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Friction Measurement System for Polk County

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Research Project
Final Report 2013-26

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16. Abstract (Limit: 250 words)

A friction measurement system was developed for Polk County and installed on two snowplows in the county's winter road-maintenance fleet. The major components of the developed system were a special instrumented wheel, a pneumatic pressure-controlled cylinder, force-measurement load cell and accelerometers, a data collection micro-processor and a data processing micro-processor. The road friction coefficient was estimated in real-time and was stored on a secure digital card along with the current GPS-sensed location of the truck. The friction coefficient information was also displayed in real-time using LED lights for the operator. Although the basic design of the friction wheel system had been used for several previous years of intermitant testing without showing significant wear, the almost identical installations on the Polk County trucks suffered bearing failures after the first few days of continuous use. The failed bearings were replaced with larger bearings in a more robust mount. Apparently, the system again failed in a few days, but the research team did not learn of this failure until the end of the project. The low budget for the project and the significant travel required to go to Crookston posed major challenges in getting a friction measurement to work effectively for Polk County.

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Friction Measurement System for Polk County

Final Report

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Executive Summary

A friction measurement system was developed for Polk County and installed on two snowplows in the county's winter road-maintenance fleet. The major components of the developed system were a special instrumented wheel, a pneumatic pressure-controlled cylinder, force-measurement load cell and accelerometers, a data collection micro-processor and a data processing micro-processor. The road friction coefficient was estimated in real time and was stored on a secure digital card along with the current GPS-sensed location of the truck. The friction coefficient information was also displayed in real time using LED lights for the operator. Although the basic design of the friction wheel system had been used for several previous years of intermitant testing without showing significant wear, the almost identical installations on the Polk County trucks suffered bearing failures after the first few days of continuous use. The failed bearings were replaced with larger bearings in a more robust mount. Apparently, the system again failed in a few days, but the research team did not learn of this failure until the end of the project. The low budget for the project and the significant travel required to go to Crookston posed major challenges in getting a friction measurement to work effectively for Polk County.

I. Introduction

This research team has previously worked on two different types of friction measurement systems for cars and snowplows.

In the first friction measurement system developed in 2003-2004 [1], the researchers used a GPS system and wheel speed measurements on the vehicle to calculate the friction coefficient. The slip ratio was calculated from the GPS velocity and the wheel speeds and estimates of longitudinal and vertical tire forces were obtained. These variables together with an adaptive parameter estimation algorithm enabled real-time calculation of friction coefficient [1].

The system worked reliably and quickly to estimate friction coefficient in real-time [1]. However, it required the vehicle to have a minimum acceleration or deceleration of 0.3 m/s/s before friction coefficient could be updated. When the vehicle was not accelerating or decelerating at all, friction coefficient information could not be updated.

Figure 1: Friction measurement wheel installed on a snowplow.

In order to overcome this limitation for snowplows (where friction coefficient might need to be known ALL the time), the research team subsequently developed a tire-road friction coefficient measurement system based on the use of a small redundant wheel on the snowplow [2]. The developed system consists of an instrumented wheel installed near the front axle of the snowplow. A photograph of the developed friction wheel is shown in Figure 1. Here the major challenge was the significant vibrations experienced by the system which corrupted all of the measured signals. The researchers developed a friction estimation algorithm in which friction coefficient changes could be estimated very quickly (in less than 150 milli-seconds) in spite of the high vibration/noise levels in sensor signals [2].

In the present project, a limited deployment of the developed system was planned on 2 snowplows at Polk County. The system to be deployed would consist of the instrumented friction wheel with sensors, a GPS location measurement system and geographic information system software. The software will be implemented on a compact microprocessor (eliminating the full laptop that was used earlier). The measured friction coefficient and corresponding GPS location would be recorded in real-time and also displayed for the operator.

The system was planned to be fabricated and installed at the start of winter 2012. This would allow in-field testing by county operators during the 2012-2013 winter season. Any hardware or software breakdowns in equipment would be addressed by the research team. Any software changes requested by county personnel in the user interface would also be addressed. Results from this limited deployment study will be documented in a report and can be used by LRRB to make future decisions on whether to pursue a wider deployment of the developed technology.

The potential benefits from this project include the following:

1) The use of friction measurements can serve as a quantitative and objective measure for determining how well winter road maintenance is being carried out.
2) Maps of measured friction coefficient as a function of GPS location would provide information on road conditions throughout the county area. These could be used for traveler information as well as for optimum scheduling of winter maintenance crews.
3) The reliability of the previous friction measurement system and its ability to work under the stress of real-world snowplowing conditions would be evaluated.
4) Finally, the use of the automated applicator control technology and further recording of the friction coefficient values and application rates could be helpful in addressing the concerns of the public and in addressing lawsuits, if there were any legal suits related to winter maintenance filed by individuals.

