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DGPS-Based Gang Plowing

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16. Abstract (Limit: 200 words)

Gang plowing is one method used by the Minnesota Department of Transportation (Mn/DOT) to increase the productivity of snowplow operations. However, these gains in productivity often come at the expense of increased driver stress. These higher stress levels are the result of the low visibility caused by localized snow clouds created by the lead snowplow, and by anxious drivers trying to pass between the moving plows. To improve the gang plowing process, a DGPS-based gang plowing system has been developed. This system uses advanced technology to allow a trailing snowplow to automatically follow a lead snowplow at an operator-specified lateral and longitudinal offset. The system is designed to improve both safety and productivity.

This report covers three areas. First, to improve driver visibility, an implementation of the virtual mirror to the left side of the trailing plow is described. Second, the lateral and longitudinal performance of a two-vehicle gang on Minnesota Trunk Highway 101 is described. Third, a system architecture for gangs of more than two vehicles is proposed, and its potential performance is documented through simulation. Finally, recommendations for further research and other potential applications are provided.

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DGPS –Based Gang Plowing

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Executive Summary

Gang plowing is one method used by the Minnesota Department of Transportation (Mn/DOT) to increase the productivity of snowplow operations. However, these gains in productivity often come at the expense of increased driver stress. These higher stress levels are the result of the low visibility caused by localized snow clouds created by the lead snowplow and by anxious drivers trying to pass the between the moving plows. To improve the gang plowing process, a Differential Global Positioning System (DGPS) based gang plowing system has been developed. This system uses advanced technology to allow a trailing snowplow to automatically follow a lead snowplow at a user-specified lateral and longitudinal offset. The system is designed to improve both safety and productivity.

Gang plow safety is addressed on two fronts. First, automatic following by the second vehicle eases the mental and physical demands on the snowplow driver. Driver stress and therefore driver fatigue will be reduced; alert drivers are in better control of their vehicles. Second, the driver assistive system facilitates a tighter formation for the plows, reducing the opportunity for a rogue motorist to try and squeeze in between the ganged snowplows. A side scanning laser sensor is used to detect the rogue motorists trying to violate the gang formation.

Productivity is improved because a tight gang formation increases the efficiency with which snow is passed from the lead plow to the following plow. Less snow is missed, minimizing the need to follow a plow operation with a clean up pass.

This system uses advanced technology to allow a second (or trailing) snowplow to automatically follow a lead snowplow at a user-specified lateral and longitudinal offset. The advanced technology includes DGPS, geospatial databases (i.e., digital maps), vehicle-to-vehicle electronic communication, radar, laser scanners, a driver interface, and steering, brake, and throttle control. The system is designed to assist the driver in the trailing vehicle. To ensure safety, the driver of the trailing vehicle can override the system at any time.

The report is organized in four main sections. Section one provides project background and motivates the need to develop a gang plow driver assist system. Section two describes the virtual mirror installed on the vehicle and how it helps a driver recognize adjacent vehicles planning to "break" the gang. Knowledge of the presence of this rogue vehicle may help a driver prepare for the threat it poses.

Section three describes the on-road performance of the gang plowing system. Limited operational test data is also available. The original goal of the project was to test the system operationally on Minnesota Trunk Highway 101 north of Rogers, MN, during the 2002-2003 winter. Unfortunately, that year produced very light snow, and full operational testing was not feasible. Because of this light snow, a no-cost extension was requested and granted. Light snowfall in the 2003-2004 winter also precluded full operational testing. As such, on-road testing was limited to good weather conditions. Performance results from those experiments are provided.

Section four describes an approach which could be taken to execute a gang plow scenario of more than three plows. Because Mn/DOT is responsible for maintaining multi-lane expressways and limited-access highways, gangs of three or more snowplows are not unusual. An architecture for a multi-vehicle gang is proposed and evaluated in simulation. The simulation uses a dynamic model of the Safeplow which was developed and validated as part of the gang plow system development process. The estimated simulated lateral and longitudinal control performance of the multi-vehicle gang is documented.

Finally, section five provides conclusions and recommendations for other applications which can benefit from the use of the technology described herein.

Chapter 1
Introduction

Gang plowing is one method used by the Minnesota Department of Transportation (Mn/DOT) to increase the productivity of snowplow operations. However, these gains in productivity often come at the expense of increased driver stress. These higher stress levels are the result of the low visibility caused by localized snow clouds created by the lead snowplow and by anxious drivers trying to pass the between the slower moving plows. These localized low visibility conditions lead to a loose formation whereby the trailing plow follows at a great distance instead of the desired tight formation.

Tight formations are desired for two primary reasons. First, by keeping the plows close together, the opportunity for rogue vehicles to try to break the gang is minimized because there simply is not room for the rogue vehicle to maneuver between the snowplows. Second, by controlling lateral spacing, the passage of snow from the lead plow to the following plow(s) will be more efficient because the gap between the wing on the lead and the front blade on the trailing snowplow is actively controlled.

To improve the gang plowing process by keeping the formation tight, a Differential Global Positioning System (DGPS) based gang plowing system has been developed. This system uses advanced technology to allow a trailing snowplow to automatically follow a lead snowplow. The advanced technology includes DGPS, geospatial databases (i.e., digital maps), vehicle-to-vehicle electronic communication, radar, laser scanner, a driver interface, and steering, brake, and throttle control. The system is designed to assist the driver in the following vehicle, and the driver of the second vehicle can override the system at any time.

Initial development of the DGPS gang plow system was initiated in a state pooled-fund project and reported in [1]. The initial DGPS gang plowing system was developed under this program, and demonstrated to Mn/DOT staff in July of 2002 at the Mn/ROAD Pavement Research Facility in Albertville, MN. After the demo, Mn/DOT personnel offered suggestions for improvement, most notably the addition of a side sensor so the driver of a trailing vehicle can identify when rogue drivers are attempting to break the gang. The laser scanner, computational equipment, and driver display were added to the Safeplow (the trailing vehicle in testing) to provide this additional information to a driver. Chapter Two describes the side scanning system.

The main goal of this research was to bring the DGPS gang plowing system from the test track to the highway in snowy, poor weather conditions. Unfortunately, unfavorable weather conditions (uncharacteristically light snowfall) during both the 2002-2003 and 2003-2004 winters precluded such operational testing. Chapter Three describes the gang plow architecture, and the performance the system achieved in on-road, fair weather testing.

Multi-vehicle gangs are also of interest to Mn/DOT because of the need to clear three and four lane expressways and interstate highways. To test the feasibility of multi-vehicle gangs, a simulation of a multi-vehicle gang plow process was developed. This multi-vehicle simulation uses the dynamic model of the Safeplow described in [1]. Chapter Four introduces an architecture proposed for multi-vehicle gangs. The expected performance of the multi-vehicle gang is presented therein. Chapter 5 concludes with recommendations for further research and suggestions for other applications of the technology developed herein.

Chapter 2
Application of the Virtual Mirror for Gang Plowing Operations

One of the key problems faced by snowplow drivers operating in a gang formation is the attempt by a motorist to pass a snowplow. What often happens is that a driver will follow a lead plow, taking advantage of the fact that the lane is clear. When forward progress is slowed, a driver becomes impatient, and tries to pass the leading snowplow. What often happens is that the passing vehicle hits the windrow created by the lead plow, spins, slows, and is hit by the trailing snowplow.

Mn/DOT snowplow operators have indicated that a device which can provide information regarding the presence of vehicles on the side of the snowplow would be valuable in the prevention of crashes instigated by these rogue vehicles. The Intelligent Vehicles Lab has developed a virtual mirror which uses a scanning laser sensor, a computer, and a driver visual display to replicate the function of an optical mirror. The development of the virtual mirror is documented in [2].

