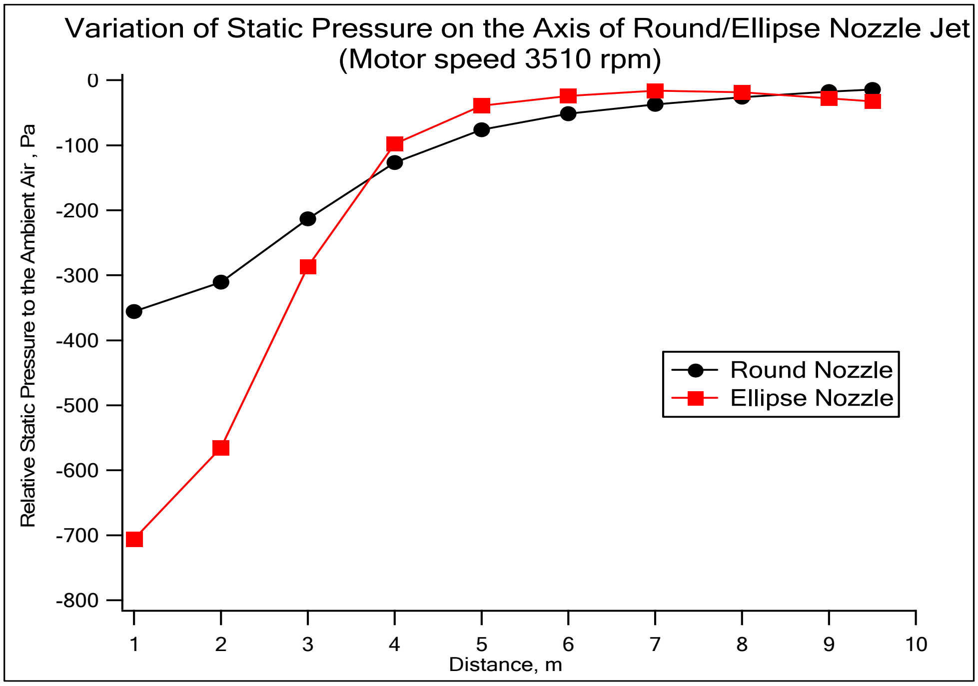


Figure 3.24 Pressure vs distance for each nozzle tested

Initial very preliminary test results show that the blower system may improve visibility of the driver (Fig. 3.25). The second phase of the research will includes additional tests of nozzle design and their performance. The goal is an optimum nozzle design that maximizes the air velocity at a given distance from the nozzle exit. The feasibility installing a similar system on a snowplow vehicle and conducting field tests. The plan is to observe the reaction of snow particles with a high speed camera to fully evaluate the effectiveness of the blower system.

Figure 3.25 Improvement of visibility with high speed blowing during a light snow storm. UNR parking lot. Blower was 8m from the truck blowing at 50 m/s

3.7 Lighting Configurations

Generally more warning lights are employed on snowplowing vehicles than for standard maintenance equipments. Common practices can be listed as flasher on the sander, strobes or rotating beacons on the top of the dump bed cab guard supplemented with retro-reflective markings or colored flags on different locations on the snowplow truck. The recent survey results indicate that several states agree on light emitting discharge (LED) lights for Brake/Tail/Turn lamps and flash lights (esp. amber color) for rear and body lighting. Agencies reported that LED lights provide less glare and greater visibility in snow clouds based on their higher directional luminance. However, their low heat discharge cited as an issue since they are unable to melt the snow packed on the lens. Most of the superintendents suggested LEDs to be incorporated with incandescents and also highlighted the need for other methods (i.e. tailgate deflector vanes) in order to guarantee the reliable use for the rear lighting. On the other hand, for the forward lighting, it is found that halogen lights are commonly employed because of their acceptable heat discharge characteristics. High intensity discharge (HID) lights are also pronounced based on their prominent increase in visibility but also result in a comparable increase in glare (Mace et al., 2001). In addition, methods suggested to prevent glare are painting the back of the plow and the hood flat black, lowering the truck lights or keeping front lights away from the hood as much as possible.

Bullough, et al. (2001) performed extensive studies to quantify and improve visibility based on the response of drivers during inclement weather. They highlighted the benefits of narrow-beam forward light sources mounted away from the driver's line of sight which can be retrofitted on snowplows by means of auxiliary headlamps with louvers. The group showed that narrow beam lights eliminate stray light which causes less back-scattered light and thus improve the subjective response of drivers. For the rear lightening of the snowplows, they acknowledge that the steady burning light bars enhances of drivers' ability to detect changes in plow's speed and provide an indication of its width. Bullough et al. (2001) further highlights the benefit of changing the spectrum of forward lighting to "warmer" or "yellowier" colors to reduce discomfort.

Based on the survey results and literature reviewed the rear lighting system suggested closely aligns with Idaho DOT winter maintenance vehicle shown in Figure 3.26.
1) LED - Brake/Tail/Turn lights - durable, high intensity at all directions
2) LED - Light bar at both sides of truck – provides conspicuity and indication of width of truck
3) Light bar at the top of sander - as a combination of LED, Halogen or Incandescent Strobe
4) Relay system - as automatic delay system for rear flashing lights

It is further advised that at least some of LEDs of the aforementioned light bar is set to the steady burning mode and the rest should be on quad/comet flash mode. As indicated before, steady burning light bars improve drivers' ability to detect changes in plow's speed and provide an indication of its width. Flashing or strobing lights provide high conspicuity and signal drivers that the plow is operating.

To conclude the forward lightening suggestions, it is found advisory to place the light sources farthest from the operator's line of sight and the hood/plow be painted in non-reflective colors (i.e. black, brown etc.) in order to prevent glare. The preference is given to narrow beam lamps (shielded headlamps, louvered or cut off type etc.) with sufficient heat discharge characteristics (incandescent, halogen) complemented with HID systems.

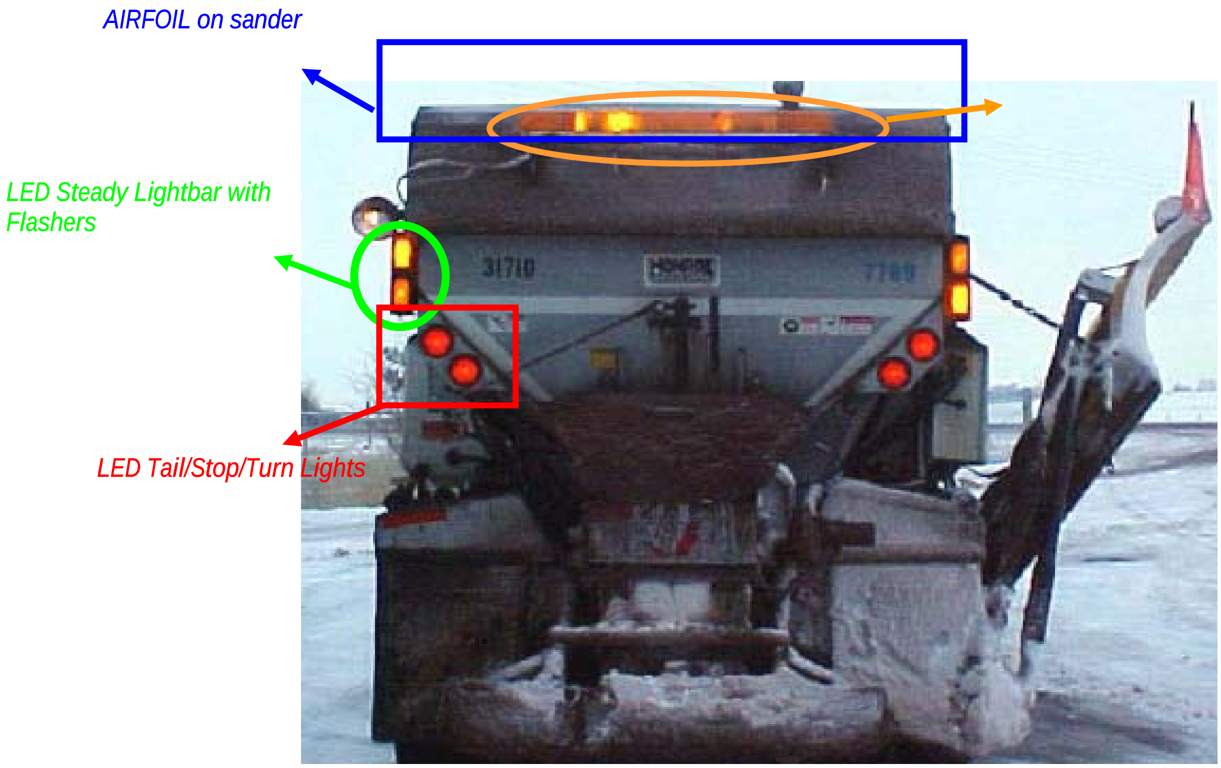


Figure 3.26 Idaho snowplow lightning configuration

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4.0 CONCLUSIONS AND RECOMMENDATIONS

GPS

GPS technology would be useful in fleet management and determining route efficiency of a fleet of vehicles. It would be possible to monitor the position of a multitude of snowplow trucks from a central location and observe delays or stoppages. However, for the purposes of reducing accidents, the capabilities still need to be developed to where the driver can obtain real time information about his position relative to the road. This implies high levels of accuracy in both the GPS receivers and the land survey data. Although Digital GPS may increase accuracy, it increases the initial investment drastically. It was decided not to pursue GPS/ DGPS technology at this stage.

Magnetic Sensing

This is a more realistic approach to detecting lane departure than GPS-based technology. Preliminary testing of this system by Caltrans has shown that the system is successful in its purpose. The major barrier however is the cost of implementing the system and amount of resources, manpower, and time required. This system could prove to be very useful, but it was too large and expensive in scope for this project.

Airfoil

The test runs using the airfoil selected based on computational study have shown a marked improvement in the visual clarity of the vehicles rear with the exception light accumulation on lower right lights. Different configurations, options will be considerd to keep these lights clear of snow as well during the next phase. Future research will also include the study of double airfoil and optimization to determine any extra benefit. The cost of modifying a vehicle with an airfoil is roughly $600 and expected to be very beneficial in preventing rear end collisions by motoring public.

Taillight Puffer System

The system in its currently configuration does not work as desired as a single system under heavy snow conditions. One option that will tested during the second stage is blocking one of its ports to increase the pressure to clear off heavy snow off one light. Air puffer will be also tested in combination with airfoil to clear the light snow left on lower right lights as described above.

Radar-based Collision Warning System

Although the model tested ended up as a failure for this project, there are other options. Radar detection is also worth pursuing because of its capabilities to “see” through snow and adverse weather when the driver can not. Another type of technology is a millimeter-wave radar that has proven effective in providing images through snow. Future research may include a feasibilty study of implementing this type of radar on a snowplow. Main disadvantage of this system is the initial investment required to apply it to the snowplow application.

Air Blower System

Limited initial laboratory testing indicated feasibility of the system to improve driver’s visbility during heavy snow fall conditions. Field testing for this system still needs to be conducted. Modeling of nozzle geometry and air flow has been successfully modeled and the next step would be to observe its capabilities while mounted on a snowplow. High speed cameras should also be able to show the response of snowflakes to the blower and can indicate the effectiveness of the blower.