II. Preliminary Experimental Data

Prior to the installation of the friction measurement systems on the Polk County snowplows an experimental system was fabricated and tested with a pick-up truck to explore the effects of changes in slip angle, trailing arm angle and pneumatic pressure. This system was designed to be installed in a standard two inch trailer hitch receiver on a pickup truck or a van. Figure 2 shows a picture of the developed system. As seen in Figure 2, the preliminary system was constructed of wood because the objective of this preliminary system was only to decide values of optimum slip angle and pneumatic pressure. The system was not intended for extensive testing or for deployment. The instrumented sensors on the friction measurement system included an Analog Devices ADXL 325 accelerometer and an Omegadyne LC703-500 load cell. During development and testing of the system, we also utilized a Measurement Specialties Inc. MSP-300-100-P-3-N-1 air pressure sensor, an Automation Direct TRD-S1000BD optical encoder and an Automation Direct SS2-ON-4A photocell. Figure 2 shows the experimental system installed on a pickup truck.

The photo cell was used in initial testing on the pick-up truck in order to detect the exact locations of the start and end of an artificial slippery patch. Figure 3 shows sample sensor signals and estimates from a test. It can be seen that the load cell signal is noisy due to significant vibrations on the truck. The scaled friction coefficient estimate generated by filtering and using the accelerometer is seen to be significantly less noisy. It can be seen that the drop in friction coefficient estimated by the system coincides with the spikes in the photo cell signals, thus indicating that the slippery patch was correctly detected.

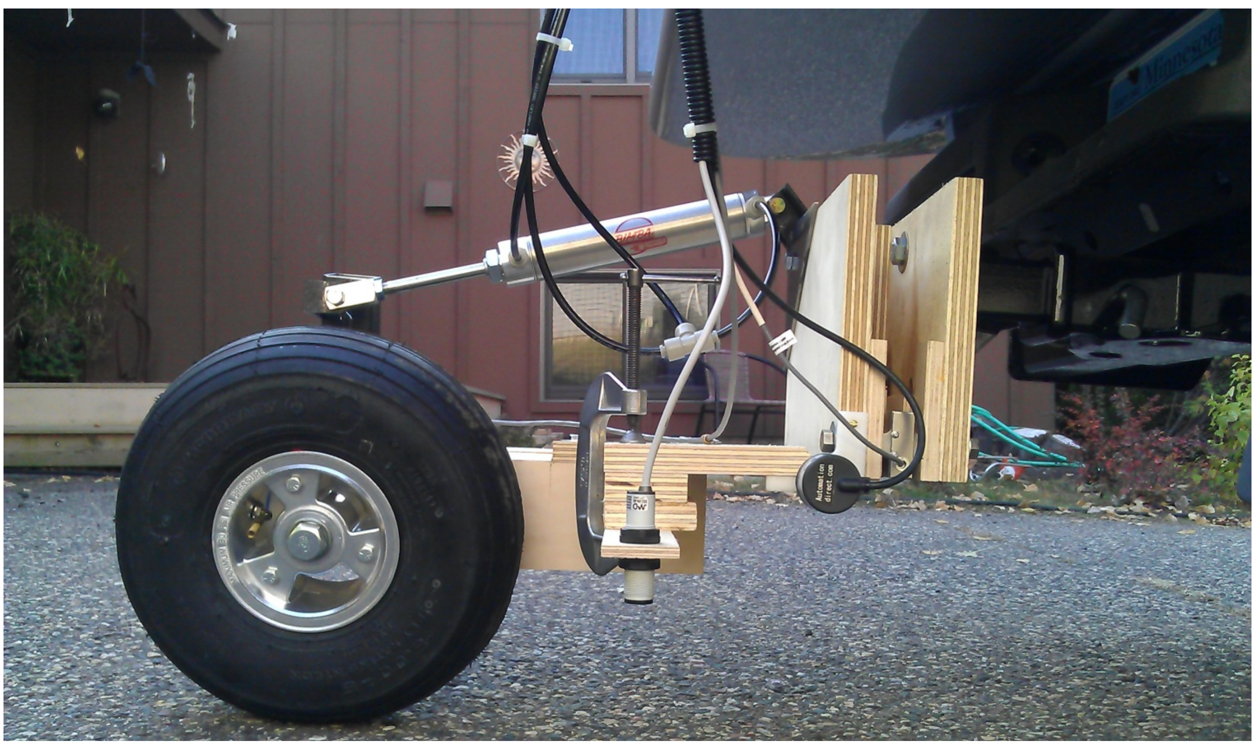

Figure 2: Experimental setup with a photocell, an optical encoder, and a pneumatic pressure sensor in addition to a load cell and an accelerometer.