The virtual mirror is comprised of three components: a scanning laser sensor, a data-processing program, and an in-vehicle driver display. The laser scanner operates by sending a beam of (laser) light in a sweep of 180 degrees (with a 0.5 degree resolution) at 10 Hz. The sensor measures the time of flight of the reflected beam at each of the points of the sweep, thereby providing a measure of the distance from the sensor to that particular point. This concept is illustrated in Figure 2-1 below. The output of a complete sweep of the sensor provides a snapshot of the environment sensed by the laser scanner.

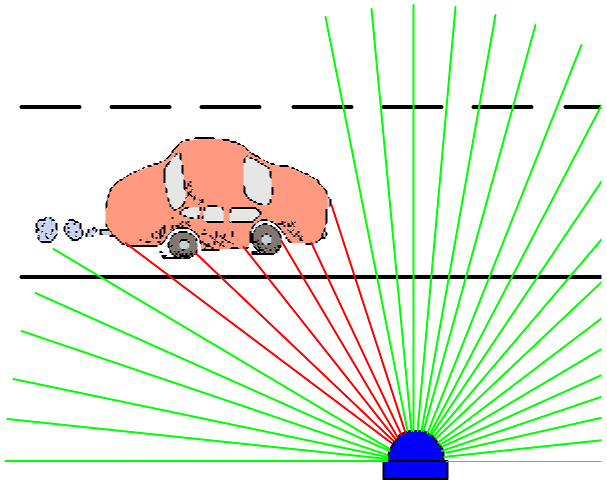


Figure 2-1. Concept of operation of laser scanner. Distance to point on object is determined by measuring the time of flight from the light beam.

In the gang plowing application, pattern recognition is used to determine whether a vehicle is present alongside the snowplow. As shown in Figure 2-2, the pattern to be recognized depends upon the position of the adjacent vehicle with respect to the snowplow. In Section A, which is ahead of the sensor, the presence of a vehicle will be indicated by a corner whose vertex is closest to the sensor. This corner corresponds to the intersection of the rear bumper and the right rear quarter panel. In Section B, the presence of a vehicle is indicated by a straight line extracted from the scan. This straight line represents the shape of the side of the vehicle along its beltline. Section C is similar to Section A in that a corner represents the presence of a vehicle adjacent to and behind the sensor. The corner represents the intersection of the front bumper and the right front quarter panel.

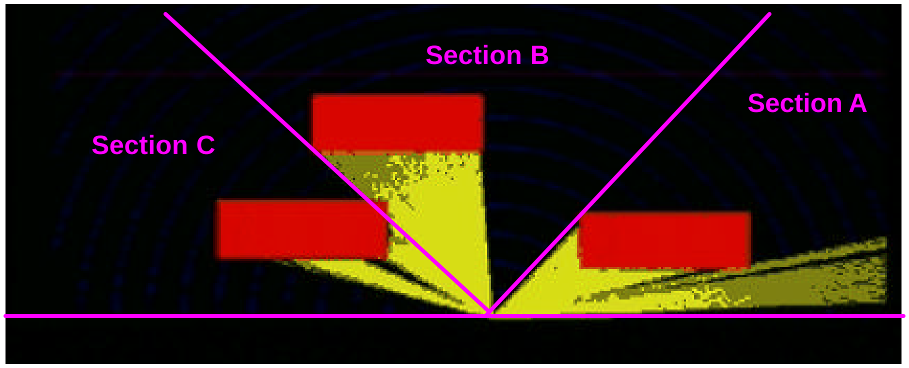


Figure 2-2. Actual output of laser scanner used to sense presence and location of vehicles adjacent to the snowplow. Vehicles are identified by the patterns found in the output of the laser scanner.

In this work, a Sick LMS 221 sensor was used for the laser scanner. It was attached to the metal steps attached to the hydraulic valve box on the left side of the Safeplow research vehicle as shown in Picture 2-1. It is mounted at a height approximately that of the center of the door on the average passenger vehicle. Positioning the sensor at this height provides the highest likelihood that light sent by the sensor will be reflected back (at this height, reflective anomalies associated with glass, fenders and wheels are minimized).

A virtual mirror process runs on one of the computers located in the Safeplow. The virtual mirror process consists of four components:

a. detection of the presence of an adjacent vehicle (pattern matching described above)

b. determination of the location of that adjacent vehicle with respect to the host vehicle (i.e., the safeplow).

c. determination of the adjacent vehicle on the roadway using the on-board digital map used as a reference by the trailing plow

d. rendering the graphical image for the driver's graphical interface.

Picture 2-1. Picture of Sick LMS 221 mounted on left side of Safeplow research vehicle. The Safeplow was used as the trailing vehicle during on-road testing.

The dataflow for this process is shown in Figure 2-3. The laser scanner, at a data rate of 5 Hz, sends laser distance and angle information to the main system computer via a RS-232 serial connection. The pattern matching process determines the presence of salient features of vehicles adjacent to the snowplow. These salient features (corners, straight lines) are used to determine the position of the adjacent vehicle with respect to the laser sensors; the position of the sensor with respect to the plow is used to determine the position of the adjacent vehicles with respect to the plow.

This information returned by the location process is used by the QNX Photon graphics process to create an accurate representation of the location of obstacles with respect to the plow. This representation is updated at a 10 Hz rate, and is displayed on an LCD display located in the Safeplow. A screen shot of the virtual mirror display in plan view is provided in Figure 2-4 below.

Because of the lack of snow, the system was not tested operationally under typical gang plowing conditions on Trunk Highway 101. However, drivers were exposed to the technology, and although the drivers found the idea to be promising, the primary response was that they hoped to drive it before passing judgment.

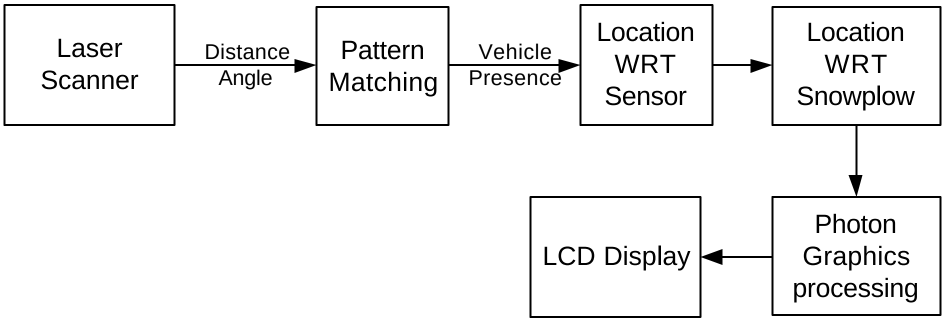


Figure 2-3. Signal flow diagram for virtual mirror process. The LCD display shows the location of the adjacent vehicles both with respect to the snowplow as well as on a global scale.