5.0 APPENDICES

5.1 APPENDIX – Snow Plowing Applications Survey

The University of Nevada, Reno (UNR) research team conducted a survey by phone and via email on 24 Northern state Department of Transportations (DOT's). The goal was to gather information on the equipments, applications or lighting configurations used on trucks to improve visibility during snowplowing.

Initially the investigation consisted of phone conversations with Snow and Ice Coordinators, Maintenance Engineers and Equipment Superintendents responsible from each state's snowplowing operations, major treatments, and their priorities for effective visibility. After many phone interviews the survey was written. The UNR Visibility Survey focused on not only the lighting equipments but also various kinds of auxiliary equipments like airfoils at the top of sander, side vanes, snow deflectors, heated lenses/wipers, blowers to keep the ice/snow off the lights, and GPS/radar systems.

Phone conversations and responses via mail and email revealed that state DOT's test different lighting configurations and establish their own standards. Overall, several states agreed on LED's for Brake/Tail/Turn lamps and flash lights (esp. amber color) for rear and body lighting. When it came to the issue of front lighting, however, states were not in agreement. One of the major concerns identified was the location of the strobe/beacon at the top of the cab which happens to cause glare for the plow operator. As far as headlights concerned DOT's use halogens, HID, conventional incandescent headlights or LED's as additional front lights depending on their own field experience. Many states have also been experimenting mechanical solutions like attaching airfoils at the back of the sander body or mounting snow deflectors on the plow.

Concerning the completeness of the investigations, UNR Team contacted 24 state DOT's and finalized the survey based on 20 state responses which were received either by phone, email, snail mail or a combination of the three. Although many states returned a single survey filled by their DOT Headquarters, a few states preferred to submit papers from all of their individual districts (Kentucky and Colorado for example).

Overall, the UNR Visibility Survey serves as a valuable source of information which combines current applications of state DOT's and the inside knowledge of snow operation coordinators based on their visibility related experience. Moreover, evoking salutary collaboration with state DOT's and enabling more acquaintance with snowplowing applications, this survey will also aid UNR research team on their ongoing visibility related studies under the contract from the Nevada Department of Transportation (NDOT). Table A.1 given on the next page summarizes the survey results.

Table A.1 Summary of Survey Results

APPICATION/STATES	AK	CA	CO	ID	IL	IN	IA	KS	KY	MN	MO	MT	ND	NY	OH	OR	SD	VT	WA	WI	% of States Using
Wing Plows	X	X	X	X	NA	NA	X	X		X	X	X	X	X	NA	X	X	X	NA	X	**94**
LED Brake/Tail/Turn lights	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	**90**
LED Flashes/Strobes	X		X	X	X			X	X		X	X	X	X	X		X	X	X	X	**75**
Halogen Headlights	X		X	X	X		X	X	X	X	X	X		X		X		X		X	**70**
Strobes, top of truck	X	X		X	X	X		X	X	X		X			X		X			X	**60**
Belly or Under body plow	X	X		NA	NA	NA	X				X		X	X	NA	X			NA	X	**50**
Airfoil on the back of sander	X			X	NA	NA					X	X		X	NA		X		NA	X	**47***
Fog lights		X	X	NA	NA	NA				X		X		X	NA	X	X		NA		**44**
Super Reflective Tape, 3M				NA	NA	X	X		X	X					NA	X	X		X	X	**44**
Rotating Beacons		X		X			X				X			X		X			X	X	**40**
Lights away from the truck		X		X		NA	X						X		NA	X	X	X			**39**
Collusion system/GPS		X		NA	NA	NA	X						X	X	NA			X	NA	X	**38**
Deflector	X			NA	NA	NA	X		X						NA		X	X	NA	X	**38**
Elevated Rear Lighting					X	NA					X		X		NA		X				**22**
HID (high intensity discharge)			X								X									X	**15**
Air Blower, air blaster etc.				NA	NA	NA	X								NA				NA		**6**
Responded by Survey	shaded	shaded	shaded		shaded		shaded	shaded	shaded	shaded	shaded	shaded	shaded	shaded		shaded	shaded	shaded	shaded	shaded	
Responded by Phone			shaded	shaded	shaded	shaded	shaded	shaded	shaded				shaded	shaded	shaded	shaded	shaded	shaded		shaded	

NA: Not Applicable (i.e. no information received regarding this item either by phone or via email or snail mail)

The percentages for each application is calculated considering only the number of states responded for this application (i.e. excluding NAs)

*Based on the pictures received from Wyoming DOT, it is identified that this state also uses airfoils on the back of their sanders. Their contribution is included in the report although no response (survey return or phone call) is received from this state.

Our survey results indicate that there is no consensus on many issues and each state has different approach for improving the visibility of the truck and driver visibility. For example North Dakota suggested **amber** colored lenses to have best visibility during night time operation, while **white** having good illumination characteristics during day Whereas, Alaska claimed that **blue lights** were most visible in dark conditions. Kansas found it important to **mount identification lights as low as possible**, as did Iowa and Kentucky. North Dakota and South Dakota offer **mounting the lights as far as possible from the truck** to reduce glare for the operator. Moreover, they also employ **elevated lights** clear above the snow cloud at the back of the truck to deliver the tail signaling to the following public (Fig. A.1).

Figure A.1 North Dakota Warning Lights Positioned Away from the Dump Body

Oregon indicated the explaining that no **fog light** land/or position works well for all occasions. If mounted too low the fog lights get covered up with snow and ice and if mounted too high and they reflect back into the cab and blind the operator. Wisconsin reported that drivers are happy with the performance of **HID lights** but their price is a concern. Idaho developed **Alternating Flasher Delay System** to distinguish what the truck is trying to convey when activating a turn signal or brake light. Idaho reported that delay system automatically deactivates the alternating flashing lights when the trucks turn signal is activated or when the brakes are applied, thus allowing actions of the truck be more apparent to following public (Fig. A.2).

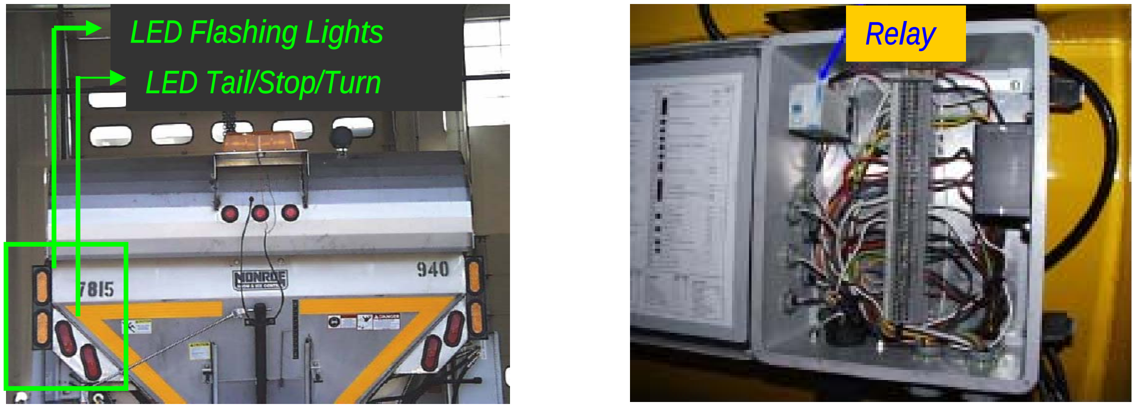
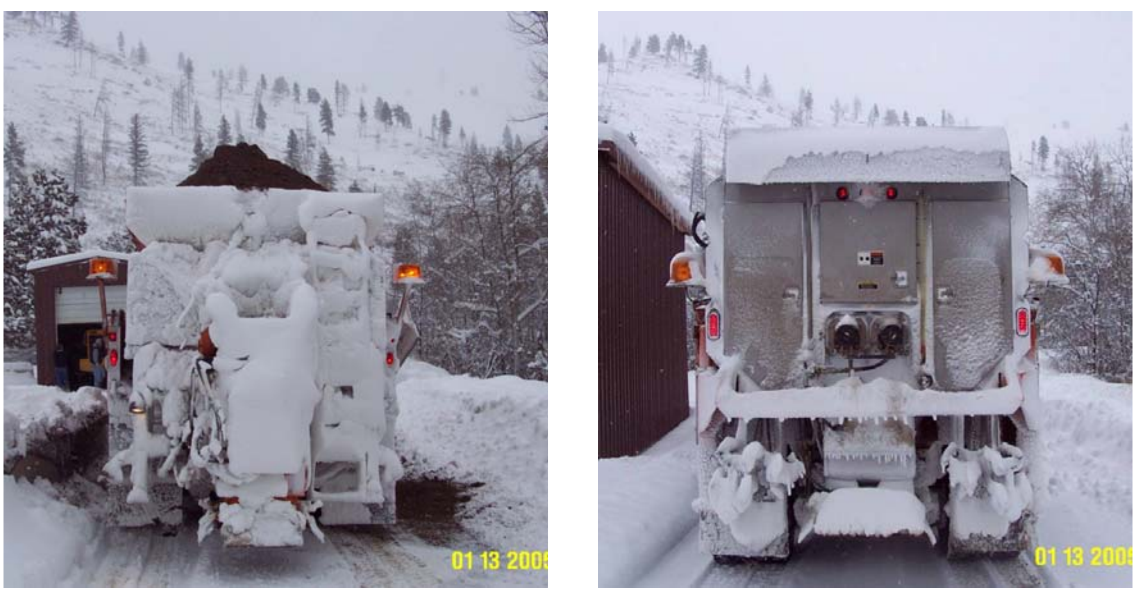


Figure A.2 Alternating flasher delay system

Finding out that a great majority of state DOT's were in favor of wing plows, the UNR research team looked further into the issue. Oregon had some information on problems they have had with the visibility of **wing plows,** the public tries to pass on right of plow truck and hits wing because it's not visible. Some of their solutions for this are **conspicuity tape**, they also tried **flashing LED's** and a **spot light** mounted behind the cab that directs light onto the wing when it's deployed.

Oregon and Iowa suggested always having a **rotating beacon** on every vehicle because this type of lighting gives a good indication of location, direction, and speed of the vehicle they are mounted on. Strobes and LED flashers don't do this as well, according to Oregon, in poor lighting (fog, snow flurries, twilight) this is especially evident. On the other hand, Idaho started mounting **self adjusting strobes** on the dump bed cab guard which provides Class I luminance in night time and Class II during night time. Missouri stated that using **upward lighting** of white lights to cause a halo glow over snow plow trucks maybe in the future for them. Vermont puts 'wax' on their LED's so to reduce snow coverage on lights. Washington claims that incandescent bulbs are best because they melt off the snow build up.