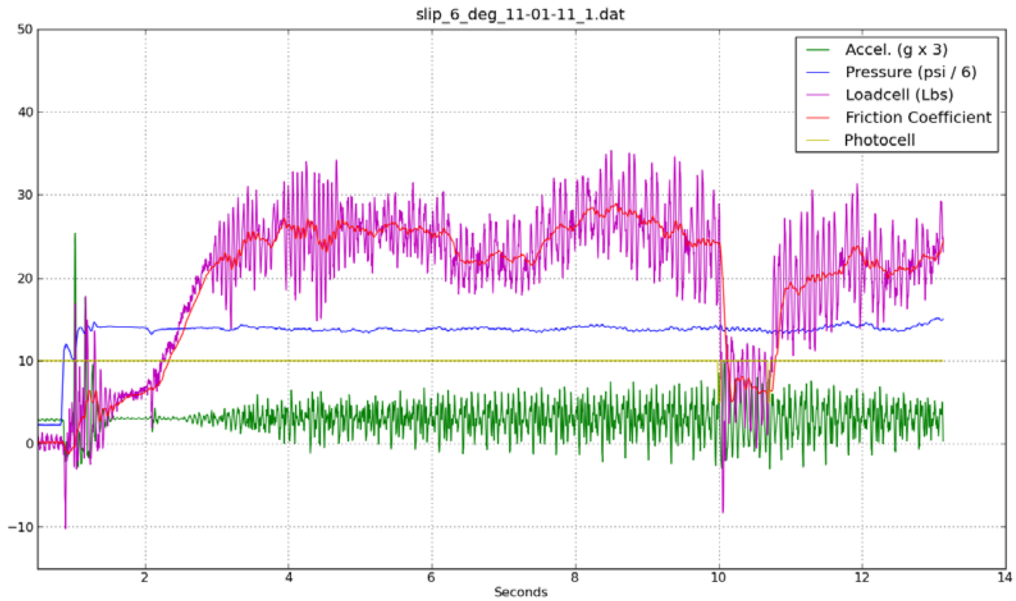

Figure 3: Plot of data from a 10 mph test run with the experimental system.

Figures 4 and 5 show similar data on friction estimation, but at higher vehicle speeds of 20 mph and 25 mph respectively. At faster speeds the noise increases significantly. These test runs were all made on a smooth new asphalt road surface, with the low friction artificial patch consisting of a slippery sheet made of rubber.

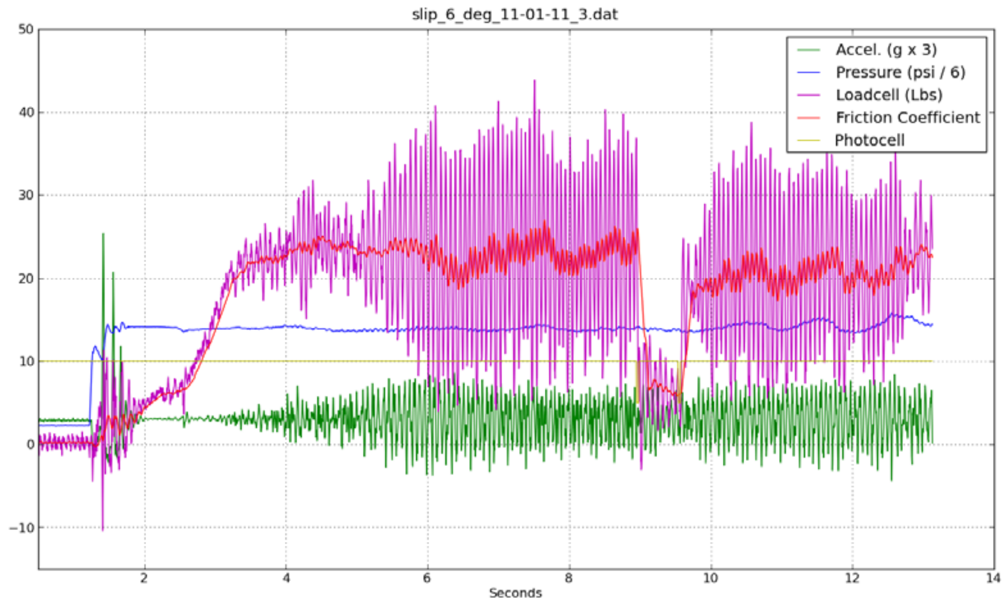

Figure 4: Plot of data from a 20 mph test run.

