Goal-Oriented Design of an Improved Displacement Snowplow

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The design process used in the development of an improved displacement plow is described. A summary of the methods used to establish the goals of a new design are outlined, as well as the design strategy developed to reach these goals. Preliminary results of the research and experimentation carried on as part of this strategy and the relation to the specific goals of the design process are outlined. The development of an experimental snowplow that serves as a platform to test the design improvements resulting from the research is described in detail.

The design process and progress in the development of an improved displacement snowplow are described. This project was initiated in October 1988 as part of the Strategic Highway Research Program Project H-206. The primary goal of this research, as presented in the project statement, is to design a displacement snowplow with 20 percent or greater energy savings over designs currently in general use.

Several methods used to obtain additional design goals that relate specifically to the end user of the snowplow included the following:

1. User Requirements Survey. Plow operators, foremen, and state engineers were surveyed in New York state in the Watertown District, in portions of Colorado, and in Wyoming. The primary concern of those surveyed was the visibility problem associated with plowing snow. Specific areas of concern included snow entrained in the wake of passing vehicles, snow/ice accumulation on the outside of the truck windows and lights, frost/ice accumulation on the inside windows of the truck, and light scattered off airborne snow by headlights. In addition, the vision of other drivers is impaired by the snow which is cast by the plow and/or the snow entrained in the wake of the truck. Equipment problems related to the low temperatures encountered during plowing operations were also mentioned. Freezing of sanders, spreaders, and hitches as well as sluggish hydraulic controls were the most common complaints. Operators mentioned that a near vertical cutting edge of the plow was necessary if ice removal was required. The operators indicated that they preferred a larger lay back angle when plowing snow. They stated that a plow with more than 10 or 15 degrees of lay back angle would ride up over ice, defeating the ice removal function of the plow.

2. State Highway Department Equipment Specifications. A survey was sent to all 50 states asking for information regarding their snowplow and truck specifications. Thirty-six replies from state departments of transportation were received and reviewed. Information regarding plow dimensions, design, and type were entered in a data base. Six state provided specifications for v-type plows, 28 states provided specifications for reversible plows, and 15 states provided specifications for one-way plows. Five weather parameters thought to be significant in snow removal were identified and representative values for each state were also put into the database. The five parameters were as follows:

- Mean relative humidity for the month of January,
- Mean annual total snowfall,
- Mean annual number of days with more than 1 in. of snowfall,
- Mean annual number of days with ice pellets, and
- Mean annual number of days with freezing rain.

Attempts to correlate the types of equipment used in a particular state with any of the listed parameters were unsuccessful.

3. Snowplow Manufacturer's Literature. Specifications of currently available snowplows, hitches, and accessories were obtained from manufacturers. This included 22 American and two foreign manufacturers.

4. Snowplow Rides. Members of the research team at the University of Wyoming spent approximately 100 hr riding with equipment operators during a winter storm. Both night and daylight rides took place. Observations made by the research team, and discussions with the operators were compiled after the rides. The visibility and equipment problems described in the user requirements survey were experienced first hand by the research team during these rides. Another result of these rides was the observation that the tripping mechanism safety feature of the snowplows was defeated by the operators. The tripping mechanism of these plows were of the full moldboard tripping style. The reason given for chaining this feature off was that the inertial forces encountered in the event of the moldboard tripping were sufficient to cause loss of vehicle control. The loss of vehicle control was evidently a larger safety concern for the operators than the ability of the plow to trip when encountering an obstacle.

5. Patent Search. A data base search of U.S. patents relating to snowplows was conducted and reviewed. US Patent Abstracts Weekly, U.S. Patents Abstracts, and World Patents Index data bases were searched for Chemical, Electrical, and Mechanical patents relating to snowplows for the dates from January 1963 through August 1989.

6. Literature Search. An extensive literature search was conducted by the research team at the University of Wyoming. A library of material relating to the project was collected and entered in a data base. Both U.S. and foreign literature was reviewed. One result of this process was the translation by

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the Department of Mechanical Engineering at the University of Wyoming of the text *Snowplows Construction, Theory and Design*, by D. A. Shalman, published by Mashinostroenie, Leningrad, the Soviet Union, in 1973.