Many of the states are using alternate methods to decrease the amount of snow that can cover the lights. Iowa is implementing an air blower or "air puffer" with satisfactory results. Missouri is trying **air foils** above several front plows to try and catch the high snow and flow it **unde**r the front bumper. Montana, Idaho and Wyoming have already implemented a successful **airfoil** to direct the high velocity air down at the back of the sander to prevent snow build up on the rear lighting (Figs. A.3, A.4). South Dakota stated that when using airfoils, the vehicles need to be going fast enough to be effective and that the airfoil only works with the right kind of snow.



a) Without Airfoil　　　　　　　　b) With Airfoil

Figure A.3 Montana Airfoil field test

Figure A.4 Wyoming double airfoil mounted on top of the sander

South Dakota also indicated that they are using **snow deflectors** on some trucks and they are very effective. Wisconsin has some trucks equipped with front plow **"snow shields"** and/or rear air foils (Fig. A.5).

Figure A.5 Wisconsin Snow Shield

To increase driver visibility there were also many ideas and suggestions given. Idaho, Alaska, and Colorado agreed that **heated wipers are ineffective** in increasing driver visibility. Idaho concluded that the best way to increase driver visibility is invest in high quality lighting, such as halogen bulbs. Kentucky has been using **heated mirrors** for three years with good results.

For the problem of **backscattered light** Iowa listed a number of ways to decrease this effect. Iowa suggested that the snowplow headlights be mounted as far forward and low as possible. Iowa is also in the process of testing a snowplow headlight with optics that reduces upward distribution of light beam to reduce glare from falling/blowing snow. Kentucky suggested painting the back of the plow flat black to reduce the glare.

Minnesota, Iowa and New York have been widely using **underbelly plows** and finding them very effective to have down pressure resulting in better scraping of the pavement. Missouri is using a **TowPlows** that can clear 24' or more per truck/operator (Fig. A.6). The truck and TowPlow can replace three truck/operators.

Figure A.6 Missouri Gang Plowing with and without Towplow plowing 28' of Pavement

New York is using a piloting system called an **A**utomatic **V**ehicle **L**ocator on about 20 of their trucks. Vermont has fitted an SWS system that works on radar detectors on some of the plow trucks. Wisconsin has experimental GPS/radar systems on its concept vehicle.

List of people contacted for this survey is given in table A.2

Table A.2 List of all contacts

Colorado	Walter Black	(303) 512-5502	Walter.Black@dot.state.co.us
Idaho	Rex Hufford	(208) 334-8415	Rex.Hufford@itd.idaho.gov
Illinois	Timothy J. Peters	(217) 782-7234	peterstj@dot.il.gov
Indiana	Andy Dietrick	(317) 232-5503	adietrick@indot.in.gov
Iowa	Bradley Osborne	(515) 239-1556	bradley.osborne@dot.iowa.gov
Kansas	Rick Keefover	(785) 296-3661	rkeefover@ksdot.org
Kentucky	Chuck Knowles	(502) 564-3730	chuck.knowles@ky.gov
Michigan	Tim Croze	(517) 322-3394	crozet@michigan.gov
Minnesota	Norm L. Ashfeld	(651) 582-1437	norm.ashfeld@dot.state.mn.us
Missouri	Robert Lannert	(573) 751-5985	Robert.Lannert@modot.mo.gov
Montana	Jim Richman	(406) 444 6151	Jrichman@mt.gov
Nebraska	Dale Piening	(402) 479-4323	dpiening@dor.state.ne.us
North Dakota	Micheal J. Kisse	(701) 328-4410	mkisse@state.nd.us
New York	Rick Stowell	(315) 214-0291	rstowell@dot.state.ny.us
Ohio	Mack Braxton	(614) 752-8829	Mack.Braxton@dot.state.oh.us
Oregon	Greg Brown	(503) 986-2725	Gregory.A.BROWN@odot.state.or.us
South Dakota	John C. Forman	(605) 773-3704	john.forman@state.sd.us
Vermont	Kenneth Valentine	(802) 828-2564	ken.valentine@state.vt.us
Washington	John Ball	(206) 768-5822	balljo@wsdot.wa.gov
Wisconsin	Thomas Martinelli	(608) 266-3745	thomas.martinelli@dot.state.wi.us
Wyoming	Ron Koehn	(307) 777-4062	Ron.Koehn@dot.state.wy.us

5. 2 APPENDIX B - 3-D Computational fluid dynamics (CFD) model of the snow plow used

5.2.1 Modeling Methodology

Due to the asymmetry of the problem caused by the one-way plow in the front, the two dimensional model cannot represent the full characteristics of the flow domain. Moreover, because of the two dimensional formulation, it is not likely to capture the highly three dimensional turbulence phenomenon inside the wake flow completely. Considering these limitations and goal of monitoring the flow over the critical locations on the truck (such as snow accumulation on the taillights) the need for the three dimensional modeling becomes prevalent. The three dimensional modeling techniques are employed on both the base configuration (i.e. without any airfoil mounted) and the Monroe Airfoil configuration in order to gain more insight about the effect of sander mounted airfoil on the wake flow dynamics. Monroe Airfoil is selected based on its superior performance over Henderson Airfoil in clearing the truck rear surface off snow based on simpler 2-D model results. Special care is given towards preserving the physical dimensions as closely as possible to the real snowplow truck geometry without major simplifications (Fig B.1). The original plow and the hitch geometries are exported from the manufacturer technical drawings only with some minor manipulations (i.e. the moldboard mounting frame, piston cylinder assembly of the hitch, complex details of the hitch support frame/geometry and edge plate of the plow are discarded).

Figure B.1 Three Dimensional Model of Class-15 Truck and Henke-4806 One-way Plow with Monroe Airfoil Mounted on the Sander

5.2.2 Numerical Solution Settings

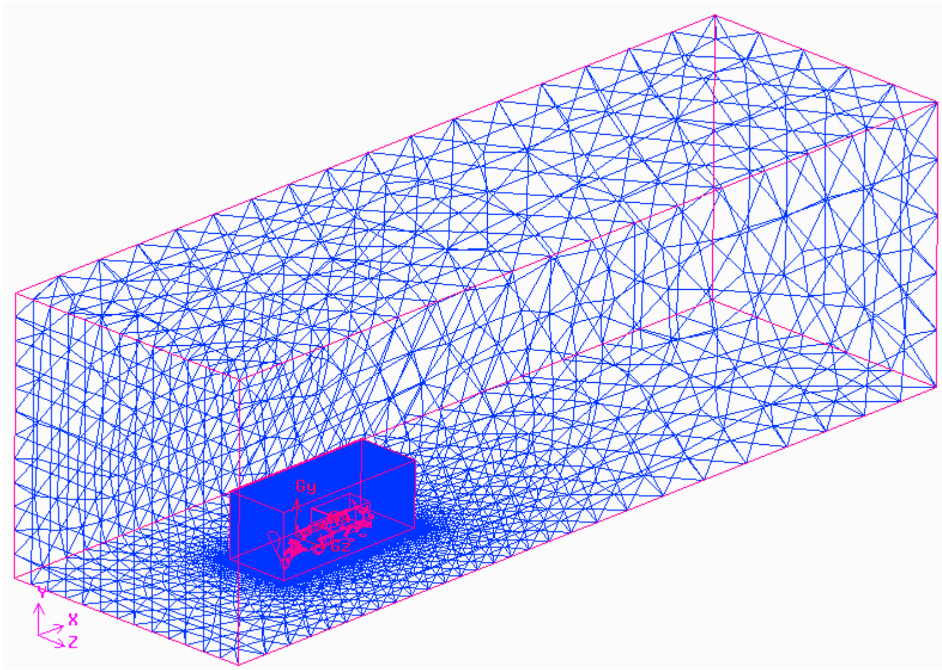
5.2.2.1 Grid Generation

The most laborious challenge of the three dimensional external airflow modeling problem appears during the preprocessing stages after importing the detailed 3D CAD model of the truck-plow assembly to GAMBIT. Based on the CAD interoperability problems (i.e. missing parts, lack of connectivity, integrity, invalid definition of vertices or edges) the grid generation can not be initiated without cleaning up these 'dirty' geometries around the detailed surface contours of the model. After obtaining a defect-free geometry the computational domain is created around it (i.e. a rectangular prism with L= 26.94 H_{truck} x H= 8.42 H_{truck} x W= 8.42 H_{truck}). The domain surrounding the truck and plow is separated from the outer portions in order to ease the high quality near-body mesh generation with adequate gradual refinement or coarsening throughout the computational domain. However, the inner subdomain is created relatively larger in length (15m ≈ 5 H_{truck}) compared to that of the two dimensional model (10m ≈3.4 H_{truck}) in order to increase the flow refinement around the truck. In addition, the truck geometry is positioned relatively further away from the inlet (i.e. fifteen meters ≈5 H_{truck} , double the upstream length of the 2-D model) letting a longer upstream region for the inlet plug flow to develop.

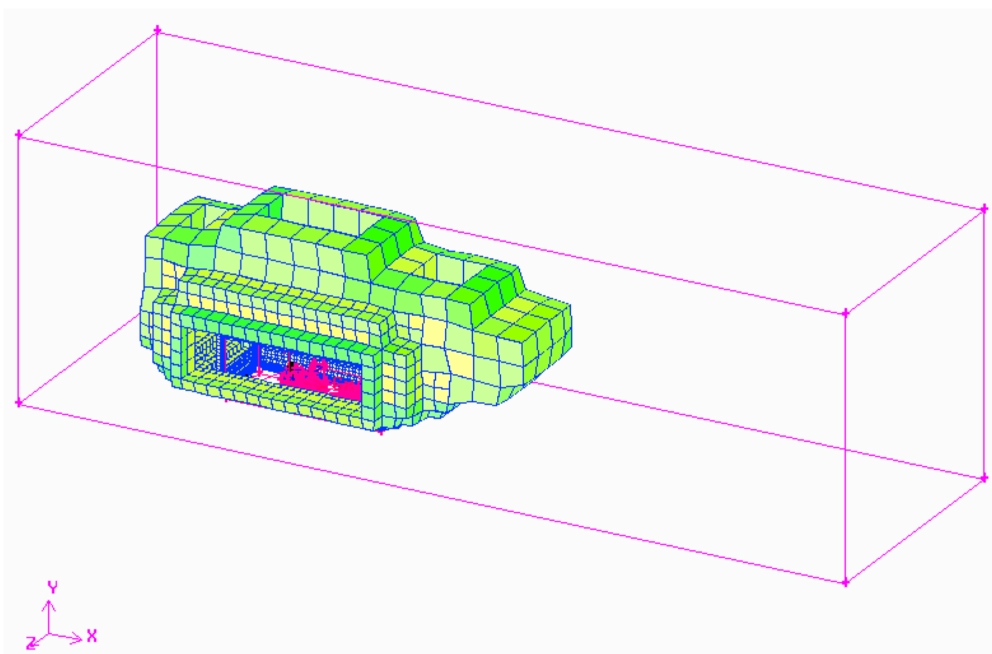
Tetragonal elements are used to generate a high-quality mesh inside the whole computational domain of the base configuration (Fig B.2-a) as well as the inner subdomain the Monroe Airfoil configuration. The outer subdomain of Monroe Model is meshed with the more laborious but equally more efficient 'Hex Core' meshing scheme of GAMBIT which produces a core of uniformly sized hexahedral elements surrounded by pyramidal and/or tetrahedral elements (Fig B.2-b). Both grids have very similar resolution. The grid parameters are summarized in Table B.1.