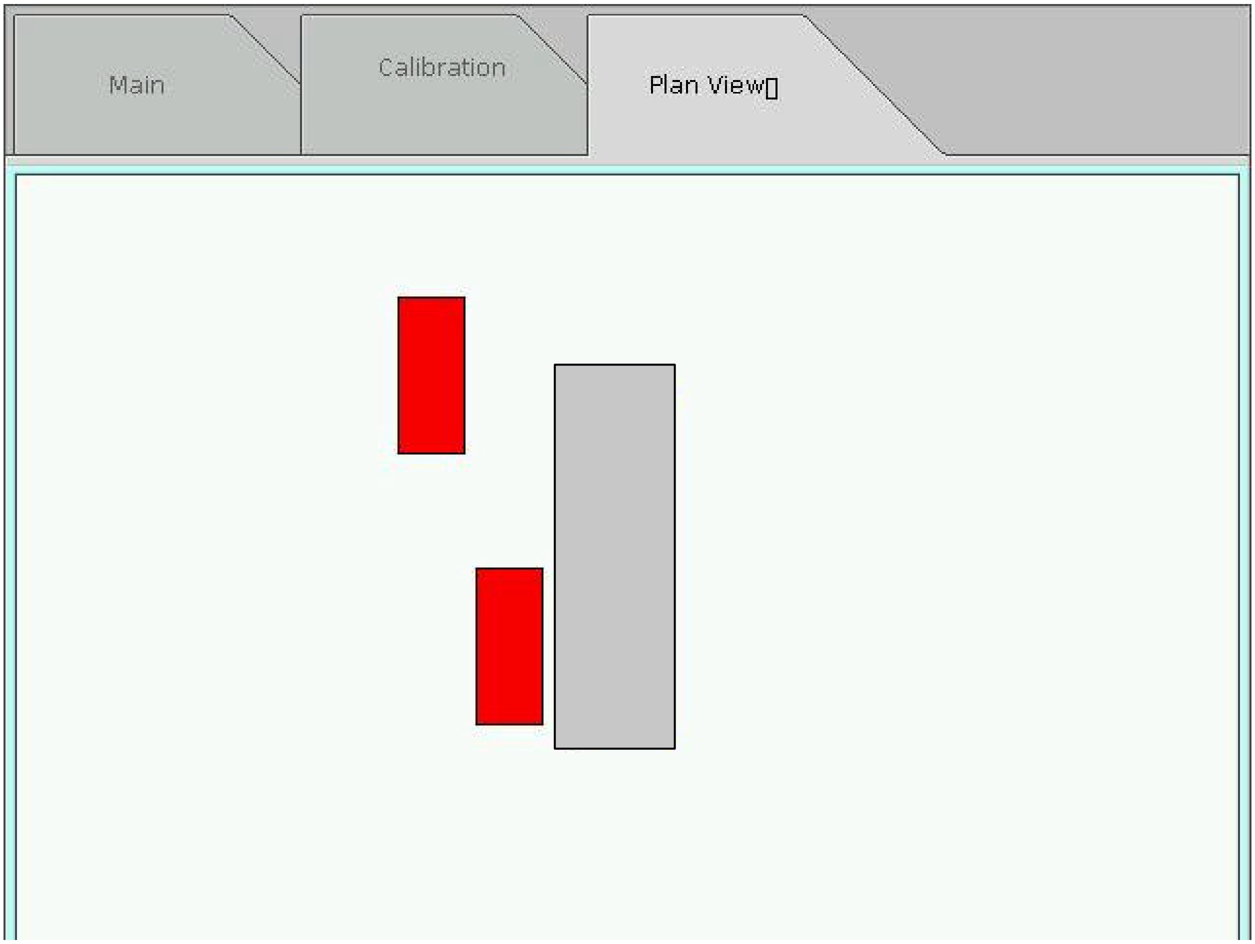


Figure 2-4. Screen capture of output of Virtual Mirror Display in Plan View mode. The cross hatched rectangle represents the trailing vehicle in the gang; the red rectangles represent the adjacent vehicles sensed by the laser scanner.

Chapter 3
Procedures and Results for Highway 101 Testing

Background.

The gang plowing system relies on a local digital map, high-accuracy DGPS for vehicle positioning, and inter-vehicle communications for reporting the position of the lead vehicle to the trailing vehicle. The automated system on the trailing vehicle uses the lead vehicle's state as reference from which to follow the lead vehicle. This is shown in Figure 3-1.

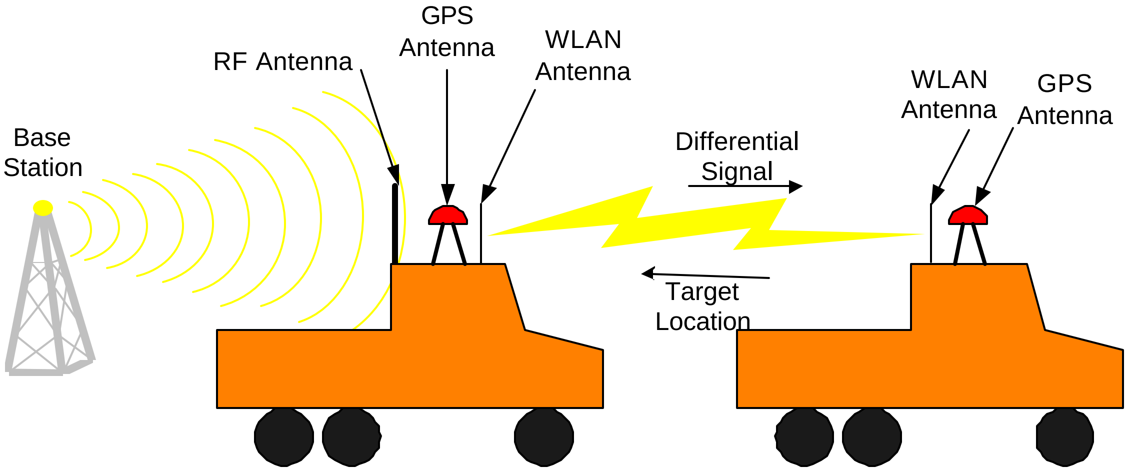


Figure 3-1 Gang plow system diagram. The trailing vehicle receives the differential GPS correction from the base station and sends it to the lead vehicle. The lead vehicle sends back its DGPS location.

The lead vehicle is equipped with a small computer, Wireless LAN station adapter, and a DGPS receiver. For the purposes of this work, this equipment was installed in a NEMA 4 (National Electrical Manufacturers Association) enclosure, and mounted on a roof rack installed on the roof of the lead vehicle. This approach minimized the intrusion into the lead plow cab and provided a weatherproof enclosure. The block diagram of the equipment is shown in Figure 3-2; mounting of the equipment is shown in Picture 3-1.

Because the trailing vehicle requires actuation of the steering, throttle, and brakes, it is significantly more complex than the lead plow. A signal flow diagram of the trailing vehicle control system is shown in Figure 3-3 below. Computer 1 uses information from the lead plow to determine steering, brake, and throttle commands. Computer 2 serves as the interface to vehicle actuators, and closes inner loops around steering, throttle, and brake actuators.

In addition to processing information regarding the position of the lead plow, the trailing plow also has on-board a high-accuracy geospatial database (aka, "digital map"). The trailing vehicle thereby can compare its position to the global coordinates of the local roadway, and can use that information to not follow a leading plow which has departed the road.

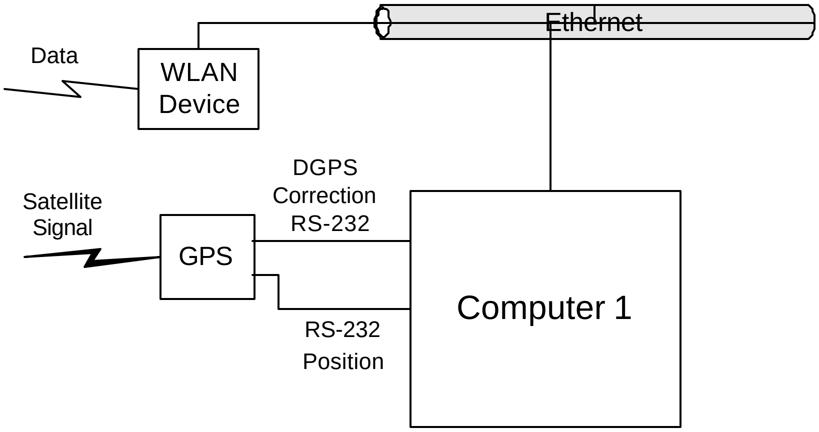


Figure 3-2. Data flow diagram for components for lead plow in gang. All components above are mounted in the cabinet located on the top of the snowplow (see Picture 3-1).