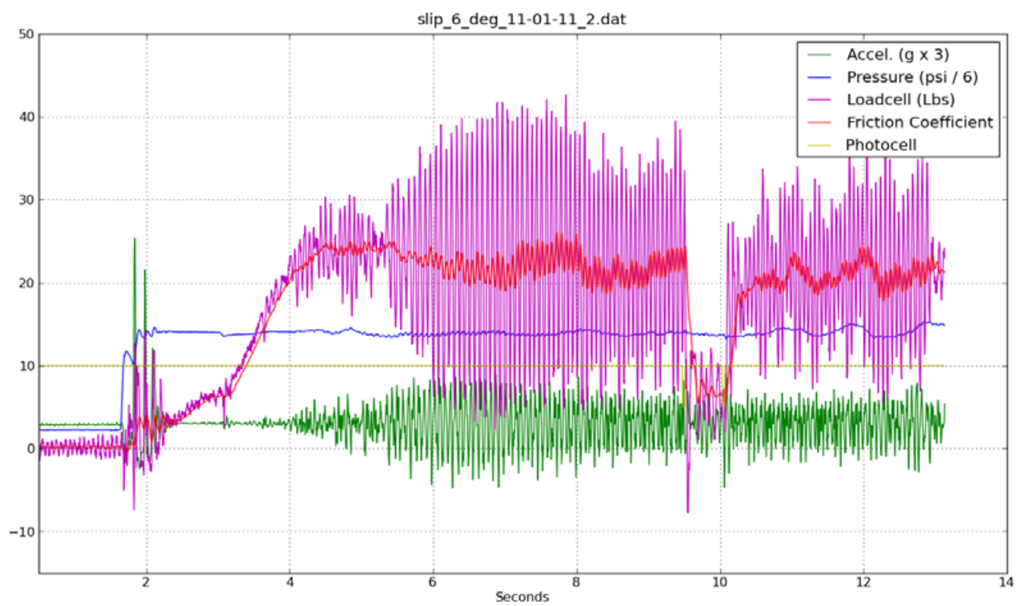

Figure 5: Plot of data from a 25 mph test run.

The data obtained from the pick-up truck confirmed that a slip angle of 6 degrees would be adequate and that friction coefficient changes could be detected reliably with the selected sensors, electronics and designed software. Subsequently, a rugged system made of steel suitable for deployment on the Polk county snowplows was fabricated.

III. Polk County Friction Measurement System Hardware

The friction measurement systems installed on two Polk County snowplows consisted of a 16-inch diameter instrumented tire installed near the front axle of the snowplow. The exact mounting location was determined individually for each snowplow. The instrumented wheel has two modular parts: a lower instrumented wheel and an upper mounting assembly. The lower instrumented wheel consists of a tire, accelerometers and a force measurement load cell. The lower instrumented wheel is common to all vehicle configurations. The upper mounting assembly is tailored to suit the specific vehicle on which the friction measurement system needs to be mounted. Figures 6 thru 12 show photographs of the friction measurement systems during fabrication and installation on the snowplows. All major mechanical parts of the system were constructed of steel.

Figure 6: Fabricated parts prior to mounting on the snowplows.

Figure 7: Road friction sensing system being installed on a Polk County snowplow.

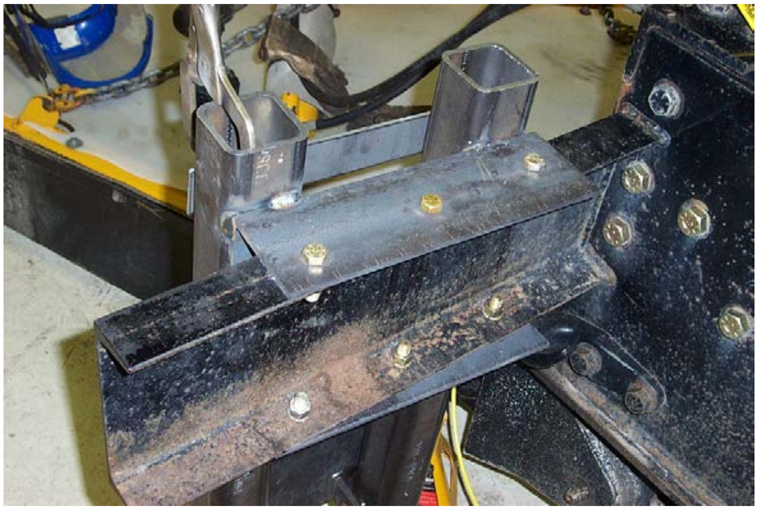

Figure 8: Details of the friction system being mounted to the bumper of a snowplow.

Figure 9: Complete road friction sensing system installed on the first of two Polk County snowplows.

Figure 10: Side view of friction wheel installation on the first truck with the wheel in the raised position.

The road friction measurement system can be deployed by the operator of the snowplow by flipping a switch. Figure 10 shows a side view of the friction measurement wheel when it is in the raised position (not deployed by the operator). Figure 11 shows a rear view of the same friction wheel when it is lowered (deployed by the operator).

Figure 11: Rear view with friction wheel lowered.

Figure 12: Friction wheel installed on the second Polk County snowplow.

Figure 12 shows a photograph of the friction wheel system installed on the second Polk County snowplow.