Table B.1 Grid Parameters

	Element Count		
CONFIGURATION	**Inner SubDom.**	**Outer SubDom.**	**TOTAL**
NO AIRFOIL	3313346	1019114	**4332460**
MONROE_ORIGINAL	4112072	488160	**4600232**



(a) Tetragonal Mesh on the Outer Domain of the Base Model



(b) Hex-Core Mesh on the Outer Domain of the Monroe Airfoil Model

Figure B.2 Three Dimensional meshing of computational domain

5.2.2.2 Solver Settings and Boundary Conditions

The solver settings of the three dimensional calculations are kept same as the ones used for the two dimensional formulization. In summary, steady-state implicit pressure based-solver of FLUENT version 6.3.26 is used with second order discretization of the convective terms, pressure, turbulent kinetic energy and dissipation rate in the governing equations. Mass conservation and pressure field correction is obtained by means of the SIMPLE algorithm. The turbulence is modeled by the Reynolds Stress Model (RSM) which solves seven transport equations in addition to the Reynolds Averaged Navier-Strokes (RANS) Equations. The convergence of the solutions is assured by the reduction of the scaled residuals of continuity equation at least by six order of magnitudes while gaining an additional level of confidence by monitoring the convergence of the velocity-pressure values at the designated points of the flow domain (such as near wake region, airfoil jet, downstream). Better accuracy and faster convergence is achieved by solving the flow fields with a lower order of accuracy scheme and setting this as the initial condition of the higher order one.

To overcome the problems (such as hanging nodes and overlapping parent-child faces at the hexagonal to tetragonal transition zones) caused during the grid partitioning of the hex-core mesh, the hexagonal cells are converted into polyhedron using *tpoly* utility tool (by Fluent Inc.). Simulations performed on the aforementioned parallel Windows cluster of 8 Xeon Processors took approximately 120 hours to obtain a 2^{nd} Order accurate converged steady flow where the turbulence is modeled with 1^{st} order RSM scheme.

Inlet and outlet boundary conditions were applied approximately five truck height upstream and nineteen truck height downstream from the truck, respectively. The free-stream boundary condition was applied at twenty five meters (≈8.4 H_{truck}) vertically away from the road surface and also on the side walls of the computational domain. Velocity on the inlet and the free-stream boundaries are assigned as 20 m/s which corresponds to a Reynolds number based on the truck height, Re_H equal to $4x10^6$. The downstream condition is set as standard pressure outlet with zero gage pressure and moving wall boundary condition is used for the bottom wall matching the speed assigned to the inlet boundary. Summary of the boundary conditions are shown in Figure B.3.

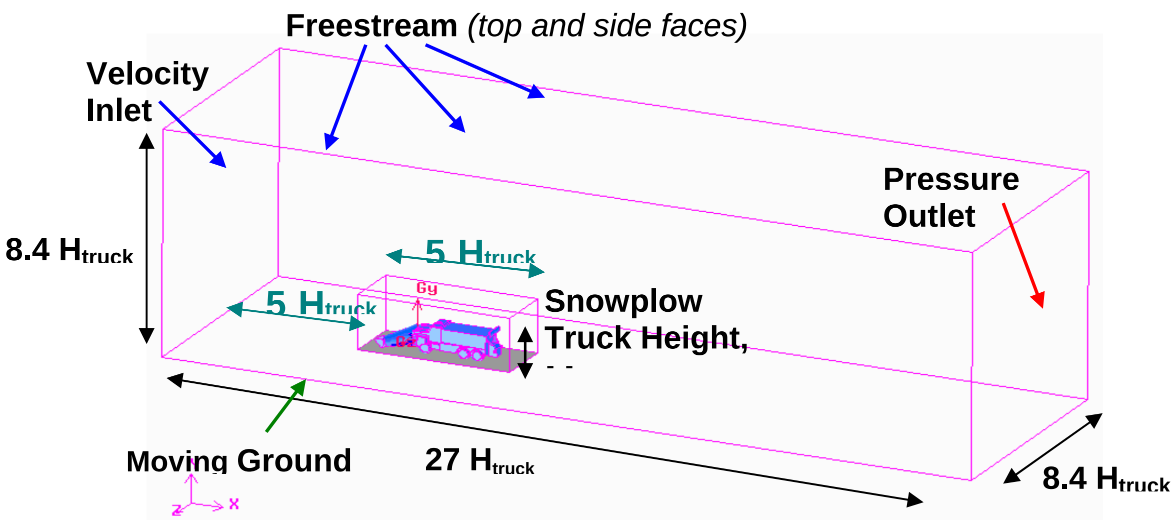


Figure B.3. Boundary conditions applied on the computational domain

5.3 APPENDIX C - Calibration of the Velocity Probes

The TSI Model 8465 Thermal Anemometer (Fig C.1) is used to measure the average flow speed normal to the wire axis. Similar to the well known character of the hot wire probes (Acrivlellis, 1980), the output voltage of thermal anemometry probes is very sensitive to angular deviations of the flow direction from the wire normal. Therefore, in addition to the requirement of using at least three sensors a non-orthogonal algorithm (Hinze *et al*. 1975) is need to determine the directional dependence of the thermal anemometers and in turn three velocity components. The effective cooling velocity, U_{eff} which represents the directional response of the thermal anemometer wire is given as a function of the velocity component normal to the wire axis (i.e. U_n), the tangential velocity component (i.e. U_t) and the yaw angle sensitivity coefficient, k in the following equation.

$$U_{eff} = \sqrt{U_n^2 + k^2 \cdot U_t^2} \qquad \text{C.1}$$

This relationship given for a single transducer (Eqn C.1) can be extended to the integrated three orthogonal thermal anemometers (Fig. C.2) which will be referred as Velocity Measurement Apparatus. The yaw angle sensitivity coefficient is found by the yaw angle variation experimentations conducted in the wind tunnel. USB 6009 National Instruments Data Acquisition Board (NI-DAQ) is used to sample the data using the VI Logger software of National Instruments.

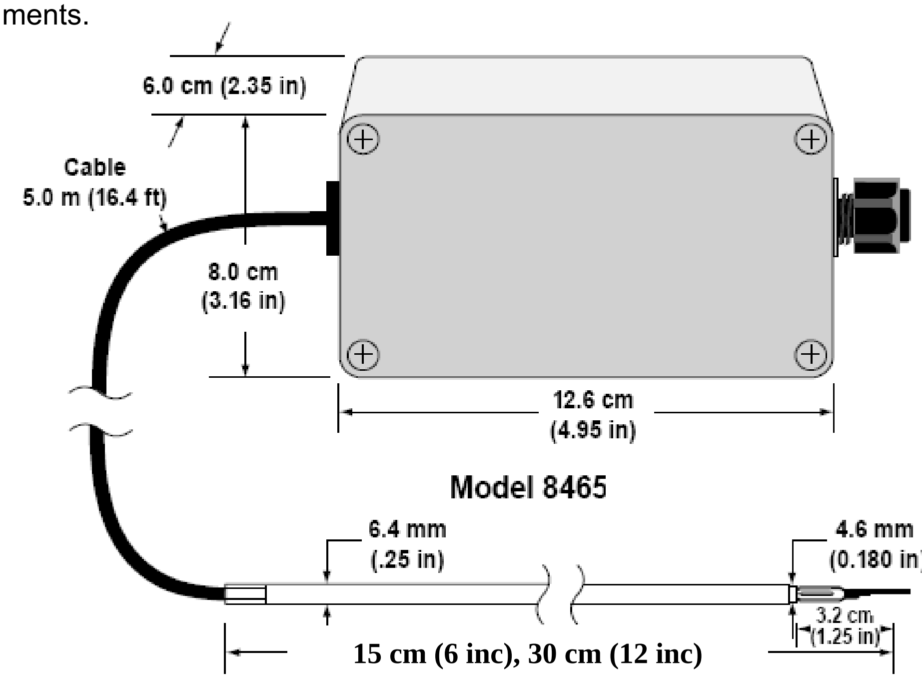


Figure C. 1 TSI Thermal anemometry transducer model 8465

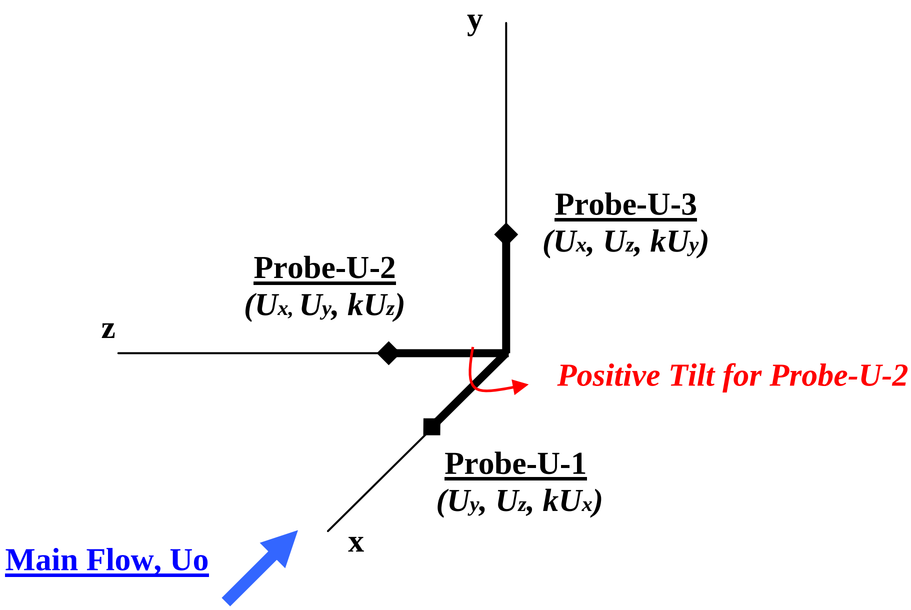


Figure C. 2 Schematic of the probe orientations on the X-Y-Z axes with their effective cooling velocity response given as a function of the velocity components

The total magnitude of the flow facing the Velocity Measurement Apparatus (VMA) can be found using the Equations C.2-5 given below.

$$U_x = \sqrt{(U3^2_{eff-y} + U2^2_{eff-z} - (1+k^2)\cdot U1^2_{eff-x}) \big/ (2-k^2-k^4)} \quad \text{..........................C.2}$$

$$U_y = \sqrt{(U2^2_{eff-z} + U1^2_{eff-x} - (1+k^2)\cdot U3^2_{eff-y}) \big/ (2-k^2-k^4)} \quad \text{........................C.3}$$

$$U_z = \sqrt{(U1^2_{eff-x} + U3^2_{eff-y} - (1+k^2)\cdot U2^2_{eff-z}) \big/ (2-k^2-k^4)} \quad \text{........................C.4}$$

$$U_o = \sqrt{U_x^2 + U_y^2 + U_z^2} \quad \text{..C.5}$$

Computational studies predict that the speed inside the wake flow ranges between 0-16 m/s. The yaw angle inclination experiments are performed for three different velocity magnitudes; $U_{W-T-1} \approx 5$ m/s (U_{W-T-i} interprets i^{th} wind tunnel speed), $U_{W-T-2} \approx 10$ m/s and $U_{W-T-3} \approx 15$ m/s in order to investigate this dependence and determine a single constant k value for the velocity range investigated. The yaw angle variation experiments shows the directional response of the positively tilted Probe_U-2 and Probe_U-1 by comparison with the Probe_U-3 measurements which remains normal to the main flow throughout the experiment.