Picture 3-1. Photo of lead snowplow showing location of DGPS antenna and NEMA 4 cabinet in which all necessary equipment resides.

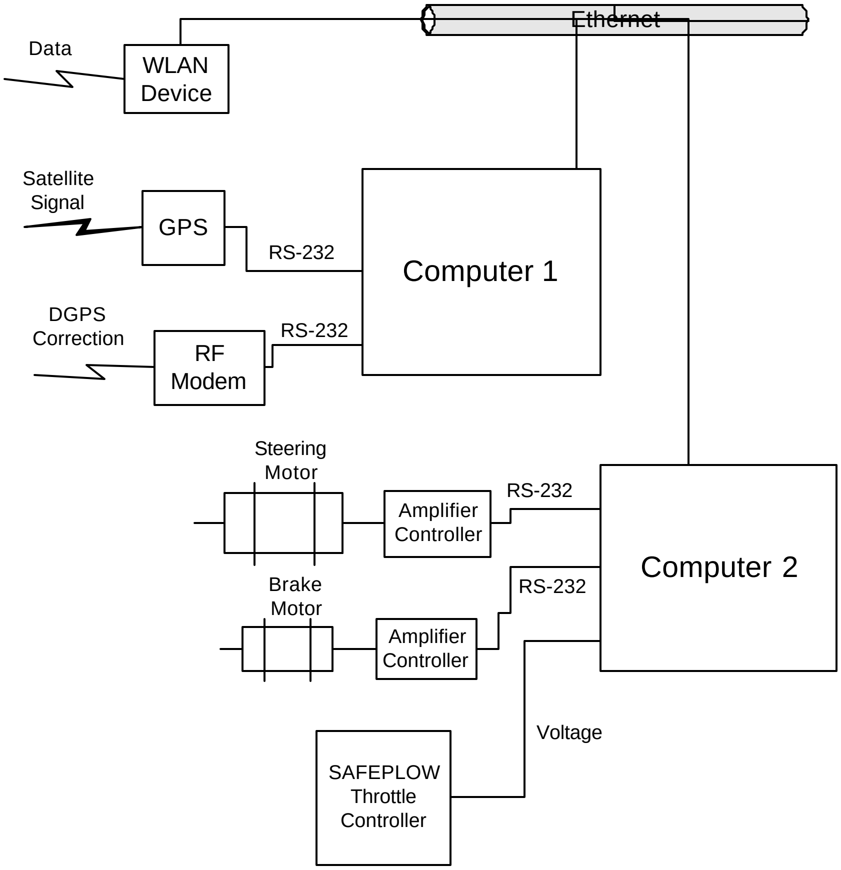
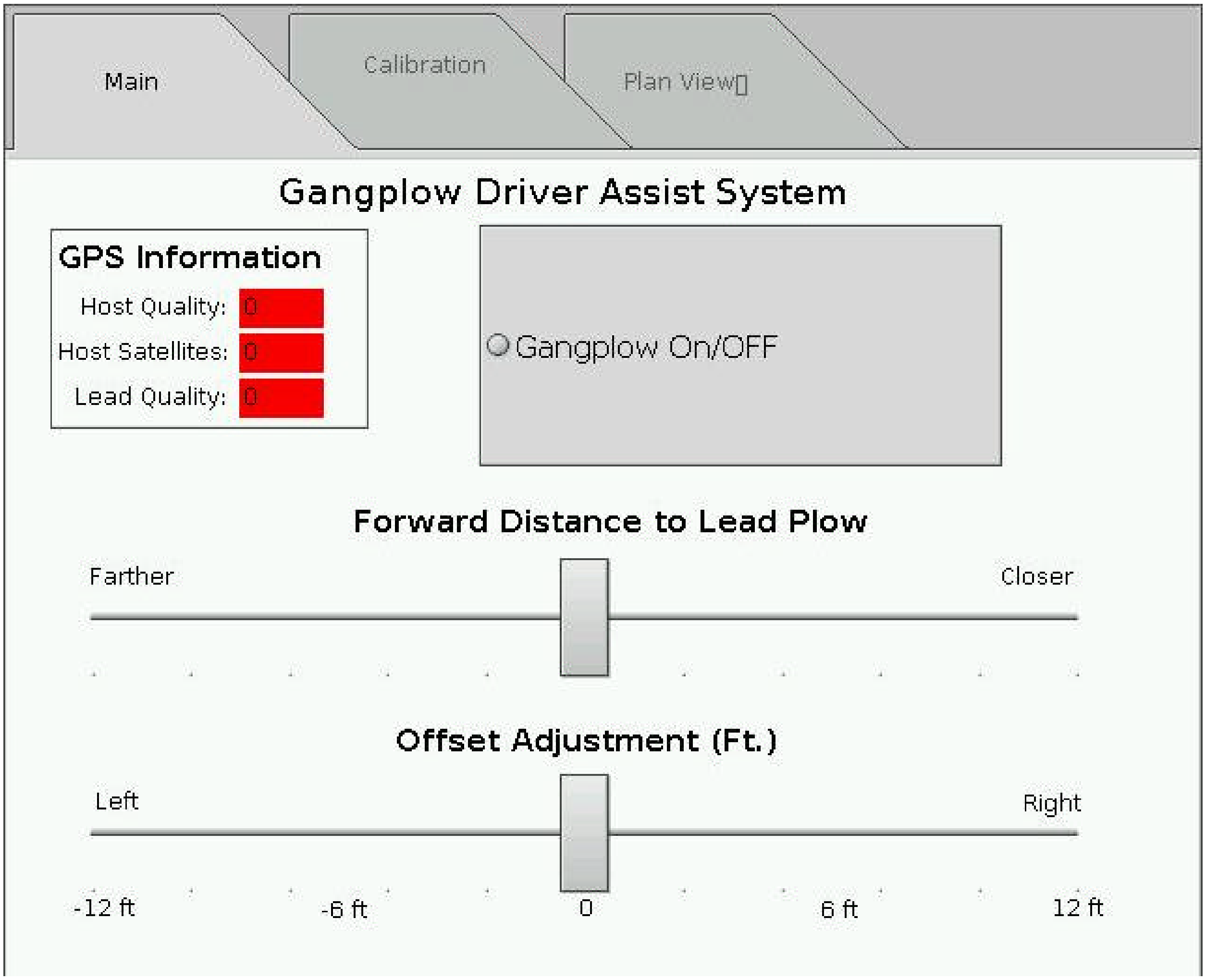


Figure 3-3. Block diagram/signal flow graph of trailing vehicle gang plow control system. Computer 1 uses information from the lead plow to determine steering, brake, and throttle commands. Computer 2 serves as the interface to vehicle actuators, and closes inner loops around steering, throttle, and brake actuators.

The control algorithms and the hardware used to actuate the steering, brakes, and throttle are used to guide the snowplow as it operates in a gang plow situation are fully described in [1]. The performance of this system as it operated on TH 101 North of Rogers, MN, is described below.

System Operation.