CURRENT RESEARCH AND DESIGN CONSIDERATIONS

Fluid Mechanics of Snow

The process of plowing snow produces a flow that can conveniently be separated into four distinct zones as shown in Figure 1. Zone I is the undisturbed snow upstream of the plow. Zone II is the compression zone in front of the plow. Zone III is the moldboard flow where snow is in a fluidized state. Zone IV represents the exit plume.

Compression Region

This research is primarily concerned with the energy absorbed in compressing the snow in front of the plow. In a companion paper in this Record, Hansen covers these studies in detail. The preliminary results of his research indicate that at plowing speeds greater than approximately 15 m/sec (34 mph), energy dissipation caused by compaction of snow can be a considerable portion of the energy available to plow the snow. The variables that influence this energy dissipation are the snow density, plowing speed, and layback angle of the blade relative to the road surface. Of these, the only parameter that is controllable in the design of a snowplow is the blade angle relative to the road surface. Hansen (*1*) indicates that for freshly fallen snow [density of 80 kg/m^3 (5 lb/ft^3)] at a plowing speed of 24 m/sec (54 mph) the horsepower consumed by compression drops from 83 kJ/sec (112 hp) for $\phi = 90$ degrees to 7.5 kJ/sec (10 hp) for $\phi = 50$ degrees, where ϕ is the angle between the blade and the road surface.

Moldboard Flow

Empirical methods have dominated snowplow design in the past. Often, full-scale testing of a design is the only method used to determine if modifications are necessary.

Analytical methods used in the past primarily involved modeling the snow as an inextensible sheet traveling over the moldboard. Developable surfaces for the moldboard were used because this should minimize losses caused by snow deformation (*1*). That is, as the snow sheet deforms, it does not tear or buckle, but flows smoothly along the moldboard. Analytical models producing design parameters for various efficiencies have been developed for a number of elementary geometries including the wedge plow (*2*), the cylindrical plow (*1*), the conical plow (*1*,*3*), and the modified cylindrical plow (*3*). In general, these models give good qualitative results but the theoretical values can vary from experimental values by as much as 50 percent for force and 25 percent for cast distance (*1*).

All of these analytical approaches ignore the effect of friction of the snow along the moldboard and the energy required to lift the snow against gravity. The effects of friction on the energy dissipated in high-speed plowing operations may be significant. Shalman (*4*) has reported that performance increases on the order of 25 to 33 percent have been observed with the use of low-friction moldboards.

John Nydahl of the University of Wyoming is currently incorporating the affects of friction and gravity into a new theoretical model. He is also including more generalized developable surfaces than the elementary geometries studied to date. A thin cantilevered plate theory as developed by Simmonds and Libai (*4*,*5*), Darmon (*6*), and Darmon and Benson

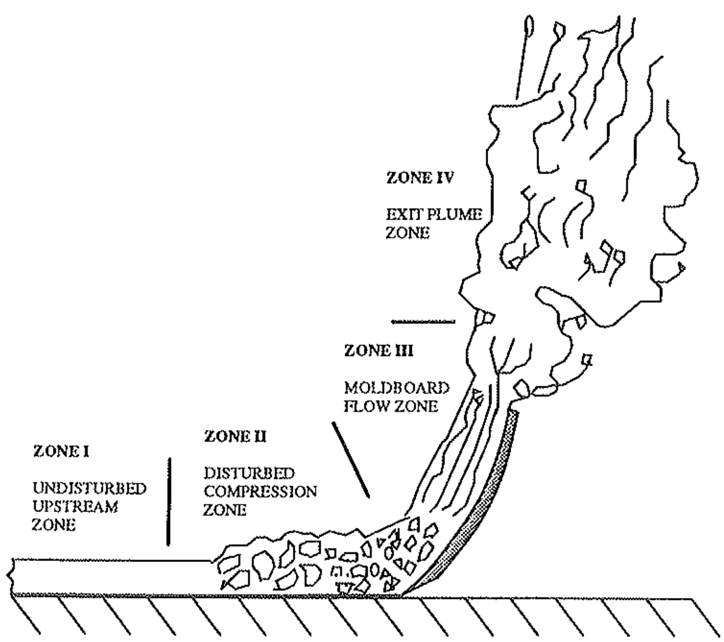

FIGURE 1 The four flow zones.