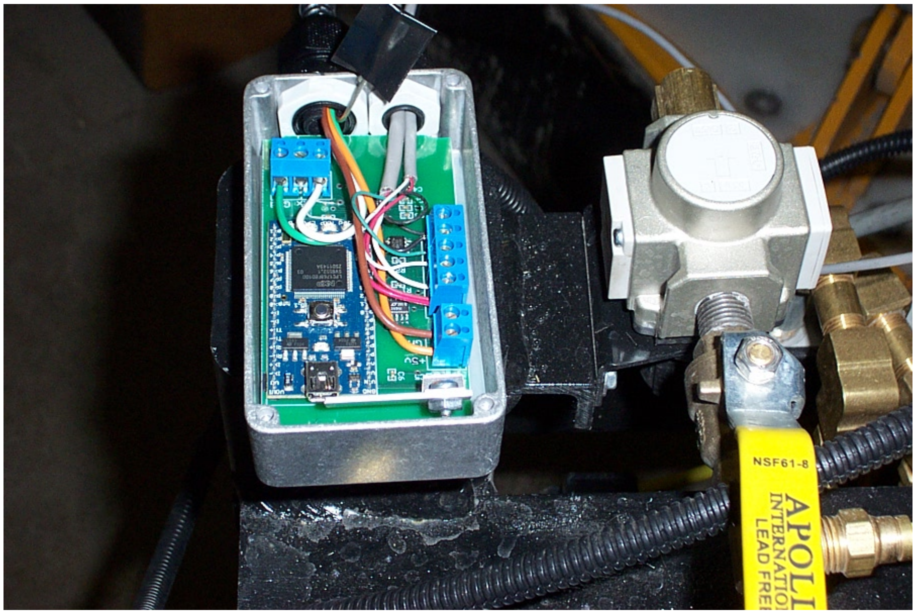

Figure 13: This is the data collection microprocessor that is mounted on the bumper of the snowplow near the friction measuring wheel.

The data acquisition, signal processing, data recording and display are done using 2 microprocessors – one near the friction wheel and another in the truck cabin near the operator.

Figure 13 shows the data collection microprocessor mounted on the back of the bumper of the snowplow near the friction measurement wheel. Figure 14 shows the microprocessor installed inside the truck cabin (during the process of installation). A serial communication link is used between the two processors.

Note that a full laptop is not used in the developed system and all tasks are handled by microprocessors.

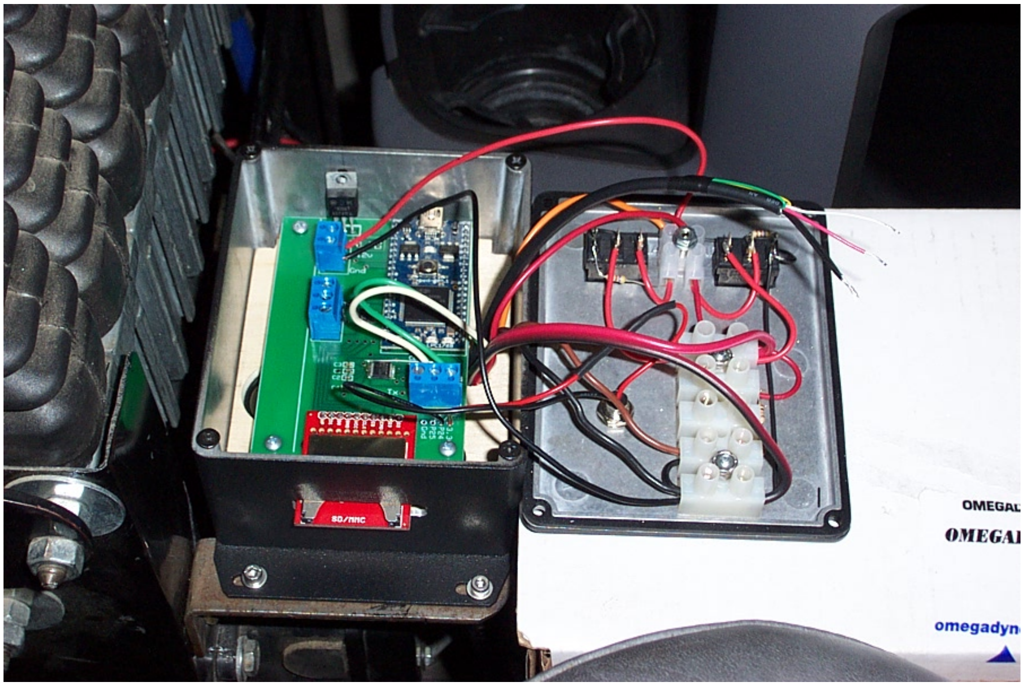

Figure 14: The NXP 1768 data processing microprocessor during installation in the cab of the snowplow.

IV. Software and Algorithms

4.1 Friction Coefficient Estimation

The static vertical force on the friction measurement tire is kept constant using a pneumatic actuator, air supply from the available compressed air cylinder on the snowplow and an adjustable pressure regulator. The lateral tire force for a given tire typically depends on the vertical tire force F_z, on the slip angle α and on the tire-road friction coefficient μ, as shown in Figure 15 [3].