The operation of the gang plowing system is straightforward. The operator has a choice of displaying one of three screens on an LCD touch screen/panel. The first screen is the output of the virtual bumper system, which was shown in Figure 2-4 above. The second screen is the primary driver interface, and is shown in Figure 3-4 below.



Gangplow Driver Assist System

GPS Information

Host Quality: 0

Host Satellites: 0

Lead Quality: 0

Figure 3-4. Driver Interface to the gang plowing system. System is implemented on an LCD touch panel, allowing the driver to control the system and view its status/virtual mirror display from a single point.

This screen provides a both a means to monitor the status of the GPS system and adjust the lateral and longitudinal offsets. As originally configured, system control input by the driver included system on/off, longitudinal distance to the lead plow, and the lateral offset from the lead plow.

The baseline forward distance (actually, time headway) to the lead plow was set at 2 seconds. The driver would then adjust his relative position using the slider bar. Moving the slider with his or her finger to the right would decrease the following distance, and vice versa. Under normal circumstances, this offset is usually "set and forget."

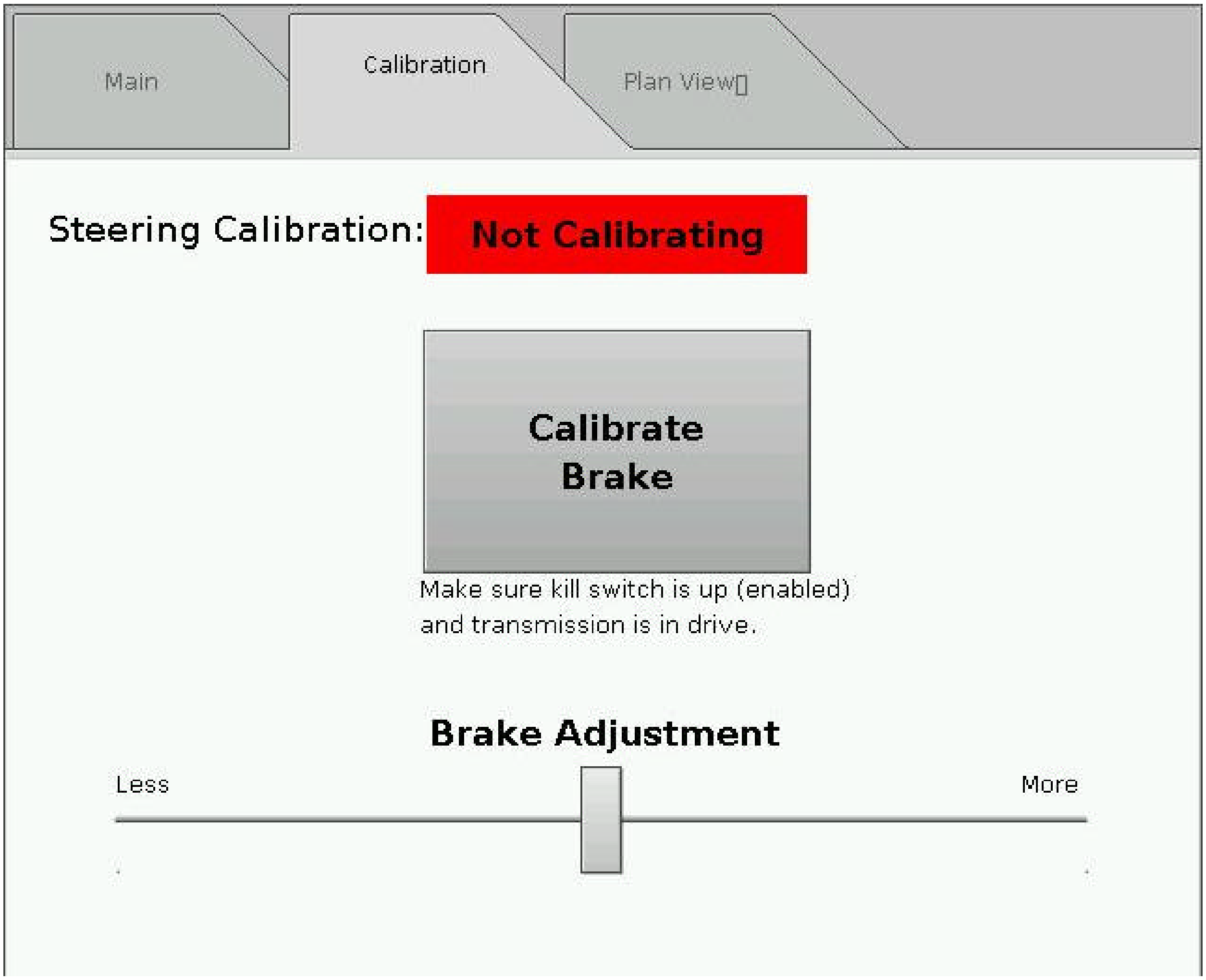
(It is important to note that the time headway controller also includes a safety buffer which prevents the trailing vehicle from getting closer than a preset distance from the lead vehicle. The actual time headway used by the longitudinal controller is the time headway a driver selects plus the safety buffer value.)

Lateral offset was originally set using the offset adjustment slider bar shown in Figure 3-4. After significant on-road testing, the approach to setting desired lateral offset was modified. Instead of the slider, the Emergency Stop (E-Stop) was used to set the offset. In this situation, the driver would manually steer the trailing vehicle to the desired offset. Once the offset was selected, the E-Stop was pulled up into its “on” position. The lateral offset measured at the time the E-Stop was activated became the reference offset the lateral controller used to control the plow.

Figure 3-5 below shows the system calibration page. The first item of note is the steering calibration. When the system was “on” and the E-Stop pulled up, the indicator would move from the red “Not Calibrating” indicator to a green “Calibrating” indicator. (The previous implementation used a semi-automated (but less efficient) calibration scheme to determine the zero point (or the point where the front wheels pointed straight ahead) of the steering system). Modifying the procedure to set lateral offset simplified the steering control and made life easier for the operator.

The second button, “Calibrate Brake” is used to determine the onset of braking for the pneumatic brake system. Before the gang plowing system is used on the highway, the following process is performed. First, the vehicle is allowed to creep along at idle with the transmission in drive. After achieving a steady speed, the brake actuator pulls the brake pedal down at a constant rate. The controller notes the position of the brake pedal at the onset of braking, and establishes that point as a control reference.

The “Brake Adjustment” slider allows an operator to adjust the sensitivity of the automated brake application system. The response of the braking system on the Safeplow research vehicle varies significantly depending on payload (loaded or empty box), temperature, humidity, and the time since the truck was last used (surface rust on the brake drums alters brake shoe/drum coefficient of friction). After the calibration is performed, the operator can change the rate at which brakes are applied to compensate for variations in the brake system and the operating parameters of the truck.



Steering Calibration: Not Calibrating

Make sure kill switch is up (enabled) and transmission is in drive.

Figure 3-5. System calibration page. Steering calibration turns green when the E-Stop is in the "System Active" position. Brake calibration is used to compensate for variations in vehicle operating conditions including payload, temperature, humidity, etc.

Gang Plowing Performance Results.

A series of tests were performed on Minnesota TH 101 North of Rogers, MN. The results from three of the tests are described in detail below. All testing took place between 15 and 22 April 2004. All measurements are based on dual-frequency, carrier-phase DGPS positions which have a mean accuracy of 2-5 cm (see [3]).

Three representative test conditions are provided:

- Low speed (average speed of the gang was 15 m/s (33 mph)). This speed represents the higher end of speeds typically achieved in a gang formation.
- High speed (average speed of the gang was approximately 25 m/s (55 mph)). This is clearly faster than the speed at which snowplows operate, but it does illustrate the performance of the system.