(*7,8*) has been investigated from which developable shapes can be numerically calculated. A case for a simple cylindrical moldboard was completed that was verified by Shalman's (*3*) work. A significant loss of velocity occurred at the exit of the moldboard that depended on the sliding coefficient of friction. These results also exhibited a significant influence of gravity in the solution.

The properties of snow vary considerably with time and temperature. Densities range from approximately 100 kg/m^3 (6.2 lb/ft^3) for freshly fallen snow to almost 500 kg/m^3 (31 lb/ft^3) for compacted snow. Friction coefficients for snow also vary widely for different temperatures and densities (*3*).

One consequence of these variable properties is that no single test can be used to determine the best plow design, because the best design will change with different snow properties. A further extension of this notion leads to the conclusion that the most favorable plow design would be one in which the geometry of the moldboard could be changed to suit changing snow conditions.

Other arguments may also be made in favor of a flexible or geometrically variable snowplow. For example, no matter which one design parameter or combination of parameters a snowplow design is optimized on, there will be plowing conditions for which the optimized plow, as far as the equipment operator is concerned, would not be optimum. For instance, the method in which the location of snow deposition if controlled in most current designs is through control of the snowplow vehicle speed. A variable geometry could allow for the snowplow vehicle to control the cast location through adjustment of the plow geometry, rather than adjustment of the plowing speed.

In addition, many relatively complex developable moldboard shapes can be obtained through use of a thin flexible plate. These developable surfaces may yield higher performance than those found in the elementary geometric shapes studied to date.

One serendipitous result of looking for a moldboard material capable of having a flexible geometry is that many of the materials that are suitably flexible also have relatively low friction coefficients. A popular material already in use in moldboard designs by several snowplow manufacturers is ultra high molecular weight polyethylene (UHMWPE). UHMWPE has excellent abrasion resistance (better than stainless steel), while also having a low coefficient of friction, high impact resistance for a plastic, good chemical resistance, and negligible water absorption (D. Walrath, informal communication). Compression-molded sheets of this material are relatively inexpensive and available in several sizes from various suppliers.

Exit Plume

This research is discussed in detail by Lindberg and Petersen in a companion paper in this Record. These studies use a water tow tank containing a negatively buoyant jet apparatus that is towed at a constant velocity along the tank. Multiple experiments in which a range of experimental parameters were studied, including jet inclinations and velocities, have been run from which photographic records were analyzed.

This research will allow prediction of cast distance and cast height as functions of plow geometry and plow speed. Knowledge gained from these experiments can be applied to the variety of snow plowing conditions found operationally to gain an understanding of actual performance. Understanding of the effect on cast distances, visibility, and plume trajectories when plowing in cross-flow conditions may be used in snowplow design considerations.

Investigations of the Plow-Truck Airflow Field

The investigation of the gross airflow features close to the plow-truck combination was carried out through both field experiments on a full size plow-truck using yarn tufts, and numerical two-dimensional analysis using the PHOENICS computational fluid dynamics package developed by CHAM Ltd. (*9*).

Both the field test results and the results of the two-dimensional numerical model show the locations of several recirculation zones at highway plowing speeds. Reversed flow near the surface of the hood of the vehicle, in front of the windshield, and behind the cab of the truck are evident. Also, two counter-rotating vortices extended behind the truck.

The placement of turning vanes at the top of the cab to fill in the recirculation behind the cab, and at the rear of the truck to damp the counter-rotating vortices in the trucks wake would likely improve visibility problems caused by the snow particles entrained behind the truck. Placing the vanes only at the rear of the truck would have little success, because it would be directly in the recirculation vortex caused by the cab of the truck. A deflector might also be useful on the hood of the truck to reduce some of the recirculation occurring in front of the windshield, thus reducing entrained snow, which reduces the forward visibility of the driver.