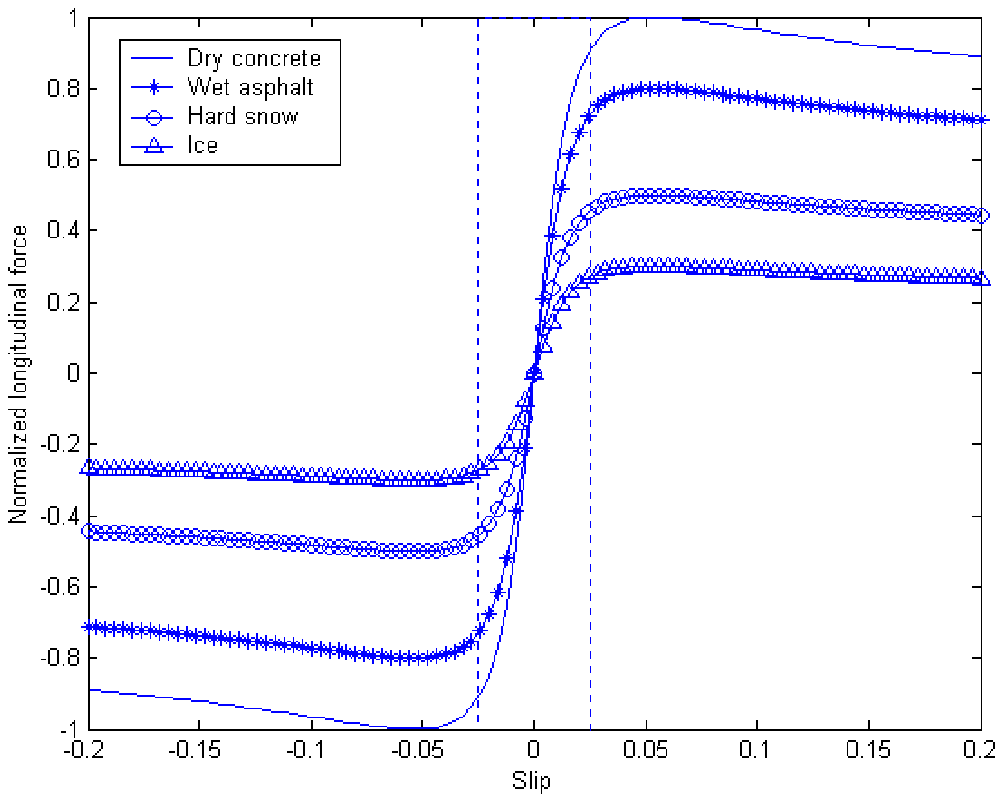

Figure 15: Typical longitudinal force versus slip ratio for a tire

If vertical tire force is assumed to be constant and if the slip angle α is assumed to be large enough, then the lateral tire force reaches its maximum value which is given by Equation (1):

$$F_{Lat}(\alpha_0) = \mu \times F_z \qquad (1)$$

Since the vertical tire force is kept constant in the developed sensor system and the slip angle α is fixed to a value high enough, i.e. $\alpha_0 \cong 6^o$, the lateral tire force F_{Lat} is assumed to be proportional to the tire-road friction coefficient. One can simply determine the tire-road friction coefficient in real-time by just measuring the lateral tire force signal and dividing it by the constant vertical tire force. However, if the vertical tire force is assumed to be constant, then the lateral tire force contains all the necessary information for detecting a surface change on the roadway. Hence the friction coefficient can be determined by measuring the lateral tire force and scaling this value appropriately.

Variations in vertical tire force that occur due to oscillations induced by the road surface cannot be compensated for by the pneumatic actuator. The pneumatic actuator only provides a constant static force but cannot prevent dynamic oscillations in this force. It should also be noted that a slip angle of 6^o is high enough to ensure that the lateral force changes with friction coefficient. For very small slip angles of 1^o or 2^o, the lateral force may not change significantly with friction coefficient and may be measured to be about the same value for all friction coefficients.

A pancake type load cell is used to measure the lateral tire force and an inexpensive MEMS accelerometer is employed to detect the vibrations and filter out the noise due to vibrations on the force signal. The signals from the load cell and accelerometer are read by an NXP 1768 microprocessor then low pass filtered and transmitted to the cab over a 115K baud serial communication link. In the cab another NXP 1768 microprocessor combines the measurements with location data from GPS and the date and time from a real-time clock on the microprocessor. The results are saved on a SD (Secure Digital) card in a format specified by the engineers in the Polk County GIS department (see section 5.1). Figures 12 and 13 show the electronic components of the friction measurement system during installation on one of the snowplows. In addition to the microprocessor system there is a Garmin GPS 18 receiver mounted on top of the cab and connected to the processor inside the cab.

Figure 16: Pneumatic valve with a supply line from a pressure regulator at the top of the picture controlling the cylinder that raises and lowers the friction wheel near the bottom of the picture.

4.2 GPS Data Coordinate Conversion

The position of the truck was sensed by a Garmin GPS 18x-5Hz receiver installed on the top of the truck cab (Figure 17).

Figure 17: GPS Puck Used for Vehicle Position Measurement.

The Garmin unit was programmed to send a NMEA GGA string to the microprocessor inside the cab. The NMEA GGA string includes the latitude and longitude of the receiver in degrees and minutes of an arc. In early discussions with county GIS personnel it was decided to store the data in Polk County coordinates to match the format in which the county stores the rest of their GIS data. The Polk County coordinate system is a Lambert Conformal map projection. In essence the transformation to Polk County coordinates involves projecting latitude and longitude from the surface of the earth onto a cone that passes through two parallels of latitude in the county then flattening the cone and using a coordinate system based on Northing (the distance north of a defined point on the flattened cone) and Easting (the distance east of the same point). The formulas that were used to make the conversion are documented in U.S.Geological Survey Paper 1395 *Map Projections – A Working Manual* written by John P. Snyder and published in 1987 [4]. The microprocessor in the cab of the truck was programmed to make the conversion and the results were verified using a set of test input data and comparing the converted output with the output of the Minnesota Coordinate Conversion Program (MnCon) version 4.0.2 using the same latitude and longitude as input.