- Weaving. In this instance, a number of lane changes were performed to illustrate the ability of the trailing snowplow to follow the lead plow. Typically, a lane change maneuver is made only to avoid obstacles or vehicles stalled on the roadway; in most instances, plows in gangs maintain desired lane position.

Low Speed. In this test, the goal of the gang was to maintain a speed of approximately 15 m/s for the duration of the test. The results of this test are shown in Figure 3-6 through Figure 3-8. This speed was maintained quite well except for the stop light approach at 5990 seconds, where speed dropped to 5 m/s. Snowplow gangs operate near 35 mph, so the results of Figures 3-6 through Figure 3-8 are representative of those expected when operating a gang in poorer weather.

The nomenclature in Figure 3-6 requires a bit of explanation. In this test, the desired position of the lead plow was the center of the lane. A positive deviation from zero means that the vehicle has moved to the left of the center of the lane; a negative deviation indicates the vehicle has moved to the right of the lane. Performance is quite good, with a maximum lateral error of approximately 20 cm.

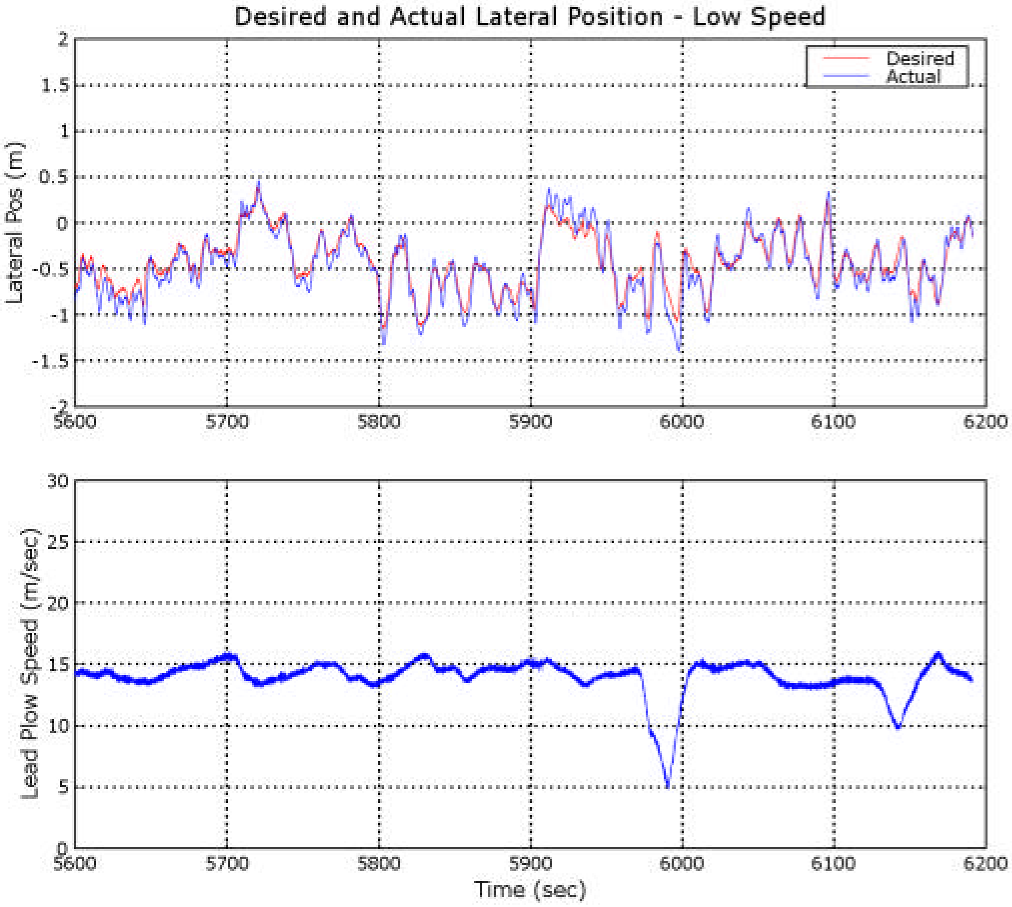


Figure 3-6. Lateral control system performance of the two vehicle gang for a gang speed of 15 m/s (33 mph) on Minnesota Trunk Highway 101 north of Rogers, MN.

Figure 3-7 shows the time headway performance for an on-road experiment. Figure 3-7 shows that the desired time headway is well regulated, but that it does not converge to the desired headway. This lack of convergence is due to the incorporation of the safety buffer into the time headway controller. The safety buffer adds a predefined distance to the time headway reference so that a minimum distance is maintained at low vehicle speeds. Figure 3-7 also shows that time headway performance regulation recovers quickly after the lead vehicle begins moving after the red light.

Figure 3-8 below shows distance headway performance for the low-speed test condition for the same experiment as was presented in Figure 3-7. The desired headway is 2 seconds; at 15 m/s, this translates to an approximate desired following distance of 30 meters. With a constant time headway approach, as the lead vehicle slows, the desired following distance decreases. This is evident in Figure 3-8. Figure 3-8 also shows that the safety buffer maintains a minimum distance between the lead plow and the trailing plow at all times. The lack of convergence from the desired to the actual distance headway is also due to the use of the safety buffer in the time headway controller.

Figure 3-7. Time headway performance for low-speed gang plow test. Safety buffer accounts for lack of convergence between desired and actual headway. Desired headway is two seconds.

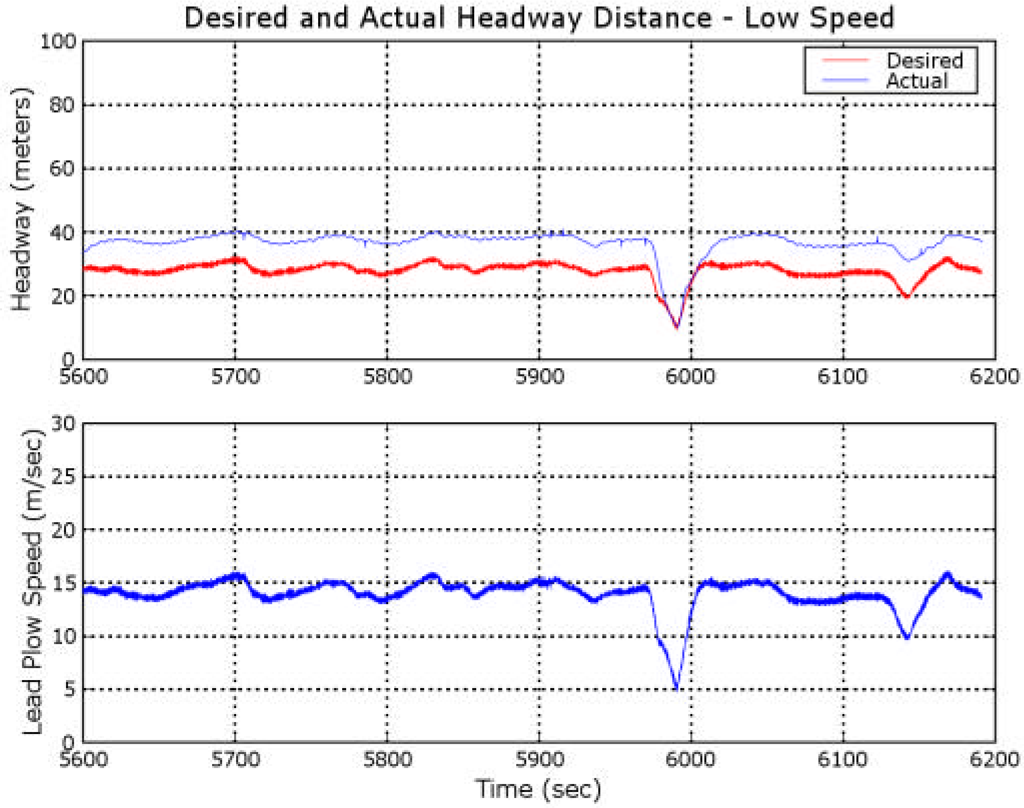


Figure 3-8. Distance headway performance of the two vehicle gang for a low-speed condition (15 m/s (33 mph)). The desired headway is 2 seconds. Safety buffer is responsible for difference between desired and actual distance headway under steady state conditions.