Mechanical Aspects

This section concentrates on the progress in the mechanical design of a suitable tripping mechanism, control arms for a variable geometry moldboard, and stability of the plow and truck.

Plow-Truck Stability

Computer models using the ADAMS commercial computer program (Mechanical Dynamics Inc.) are currently under development (*10*). These models investigate tripping mechanism dynamics and vehicle stability when the truck or plow encounter an obstacle during the plowing operation. Output from these models should provide information as to the forces arising on the snowplow and truck.

Tripping Mechanism

The surveys of operators, manufacturers, and state departments of transportation showed that tripping mechanisms currently in use on snowplows fell into two general categories: those designs in which the entire moldboard assembly trips, and those in which only the cutting edge, or a section of the edge, is allowed to trip.

The large inertial forces arising in the case of tripping of the entire moldboard assembly tripping mechanism may cause severe safety hazards caused by potential loss of vehicle control. The coil springs used in some existing full moldboard tripping designs can have dangerous failure modes. Lack of containment of these springs during a failure could cause potentially lethal debris being projected in the path of vehicles and pedestrians. The above problems have eliminated this type of design from further consideration.

Problems with many of the cutting-edge tripping mechanisms also exist, however. If the pivot of these mechanisms is located behind the plow, the cutting edge of the plow must either dig into the road surface, or lift the entire mass of the plow, or both, to clear an obstacle. This condition can cause severe gouging of roadways, especially on open graded surfaces. Large forces are imposed on the truck, degrading control. This process can also cause increased wear on the cutting edge surface.

INCORPORATION OF RESULTS INTO EXPERIMENTAL SNOWPLOW

An experimental plow that will serve as a test unit for the application of the goals of the project and the verification of research results is currently under development. The main design features of the experimental plow are a unique tripping edge, a front edge snow scoop, and a variable-geometry moldboard. These features are being added to a surplus drive frame acquired by the research group from the Wyoming Highway Department.

Variable Geometry Moldboard

The moldboard material chosen was a 4- × 12-ft, ⅜-in.-thick, sheet of UHMWPE. The sheet is controlled by arms adjustable through the use of large turnbuckles. The attachment and control of this sheet are such that the inextensible cantilevered plate theory is directly applicable. This theory can be used to predict and compare the actual shapes achieved by the moldboard under certain loading conditions. Field studies of snow flow over these various shapes will allow for comparison to analytical models being developed.

Tripping Edge Design

After reviewing current tripping edge designs, the research team decided to try a novel approach. The basic components of the tripping edge are a sectioned cutting edge, the front edge snow scoop, and a compressed air cylinder in place of a conventional spring.

One advantage of using an air cylinder is that the air pressure may be varied to allow different tripping strengths under different plowing environments. For instance, this feature would allow the snowplow operator to set a lower tripping force in a municipal setting where the vehicle is plowing at a lower speed, then increase the pressure if part of the route was in a highway setting.

Another advantage incorporated in the tripping edge design is nonlinear characteristics caused by the kinematic design that reduce the vertical forces transferred to the vehicle during tripping.

Three separate sections were designed into this tripping edge. Most obstacles encountered during plowing operations will only trip one or two of these sections. In concert, these design features reduce the potential for loss of vehicle control by decreasing the inertial forces and maintaining the friction forces between the front tires and the road, as compared to most other tripping designs.

The location of the pivot for the tripping edge is located in line with the edge itself. This feature allows a blade section to trip without lifting the weight of the plow when the cutting edge is in a vertical orientation. Castor assemblies have been designed that will keep the plow from dropping onto the road surface during a trip that should reduce, or eliminate, gouging of the road surface.

Front-Edge Snow Scoop

As noted previously, a layback angle of almost 50 degrees with the road surface would be preferable for the high-speed plowing of snow. Also, conversations with plow operators, foremen, state engineers, observations of current plowing practices, and recent investigations into ice fracture mechanics, lead to the conclusion that a layback angle of 90 degrees with the road surface is preferable when cutting ice.