In order to find the yaw inclination sensitivity coefficient, k two different regression approaches are followed. First the nonlinear least squares fit method (NLSFM) is applied to the directional response data of the positively tilted Probe-U-2 using the effective cooling velocity algorithm to find an optimized representation for the response of this probe. Among optimized-k values presented in Table C.1, k_opt-**U-2** = 0.231 yielded the best results matching the directional response of the positively tilted Probe-U-2 with an average overall error of seven percent.

Table C. 1 Optimization of the yaw angle sensitivity coefficient, k by non-linear least squares fit method applied to the effective cooling response of the tilted probe-U-2

Optimization of the Effective Cooling Formulation for Single Probe Reading			
Flow Speed	$U_{W-T-1} \approx$ 5m/s	$U_{W-T-2} \approx$ 10m/s	$U_{W-T-3} \approx$ 20m/s
Kopt-U-2	0.208	0.231	0.306

As a second approach, the non-linear regression method is applied in order to minimize the sum of offset errors between the total velocity magnitudes calculated using the flow data acquired with the VMA and the velocity measured by probe U3 perpendicular to flow for each yaw angle. This method provides a more comprehensive optimization since it does not only focus on the error between the effective cooling algorithm and the response of the inclined probes but also on the experimental errors caused by the mismatching measurement locations of the probes, flow disturbance and the obstruction caused by the support brackets and any unforeseen thermal interference between the probes during the yaw angle inclination. The results (Table C.2) shows that the smallest average percent error appear when k_{opt} = 0.337. In general, the maximum deviation from the test velocity appears at the highest flow speed, $U_{W-T-3} \approx$ 15 m/s calculated as 6.7 percent for k_{opt} = 0.337 . The maximum deviations from the actual flow velocity are observed between the yaw angles 40°-50° degrees.

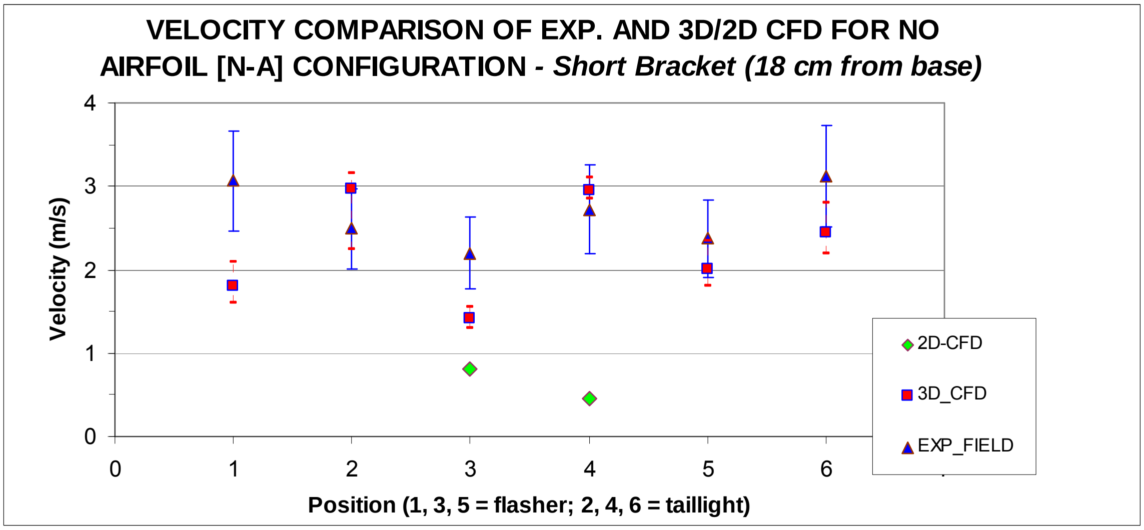
Table C. 2 Summary of the Error Analysis Comparing Different Formulations for Each Optimized the Yaw Angle Sensitivity Coefficients, k with the Known Flow Velocity

THE PERCENT ERROR OF THE FORMULATIONS FOR EACH K VALUE								
OPT. YAW ANGLE SENS. COEF.	UW-T-1 ≈ 5 m/s		UW-T-2 ≈ 10 m/s		UW-T-3 ≈ 15 m/s		OVERALL ACCURACY	
	$Error_{max}$	$Error_{avg}$	$Error_{max}$	$Error_{avg}$	$Error_{max}$	$Error_{avg}$	$Error_{max}$	$Error_{avg}$
$K_{opt\ @5\ m/s}$ = 0.562	-	-	-	-	-	-	-	-
$K_{opt@10\ m/s}$ = 0.337	1.8	0.35	4.2	1.5	6.7	3.1	4.3	1.7
$K_{opt@15\ m/s}$ = 0.257	1.4	0.88	3.7	1.7	7.9	3.8	4.0	2.1
K_{opt-U_2} = 0.231	1.7	1.2	2.7	1.8	8.3	4.1	4.2	2.4

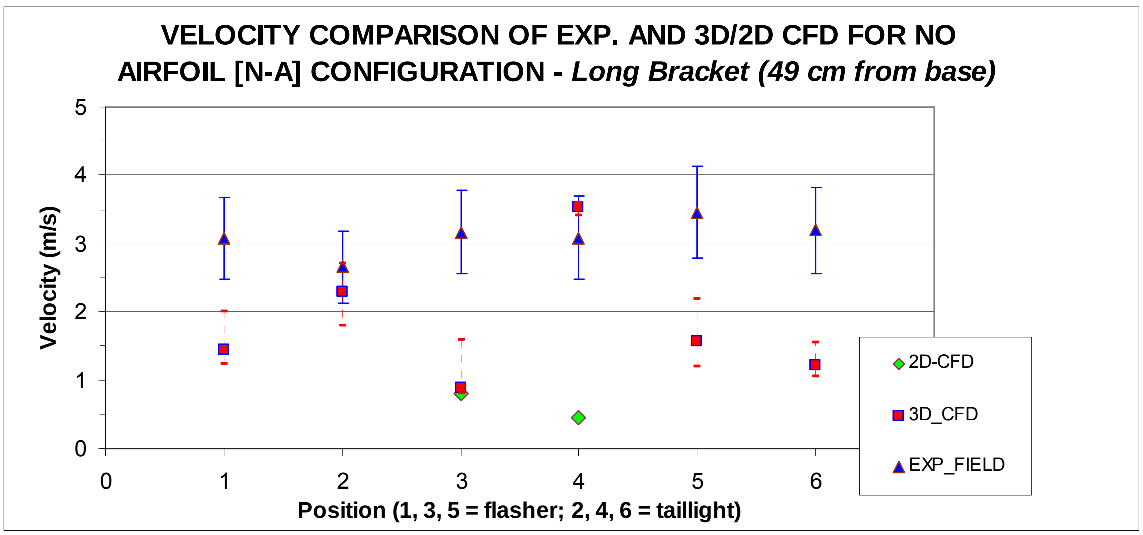
5.4 APPENDIX D - Comparison of the Measurements with the CFD Predictions

In order to evaluate the accuracy of the flow variables (velocity, pressure) predicted by the computational models inside the separation bubble quantitatively the field test measurements are compared with the flow variables calculated around the measurement points. The comparison of the velocity magnitudes is presented in Figure D.1 and Figure D.2 for the Base Configuration (no airfoil mounted) and the Airfoil Configuration respectively. The error bars for the experimental data is calculated combining the maximum error of the effective cooling velocity formulation (E_{max-F} = 6.7 %) found based on the data acquired from the wind tunnel calibrations tests and the accuracy error specified for each thermal anemometer ($E_{max-TA@10m/s} \approx$ 5 % for U~10 m/s and $E_{max-TA@3m/s} \approx$ 12 % for U~3 m/s). Hence, the total experimental error is specified as $E_{total@10m/s}$ = 12.6 % of the calculated value for U~10 m/s which is the typical average speed observed for the airfoil configuration. Likewise, the total error for the velocity measurements taken behind the truck without the airfoil is calculated as $E_{total@3m/s}$ = 19.5 %. The comparison of the experimental data with the velocity values extracted from the individual locations of the computational domain does not provide an adequate overall evaluation due to the design of the measurement equipment (i.e. the measurements probes attached 3.81 cm away from each other on the VMA). In other words WMA performs measurements inside a half square cube instead of on a measurement point. Moreover, although not being linked to the accuracy of the computational model, the errors associated with the assessment of the measurement points on the truck base will further decrease the agreement of the computational results with the experimental data especially around the areas with the high velocity gradients (around the high velocity jet directed down by the airfoil). Therefore, the computational results calculated at the measurement point are extended to the velocity ranges by scanning the area around the each measurement points in all directions. The error bars specified for each computational data represents the minimum and maximum values of the velocity magnitude calculated inside a sphere with 5 cm radius around the measurement point.

The comparison shows that velocity values measured at three out of six locations inside near wake (SB - 19 cm away from the truck base) of the airfoil configuration agree with the velocity predictions of the three dimensional computational model for the concerning configuration (Fig 4.13-a). For the far wake (LB - 55 cm away from the truck base) all of the predictions agree with the field measurements within the specified error range (Fig 4.13-b). Hence, the airfoil model predicted the velocity inside the wake with 75% success rate. On the other hand, four out of six the near wake measurements of the base configuration agree with the results of the computational model. Whereas, the three dimensional computational model of the base configuration shows the poorest performance (33% success rate) when it comes to the prediction of the velocity values for the far wake zone. As a general trend, the velocity predictions by the computational model of the base configuration appears smaller than the values measured during the field test unlike the predictions of the airfoil model which are generally higher than the measured data. The highest percent error of the computational results is found as 42% of the experimental data acquired at the upper midplane (measurement point, P-3) of the truck on the far wake of the base configuration. The maximum error of the airfoil model estimated as 13% of the measured value which is also found at the same location (P-3) in the near wake of the truck.