High Speed. A test procedure similar to that describe above for low-speed conditions was undertaken for the high speeds. Typically, gangs of snowplows operate at speeds no higher than 54 kph (35 mph). High-speed tests were undertaken primarily to show the capability of the system, and that it is stable at higher speeds.

Figure 3-9 shows lateral performance at 25 m/s. The lateral control algorithm exhibits higher variability at high speeds than it does at lower speeds. However, the system remains stable, even to abrupt inputs. In Figure 3-9, the lead vehicle makes an abrupt left-shift in the lane at about 9445 seconds. The trailing vehicle follows that shift, but shows a bit of overshoot (approximately 1.5 meters). The lead vehicle continues to vary its lane position, which further excites the trailing vehicle. However, by 9500 seconds, the trailing vehicle oscillation damps out, and continues to follow the lead vehicle.

By lowering system gains, the lateral control system could be made more stable at 25 m/s, but doing so would decrease its performance at the slower speeds at which gang plowing typically occurs. This decreased responsiveness is an undesired side effect. Robustness has been demonstrated by operating at 25 m/s, and lateral control system performance at the 15 m/s (34 mph) speed remains very good.

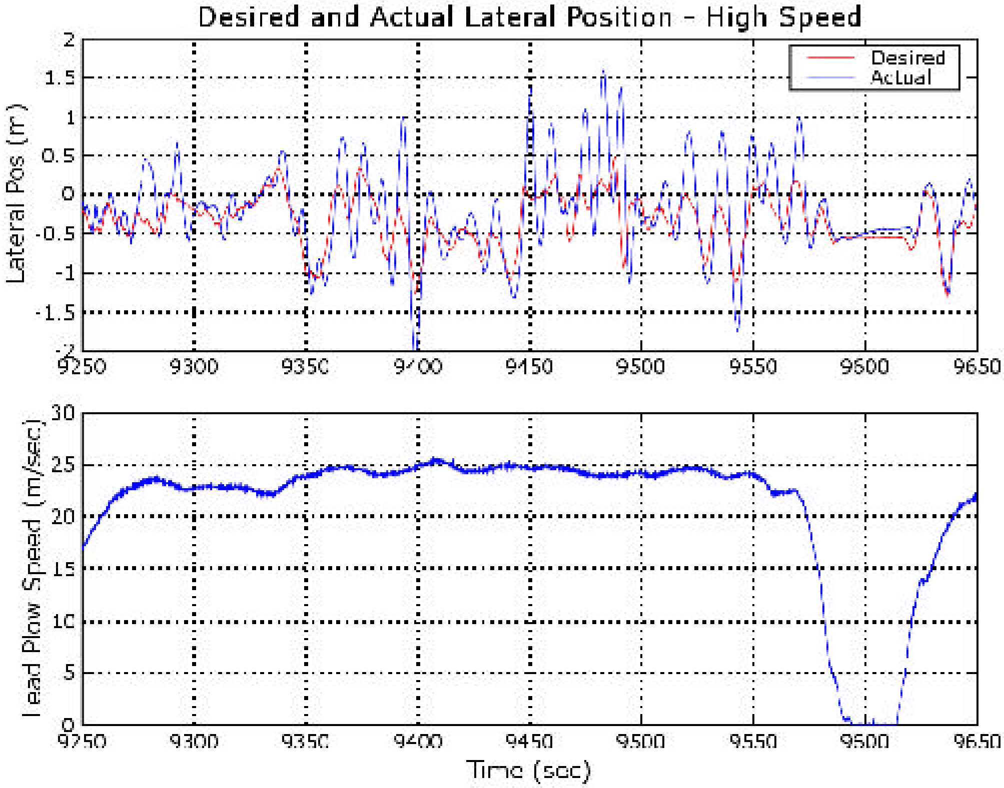


Figure 3-9. Lateral control system performance of the two-vehicle gang for a gang speed of 25 m/s (55 mph) on Minnesota Trunk Highway 101 north of Rogers, MN.

Time headway control performance at the higher speed is shown in Figure 3-10. In this experiment, the desired headway is 3 seconds (compared to the 2 seconds used for the low-speed tests). Figure 3-10 shows that the desired time headway is well regulated. Figure 3-10 also shows that time headway performance regulation recovers quickly after the lead vehicle begins moving after the red light. The safety buffer is responsible for the offset between the desired time headway and the actual time headway measured by the system. It should be noted that the actual time headway is calculated from the distance between the plows divided by the speed of the following plow. This is why the time headway becomes very large as the following plow achieves very low speed in response the lead plow stopping.

Figure 3-11 again illustrates the safety buffer built into the gang plowing control system. In this application, the safety buffer has been set at 7 meters. The safety buffer is also evident in Figure

3-11 at approximately 9610 seconds and at 9690 seconds, where a 7-meter gap is maintained when the vehicles come to a stop.

Figure 3-12 illustrates the ability of the trailing vehicle longitudinal controller to match the speed profile of the lead vehicle. A periodic variation in the speed of the trailing vehicle is displayed in Figure 3-12 from 9300 to 9600 seconds, where the vehicles are traveling at a nearly constant speed. In order to be responsive to variation in speed by the lead plow, the speed controller requires a fairly heavy gain. This gain leads to some oscillation in the speed regulation where constant speeds are the norm. It is important to note that the frequency of this oscillation is sufficiently low as to not be noticed by the driver or passengers in the trailing vehicle.