4.3 User Interface and Operator Instructions

One of the design goals of this project was to make the user interface as simple as possible, so that the snowplow operator had minimal distractions and needed minimum training. The county did not want a “computer” in the cab that would take up scarce space and act as a distraction to the driver. With that in mind, and based on the advice of county personnel, we set up the system with one LED and two lighted switches on a small (5” x 5” x 2.5”) cast aluminum box that containes the data storage microprocessor. One switch turns the two microprocessors on and off and the other switch raises and lowers the friction wheel. The LED turns ON when the road is judged to be slippery (friction coefficient of 3 or lower on a scale of 1 to 5). The LED will flash twice and pause then repeat while the GPS is initializing and it flashes rapidly if a

Secure Digital card is not seated properly in its slot. The entire “User Manual” consists of the one sheet shown on the following page (Figure 18).

Polk County Friction Recorder Instructions

1. Insert SD card.
2. Turn top switch to "ON". (See notes 1 and 2)
3. To record low road friction lower the measuring wheel by setting the lower switch to "DOWN".
4. Raise and lower wheel as required.
5. At the end of the day, turn the top switch to "OFF" and remove the SD card which should now have files containing locations of icy roadways.

Note 1: A rapidly flashing LED means that the SD card is not connected. Turn the top switch "OFF" and try reseating the SD card.

Note 2: When the LED is making a double flash (two flashes then a slight pause and two more flashes and so on) it means that the GPS receiver has not initialized. GPS initialization will take several minutes after the top switch is "ON", the truck is outside and the GPS antenna has a clear view of the sky.

Figure 18: Operating Instructions for Friction Measurement System.

V. Sample Experimental Data

5.1 Data collected in Polk County from a January 14, 2013 Ice and Snow Storm.

The data is saved in the following format:

RF: [an integer from 1 to 5 representing relative **R**oad **F**riction]
N: [**N**orthing in Polk County coordinates (feet)]
E: [**E**asting in Polk County coordinates (feet)]
[Date and time]

Here an RF value of 1 indicates highly slippery and 5 implies nominal dry road (high friction coefficient).

There were 3276 road friction readings taken during a six and one half hour snowplow run. Here is a sample of some of the actual data collected during this storm:

```
RF: 5   N: 195501.0   E: 433602.4   Mon Jan 14 06:34:51 2013
RF: 5   N: 195510.2   E: 433503.3   Mon Jan 14 06:34:55 2013
RF: 5   N: 195509.2   E: 433403.2   Mon Jan 14 06:34:58 2013
RF: 4   N: 195507.2   E: 433299.9   Mon Jan 14 06:35:01 2013
RF: 3   N: 195508.9   E: 433196.5   Mon Jan 14 06:35:04 2013
RF: 5   N: 195511.2   E: 433090.6   Mon Jan 14 06:35:07 2013
RF: 5   N: 195513.1   E: 432986.9   Mon Jan 14 06:35:09 2013
RF: 4   N: 195512.8   E: 432882.2   Mon Jan 14 06:35:12 2013
RF: 5   N: 195511.5   E: 432776.6   Mon Jan 14 06:35:15 2013
RF: 5   N: 195512.1   E: 432676.2   Mon Jan 14 06:35:18 2013
RF: 3   N: 195513.8   E: 432577.8   Mon Jan 14 06:35:20 2013
RF: 5   N: 195512.8   E: 432475.7   Mon Jan 14 06:35:23 2013
RF: 5   N: 195514.4   E: 432007.9   Mon Jan 14 06:35:37 2013
RF: 5   N: 195515.1   E: 431808.4   Mon Jan 14 06:35:41 2013
RF: 1   N: 195517.1   E: 431709.3   Mon Jan 14 06:35:43 2013
RF: 1   N: 195520.3   E: 431604.7   Mon Jan 14 06:35:46 2013
RF: 1   N: 195521.0   E: 431497.7   Mon Jan 14 06:35:48 2013
RF: 2   N: 195521.0   E: 431398.0   Mon Jan 14 06:35:50 2013
RF: 1   N: 195517.4   E: 431295.9   Mon Jan 14 06:35:52 2013
RF: 1   N: 195517.4   E: 431192.6   Mon Jan 14 06:35:54 2013
RF: 4   N: 195518.7   E: 431089.9   Mon Jan 14 06:35:56 2013
RF: 1   N: 195521.0   E: 430983.3   Mon Jan 14 06:35:58 2013
RF: 1   N: 195523.6   E: 430878.9   Mon Jan 14 06:36:00 2013
RF: 1   N: 195522.6   E: 430773.0   Mon Jan 14 06:36:02 2013
RF: 1   N: 195522.0   E: 430671.9   Mon Jan 14 06:36:04 2013
```

These records show conditions near the beginning of the snowplow's run where there is a fairly tractive surface (RF: 5) and then transitions to a very slippery surface (RF: 1). Recorded points are at least 30 meters apart and if the sensed road friction is close to that of a normal dry road then no data is recorded on to the SD card for that location.