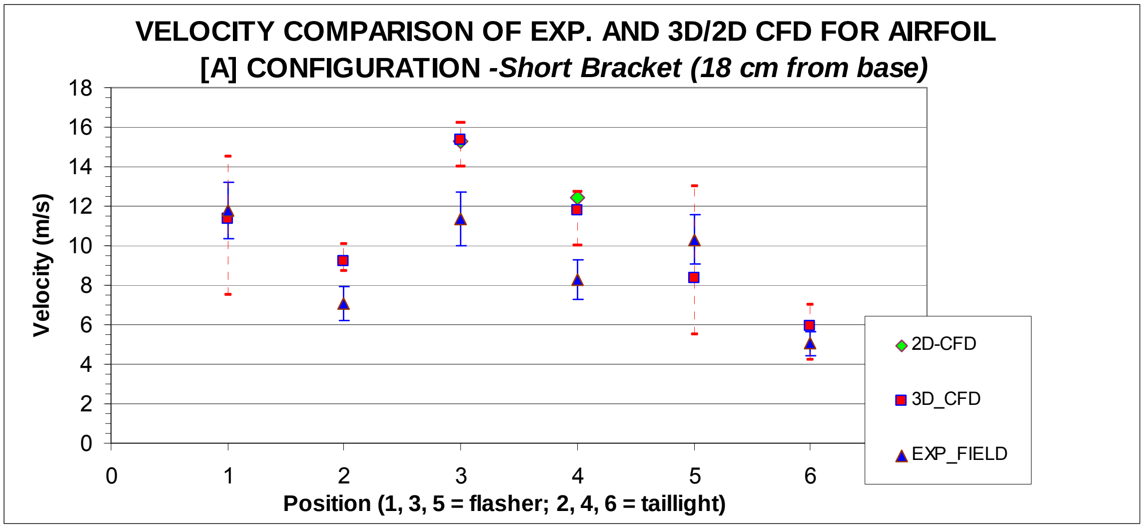


(a) Velocity Comparison of the Base Model for the Near Wake Zone - 18 cm from base

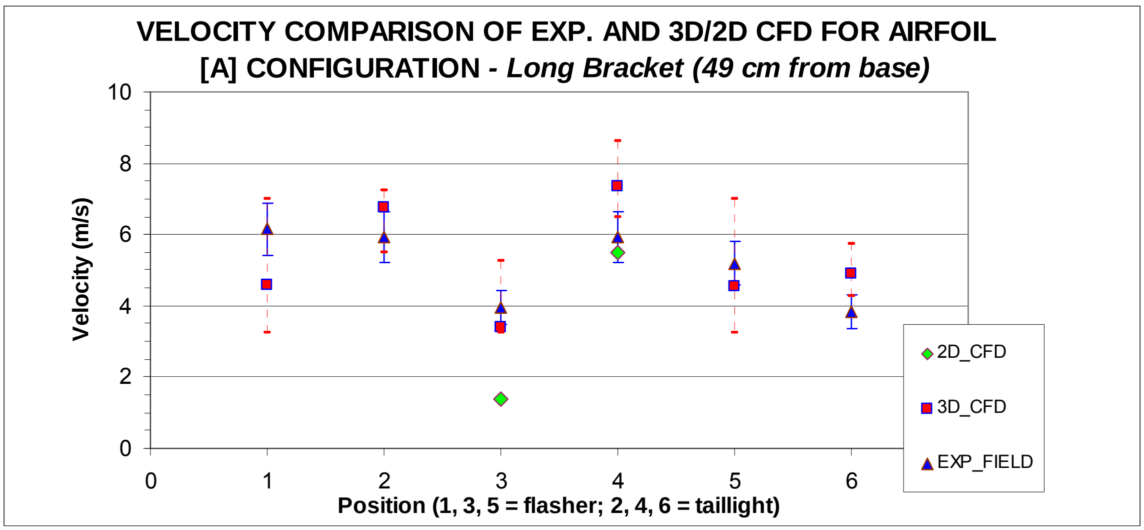


(b) Velocity Comparison of the Base Model for the Far Wake Zone – 49 cm from base

Figure D.1. Comparison of the velocity field test results with 2D/3D CFD predictions by the Model Generated for the Base Configuration at the Measurement Points *(Positions shown in the X-axis indicate the Locations of the Measurement Points i.e. 1-3-5 are Close to the Upper Edge of the Truck Base Near the Flasher Lights and 2-4-6 are Close to the Lower Edge of the Truck Base Near the Taillights)*



(a) Velocity Comparison of the Airfoil Model for the Near Wake Zone - 18 cm from base



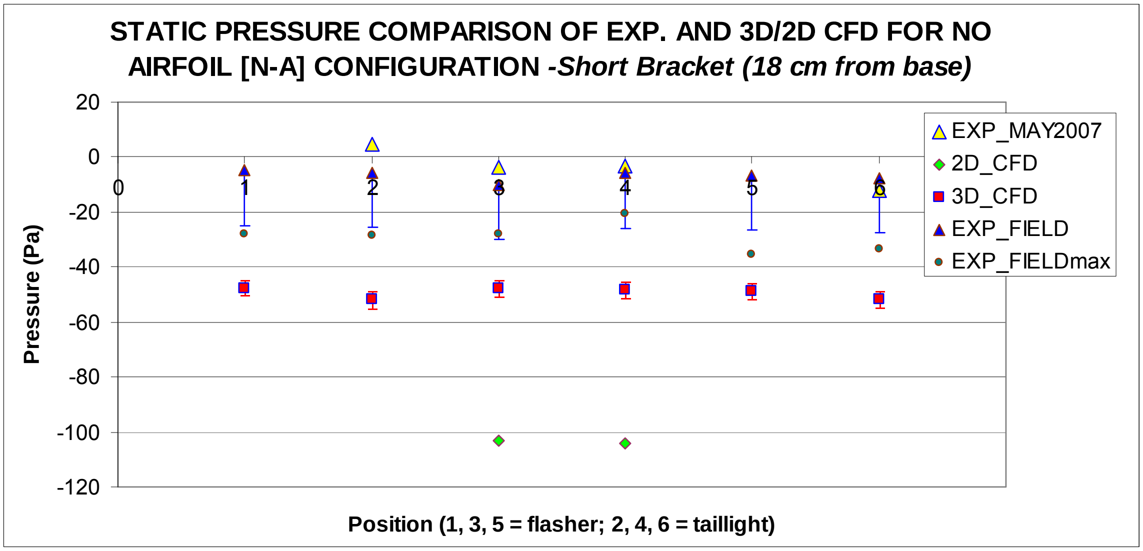
(b) Velocity Comparison of the Airfoil Model for the Far Wake Zone - 49 cm from base

Figure D.2 Comparison of the velocity field test results with 2D/3D CFD predictions by the Model Generated for the Airfoil Configuration at the Measurement Points *(Positions shown in the X-axis indicate the Locations of the Measurement Points i.e. 1-3-5 are Close to the Upper Edge of the Truck Base Near the Flasher Lights and 2-4-6 are Close to the Lower Edge of the Truck Base Near the Taillights)*

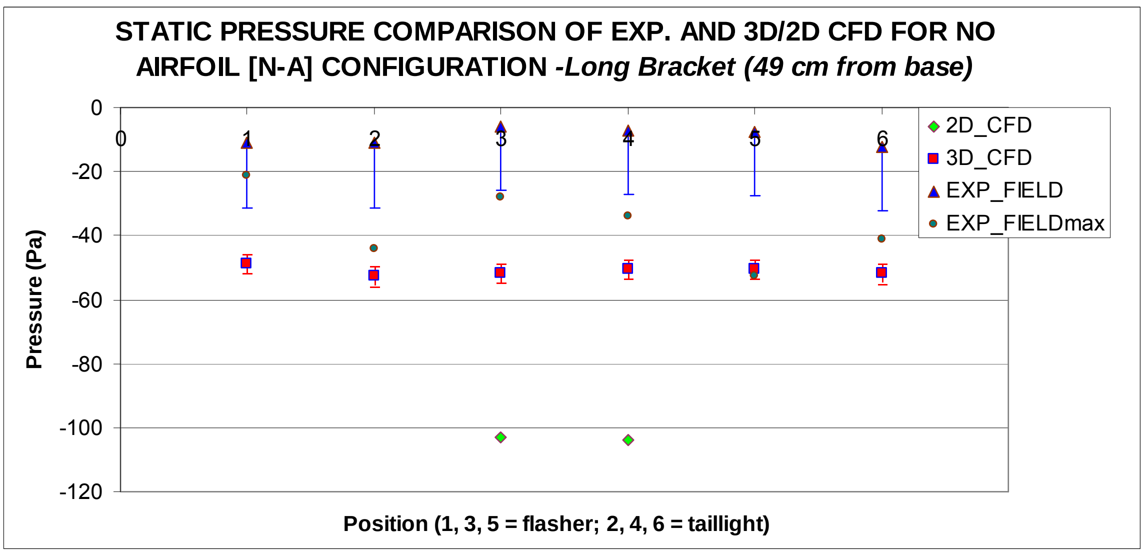
Overall, three dimensional computational models showed 63% success rate to predict the velocity values inside the wake of the truck within the specified accuracy range based on formulation errors, accuracy error of the measurement transducers and errors associated to the mounting location and design of the measurement apparatus. The velocity values calculated around the flasher lights (designated with numbers 1, 3, 5) appear to have highest divergence (5 out of 6 locations for the base configuration) from the experimental values measured at the same locations. This might be attributed to the insufficient accuracy on the prediction of the upper vertical horseshoe vertex and the reattachment on the rearside of the truck. Moreover, there is a considerable discrepancy at the calculations performed on the midplane (on x-y coordinates) of the truck which would possibly be related to the simplifications employed on complicated sand spreader geometry and the flow complication caused by the motion of spinner inside the spreader which is not modeled either.

Concerning the two dimensional model based on the two measurement points located in plane, very limited quantitative information could be acquired. Figures D.1b show that only 2 out of 8 data points are aligned well (within 5% error) with results of the three dimensional calculations at the same measurement points. Moreover, only 1 out of 8 data points agreed with the experimental results. Such a high inconsistency can be related with the highly three dimensional nature of the turbulence phenomenon, the asymmetry of the flow field due to the one way plow and the aforementioned complication based by the simplified spreader geometry.

Based on the poor accuracy of the pressure transducers in the low pressure range and also poor directional response of the static pressure probes, the pressure measurements performed in the suction zone behind the base of the truck are not considered to be reliable. Since the measured pressure values (-20Pa to -100Pa for base configuration) and the associated errors (12Pa; fixed error of the transducer + 40% of the reading; due to directional response of the probe) are in the same order of magnitude considerable portion of the fluctuations from the mean pressure value went out of the measurement range (i.e. moved to the positive pressure). Therefore, the pressure data acquired with available equipment does not represent the actual pressure field with acceptable accuracy. Following the same method explained for the velocity comparison, the pressure data acquired on the field and the pressure data calculated with the computational models are compared in Figure D.3 and Figure D.4 for the Base Configuration (no airfoil mounted) and the Airfoil Configuration respectively. A fixed error range of -20 Pa and -30 Pa is used to represent the discrepancy in the measured pressure data for near wake and far wake regions respectively. However, there is still an unperceivable error margin between the measurement and the CFD data (around 70% of the measurement value) which indicates that the error assigned for the pressure measurements is clearly underestimated.