A possible solution to this dichotomy is the concept of the front-edge scoop. This is a flexible deflector attached to the front of a conventional, near-vertical, cutting edge. The deflector has been designed to be rigid enough to allow for the weight of snow carried up its surface, but to be flexible enough to endure the tripping of the cutting edge. The most recent design consists of a 1-in.-thick sheet of UHMWPE mounted on webs at about a 50 degree layback angle. Gaps between the flexible sheet and the cutting edge allow for a path for the material collected by the vertical cutting edge to migrate onto the moldboard, while the bulk of the snow will be carried up the snow deflector face onto the moldboard. Figure 2 shows a detailed view of a single 4-ft section of this snow deflector.

FUTURE GOALS

The experimental snowplow is approximately 90 percent complete at this time. Figure 3 shows the arrangement of the previously discussed items. This plow will be used during the winter of 1990–1991 to obtain data necessary for the refinement of the design to be used for the two prototypes deliverable on the project. The innovations that have been incorporated in this experimental plow are direct outcomes of research on snow and snowplows, as well as reviews of requirements and current practices. Additional modifications

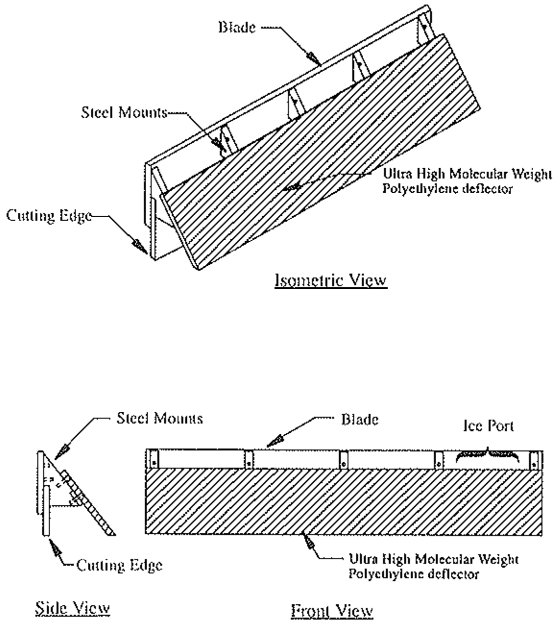

FIGURE 2 Snow deflector geometry.

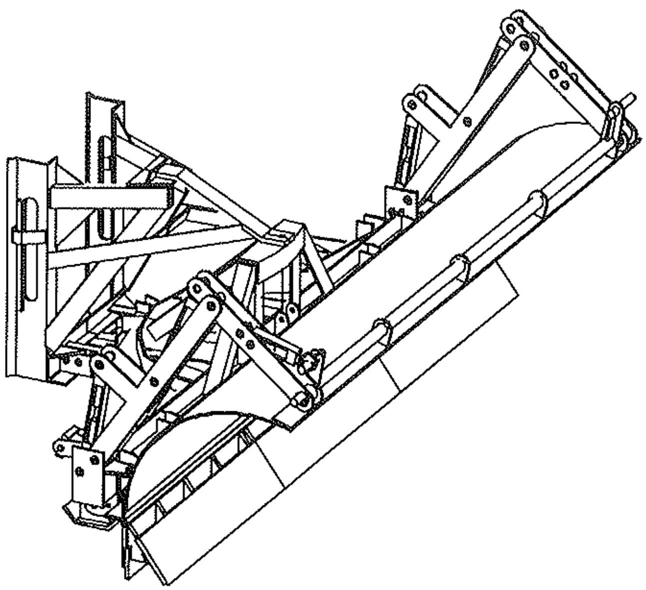

FIGURE 3 Experimental snowplow.

and innovations may arise from the field experiments and research that are continuing.

ACKNOWLEDGMENTS

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987. The authors would like to thank the rest of the research and design team at the University of Wyoming, the manufacturers, state highway departments, and the SHRP staff for their continuing support and critical review of this program.

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This paper represents the views of the authors only, not necessarily those of the National Research Council, SHRP, or SHRP's sponsors. The results reported here are not necessarily in agreement with the results of other SHRP research activities. They are reported to stimulate review and discussion within the research community.

Publication of this paper sponsored by the Committee on Winter Maintenance.