Figure 19 is a plot the recorded data for the storm on January 14th, 2013. This data was recorded over the duration of the six and a half hour snowplow run starting with the data in the sample above. County road names and the locations of Crookston and the town of Fisher have been added to the plot.

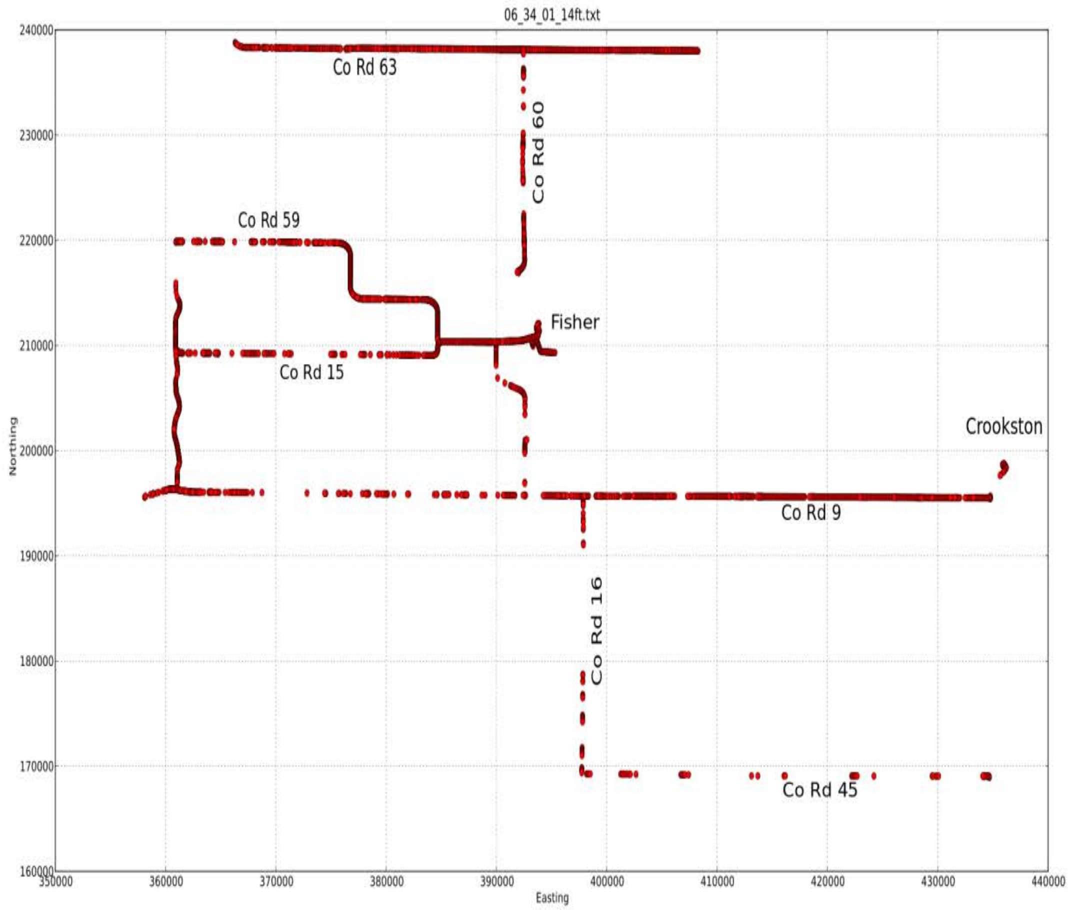

Figure 19: Plot of data from a snowstorm on Monday January 14th 2013 in Polk County. This is an area approximately 17 by 15 miles. The red dots indicate that the road friction is below a chosen threshold at those locations. Spaces between the red dots are where the roadway has close to normal traction.

VI. Conclusions

A friction measurement system was developed for Polk County and installed on two snowplows in the county's winter road-maintenance fleet. The system performed as expected for the first snowstorm, but an inspection after a few more days revealed that the plain bearings in the pivot that raises and lowers the wheel had failed on both snowplows. We speculate that the friction wheel was driven into an oscillation, possibly by the larger tire forces caused by a relatively coarse seal coat aggregate on the roads, and the constant hammering caused the bearing to fail. The systems were rebuilt with larger stainless steel ball bearings in reinforced mounts. This reinforced design also apparently failed after a few days of use. However, the research team did not learn of this failure until a few days ago, at the very end of the project. Unfortunately, due to the very small amount of funding for this project ($40,000), all of which has been spent, it is not possible to evaluate this system again next winter.

The value of the developed system is best illustrated by Figure 19. Figure 19 shows which roads are slippery and which are not. It provides a bird's eye view of road conditions. This also serves as a measure of how well roads are being maintained in winter in Polk County during various snowstorms.

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