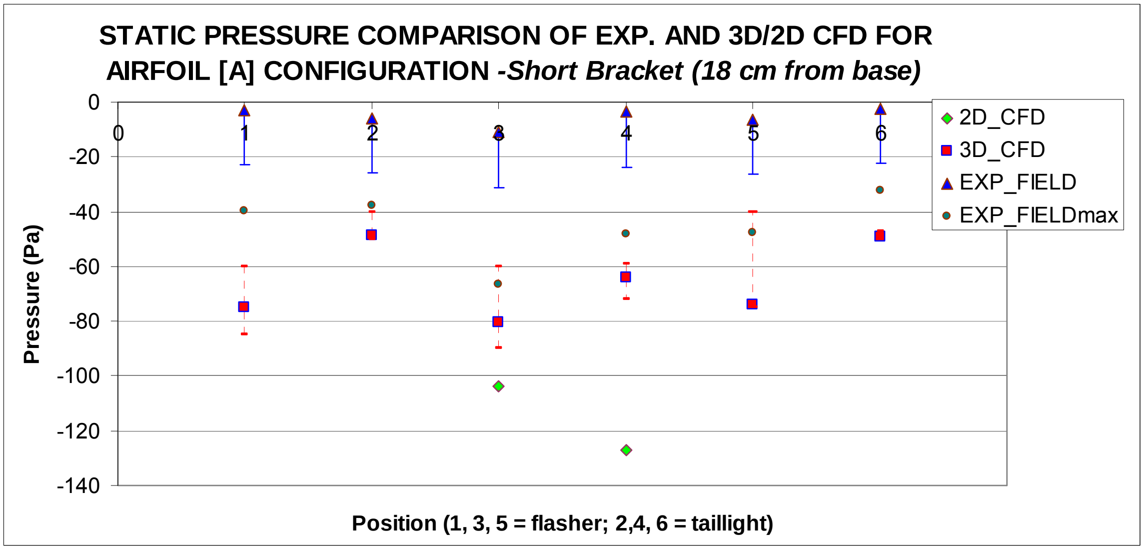


(a) Pressure Comparison of the Base Model for the Near Wake Zone - 18 cm from base

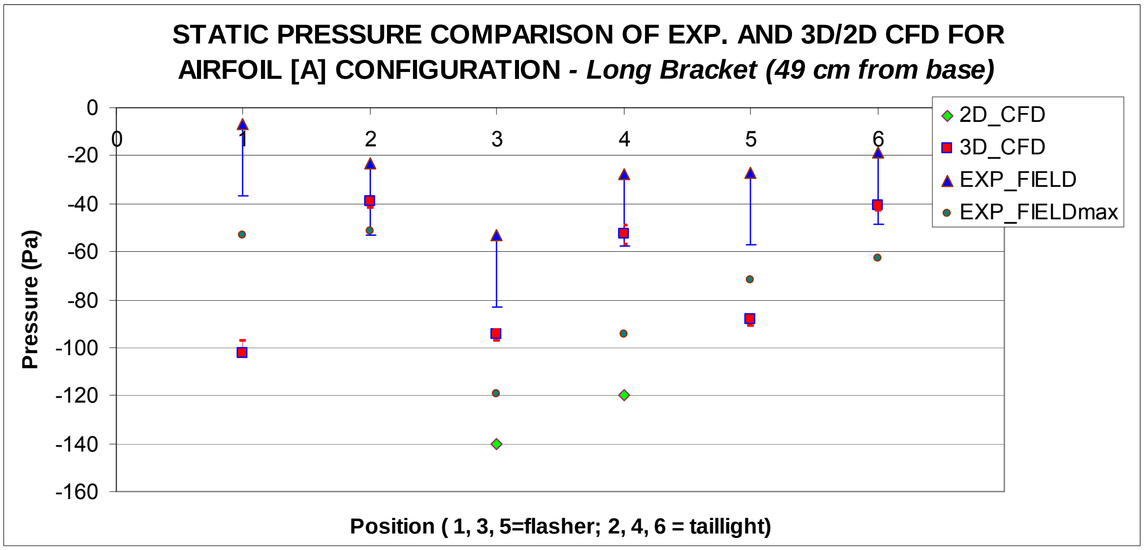


(b) Pressure Comparison of the Base Model for the Far Wake Zone - 49 cm from base

Figure D.3 Comparison of the pressure field test results with 2D/3D CFD predictions by the Model Generated for the Base Configuration at the Measurement Points *(Positions shown in the X-axis indicate the Locations of the Measurement Points i.e. 1-3-5 are Close to the Upper Edge of the Truck Base Near the Flasher Lights and 2-4-6 are Close to the Lower Edge of the Truck Base Near the Taillights)*



(a) Pressure Comparison of the Airfoil Model for the Near Wake Zone - 18 cm from base



(b) Pressure Comparison of the Airfoil Model for the Far Wake Zone - 49 cm from base

Figure D.4 Comparison of the pressure field test results with 2D/3D CFD predictions by the Model Generated for the Airfoil Configuration at the Measurement Points *(Positions shown in the X-axis indicate the Locations of the Measurement Points i.e. 1-3-5 are Close to the Upper Edge of the Truck Base Near the Flasher Lights and 2-4-6 are Close to the Lower Edge of the Truck Base Near the Taillights)*

5.5. APPENDIX E – Airfoil Technical Drawings and Instillation

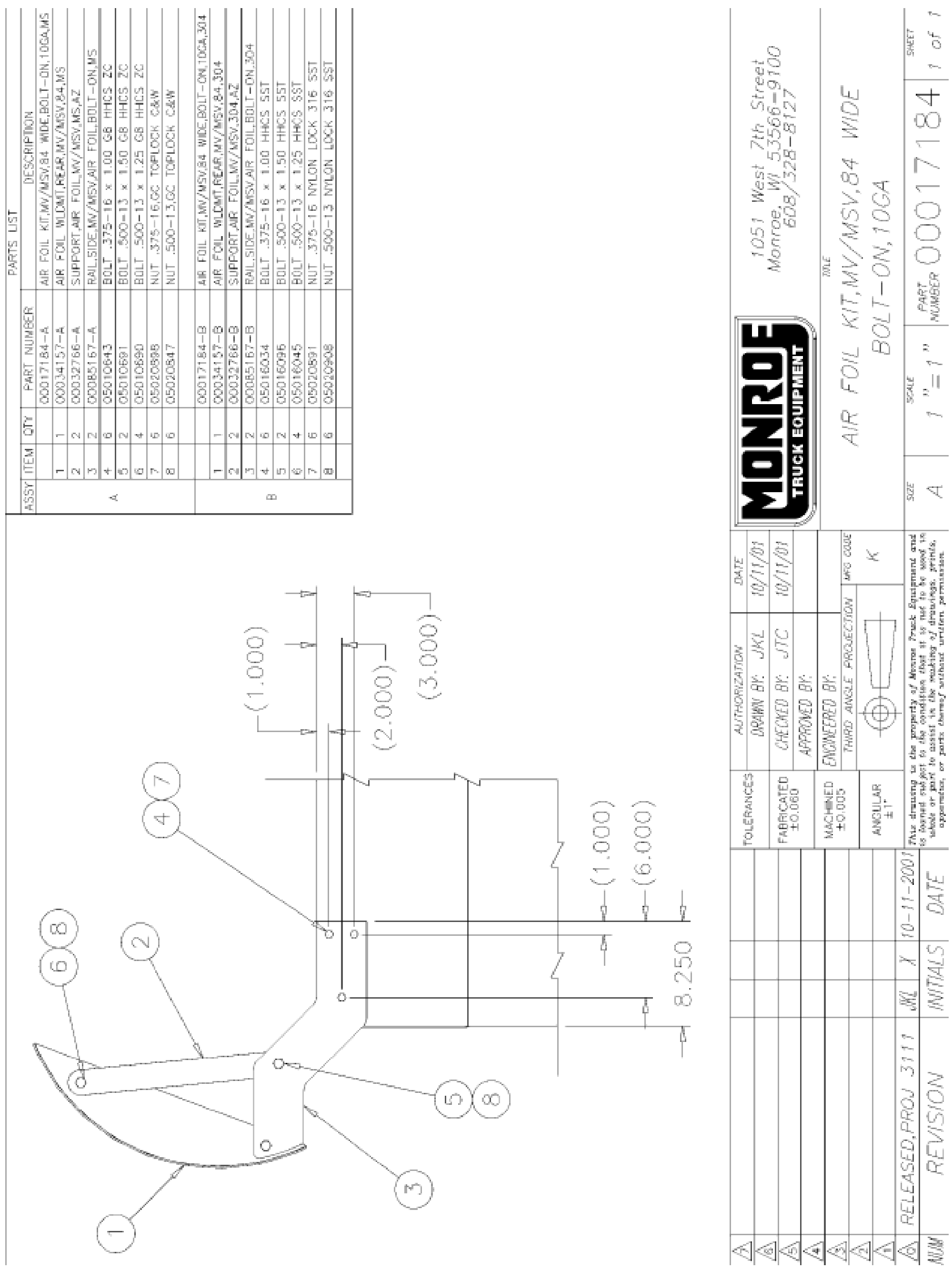


Figure E.1 Monroe airfoil technical drawing

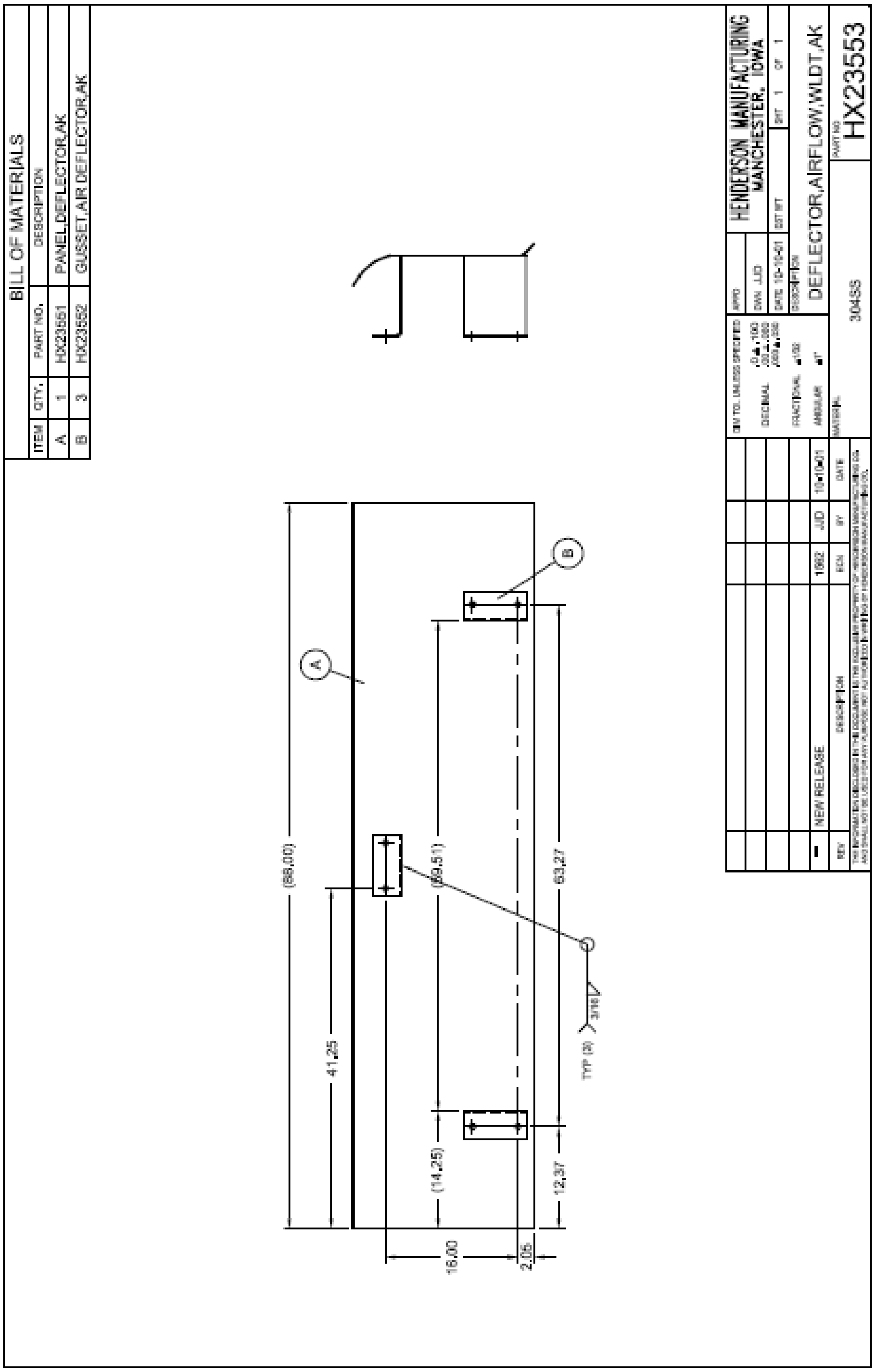


Figure E.2 Henderson airfoil technical drawing

Figure E 3. Alternative Installations of Airfoil

5.6 APPENDIX F - Nozzle Jet Modeling

Two computational models were created to simulate the flow behavior of two types of nozzle. The circular jet was created two-dimensionally while the elliptical jet was created three-dimensionally. This model was constructed for the prediction of the free jet effect of blowing away the falling snow on the vehicle front.

5.6.1 Model layout

Considering the axisymmetry nature of the circular jet model, a two-dimensional model consisting of a 1m×10m rectangular domain was developed for computation. Domain boundaries were defined as pressure outlets and centerline. The inflow end of the nozzle was set as a velocity inlet, with magnitude of 60 m/s consistent with the value calculated from the experiment. The outflow end which ducts the air all through the nozzle to the domain was set as interior. The total mesh element number is 26,784 for the entire computational domain. It should be noted that the entire domain referred here is only one side of the area (either the upper side or the lower side on the centerline) shown in Figure F.1. Because of the axisymmetry, the values from the other side can be obtained accordingly.

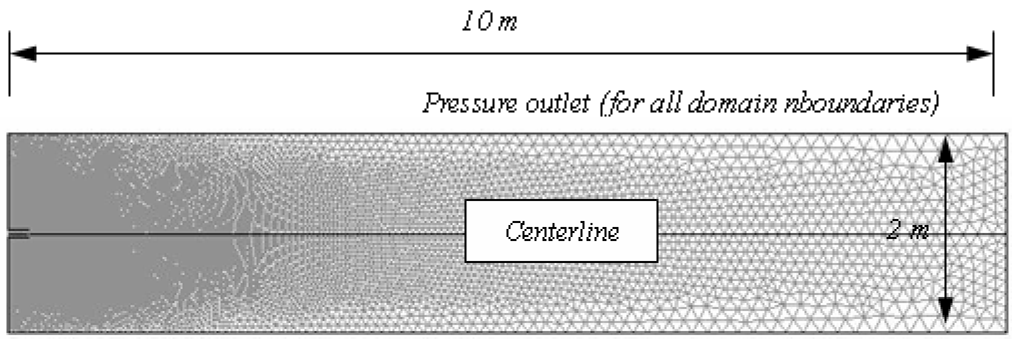


Figure F.1 Finite element mesh for circular nozzle, 2D axisymmetric model

The three-dimensional model was constructed for the elliptical nozzle jet, the domain was created as a 2m×2m×10m three dimensional rectangular with nozzle centered alone the axis of the larger size (shown as in Fig, F.2). The boundary type setting is mainly the same as what is described in 2D model for circular jet. The velocity inlet was set as 90 m/s to coincide with the calculation value from experiment. Tetrahedral elements are used as the optimum mesh for both nozzle continuum and the rest of computational domain. The total number of tetrahedral elements is 1,217,248. Corresponding material properties of air is given in able F.1.

Table F.1 Material Properties used in free jets simulation for both 2D and 3D

Density	$1.225\ kg/m^3$
Heat capacity	$1006.43\ J/kg\cdot K$
Thermal conductivity	$0.0242\ W/m\cdot K$
Viscosity	$1.79\times10^5\ kg/m\cdot s$

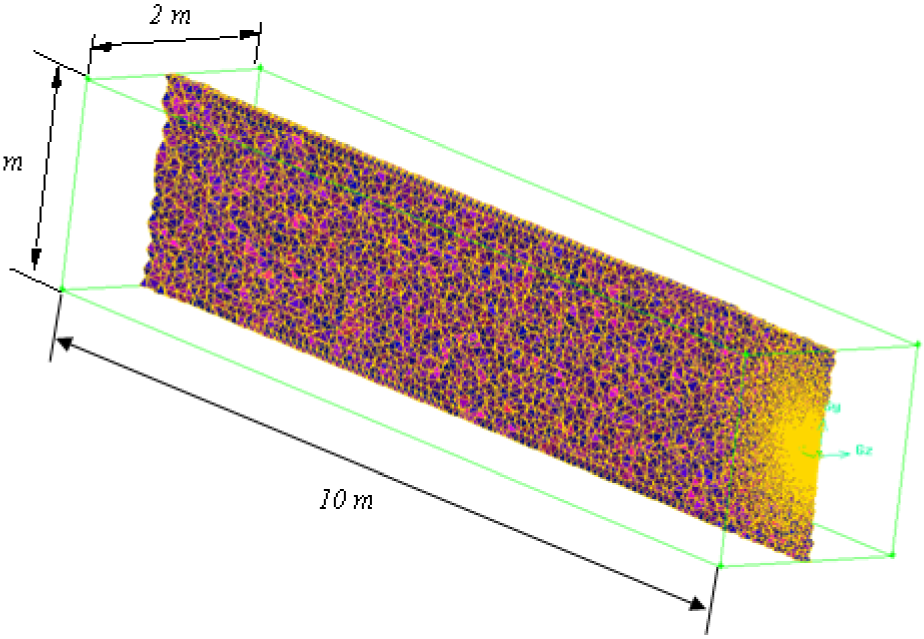


Figure F.2 Finite element mesh for elliptical nozzle, 3D model

5.6.2 Results

Figure F.3 shows the velocity distribution of the 2D axisymmetrically modeled free jet with circular nozzle by computational fluid dynamics, corresponding to the mesh and domain as is extensively investigated by previous researchers. The condensed velocity contour line at the discharge area indicates the high velocity area near the nozzle region.

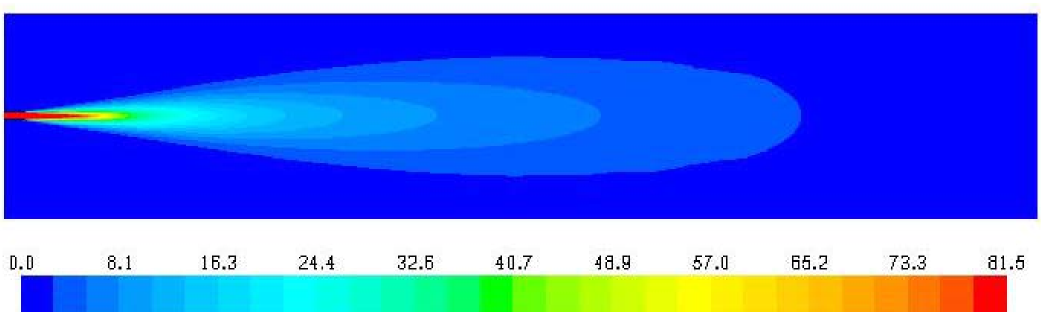


Figure F.3.Velocity distribution of the free air jet with circular nozzle

Figure F.4 shows the three dimensional velocity profile of the air jet issued from elliptical nozzle. The velocity contour maps at the cutting planes provide better understanding of the radial velocity magnitude decay with the increasing axial distances from the nozzle exit. At a relative short distance from the nozzle i.e., 0.2 m to 1 m, the jet cross-section stays a distinguishable elliptical shape as it is confined by the nozzle before discharging. As the axial distance increases, the radial velocity discrepancy of the major and minor axes at one single cross-section diminishes.

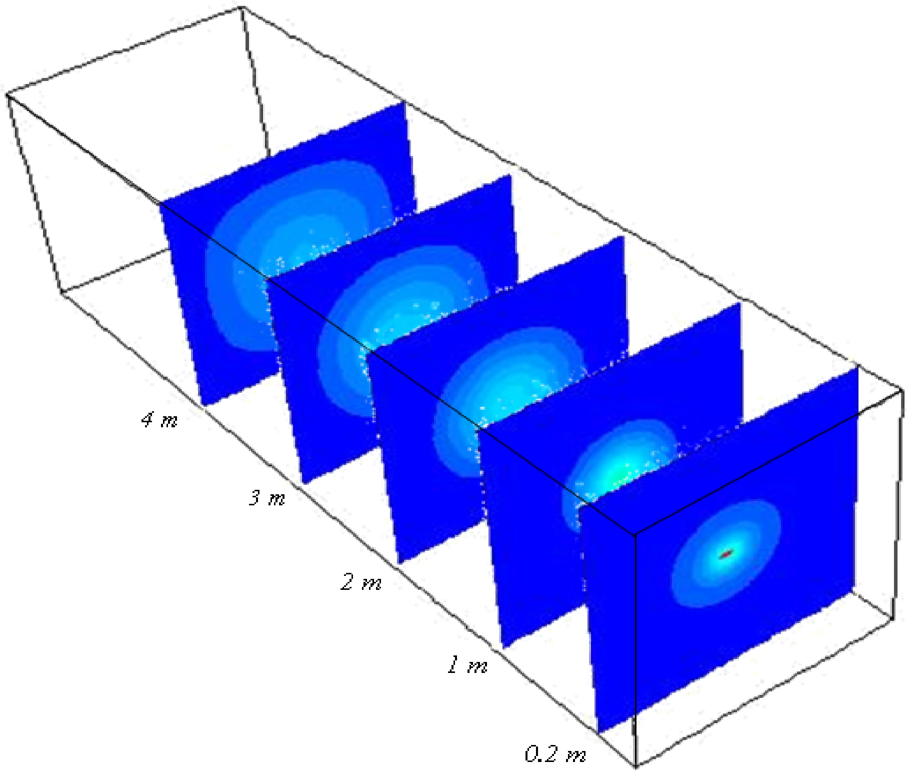


Figure F.4. Velocity distribution of the free air jet with elliptical nozzle

5.6 APPENDIX G - References

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