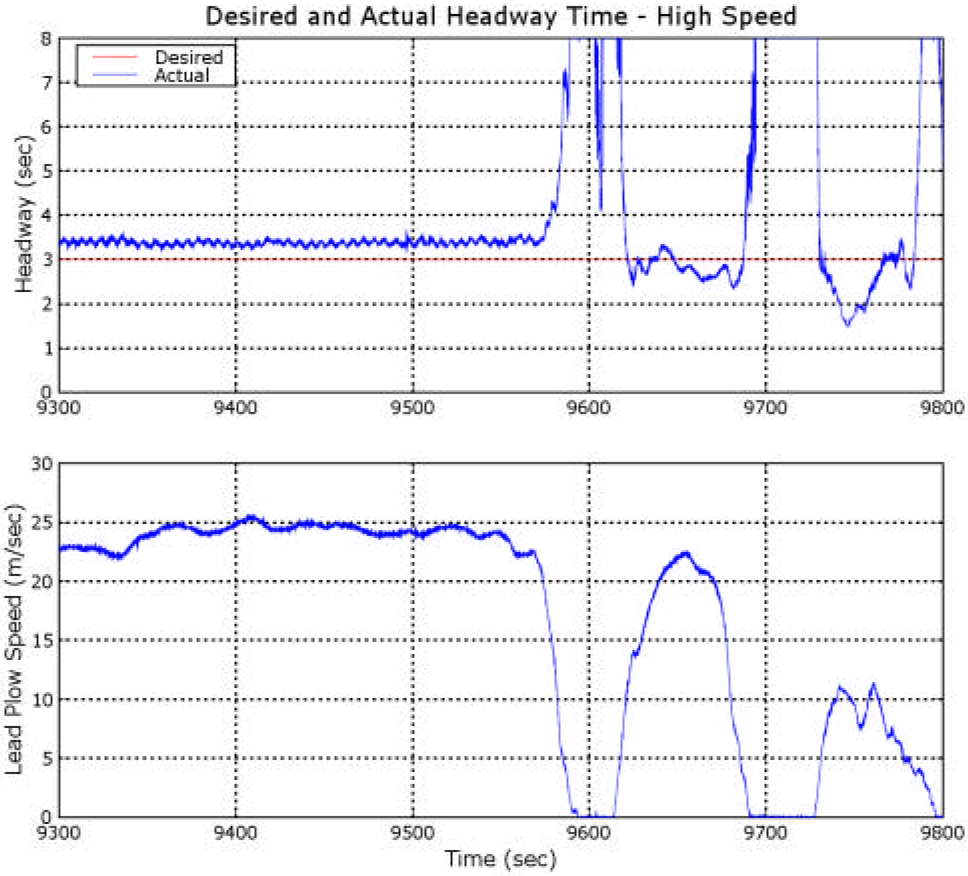


Figure 3-10. Time headway performance for high-speed gang plow test. As vehicle speeds approach zero, desired headway tends toward infinity. The desired headway in this experiment was three seconds.

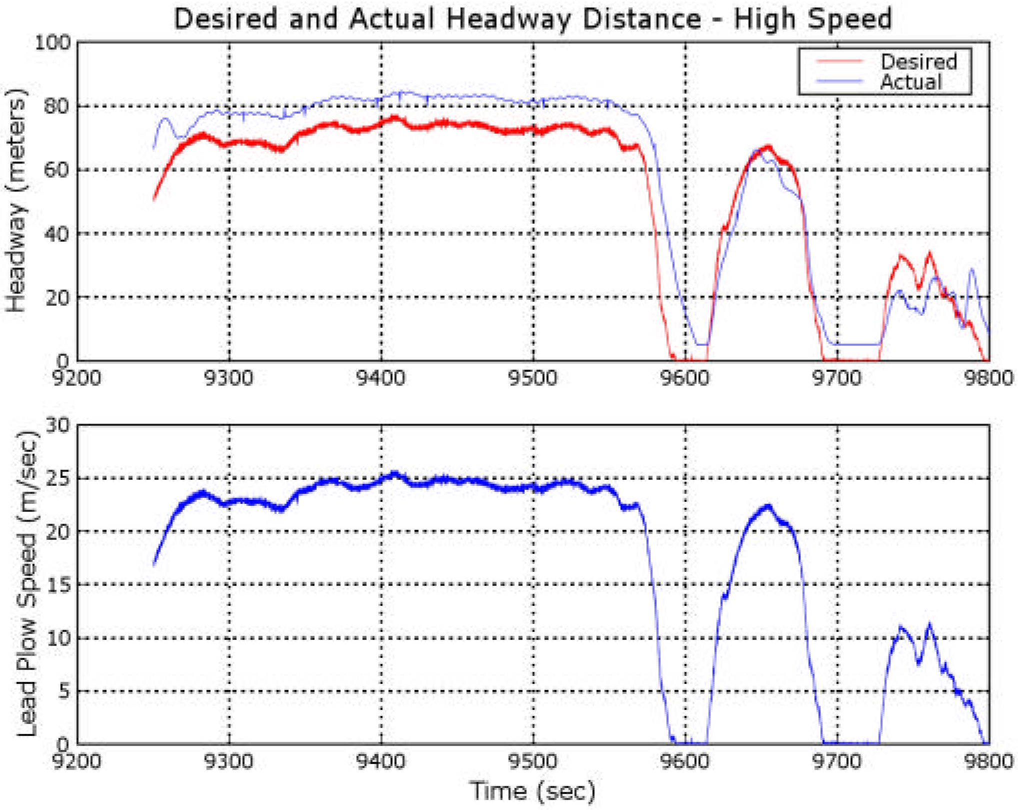


Figure 3-11. Distance headway performance of the two -vehicle gang for a high-speed condition (25 m/s (55 mph)). The desired headway is three seconds.

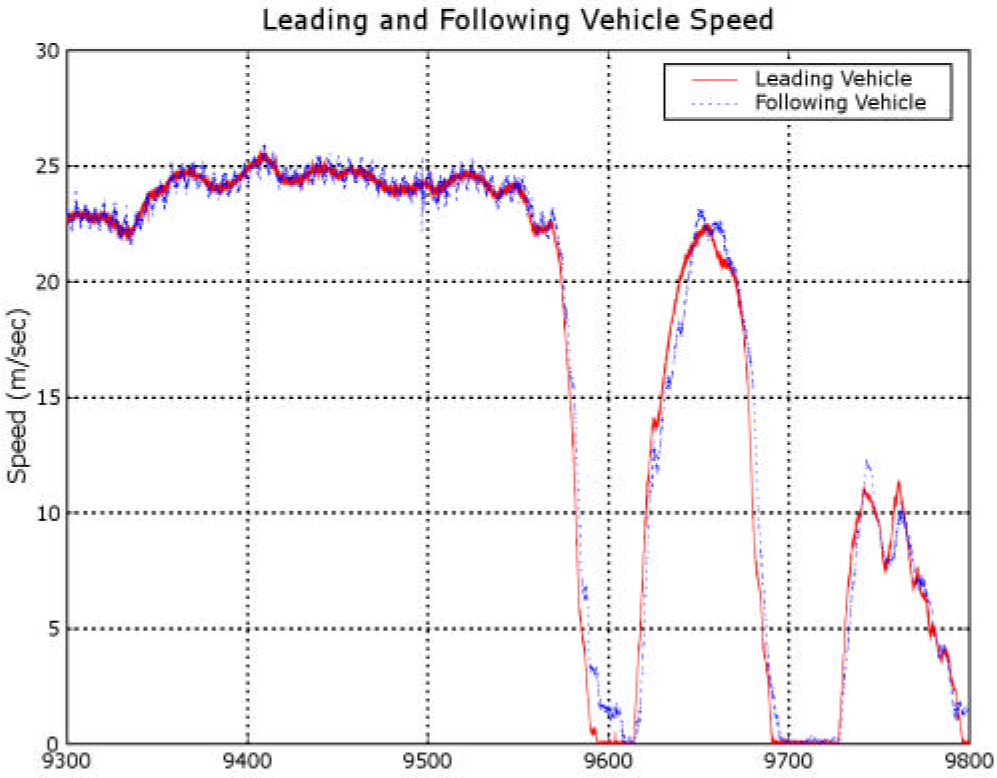


Figure 3-12. Velocity control performance for high-speed (25 m/s) tests.

Weaving. The low-speed test of the gang plowing system most closely represented conditions under which gang plowing occurs. Gang plowing is done at relatively low speeds on fairly straight or slowly curving roads. The high-speed test was performed to provide a measure of the stability and/or robustness of the gang plowing system to higher system speeds. As was shown, the lateral performance of the gang plow system suffered slightly at higher speeds, but the longitudinal performance was only slightly adversely affected.

The weaving test was designed to illustrate the robustness of the system to lateral perturbations to the system. For this test, a lateral offset of zero was selected.

Once the system offsets were configured, the lead plow driver was instructed to weave back and forth in the lane, crossing lane boundaries when it was safe to do so. (Testing occurred during the evening; significant traffic was on the road, making full lane changes difficult). Graphical results are provided in Figure 3-13 below.

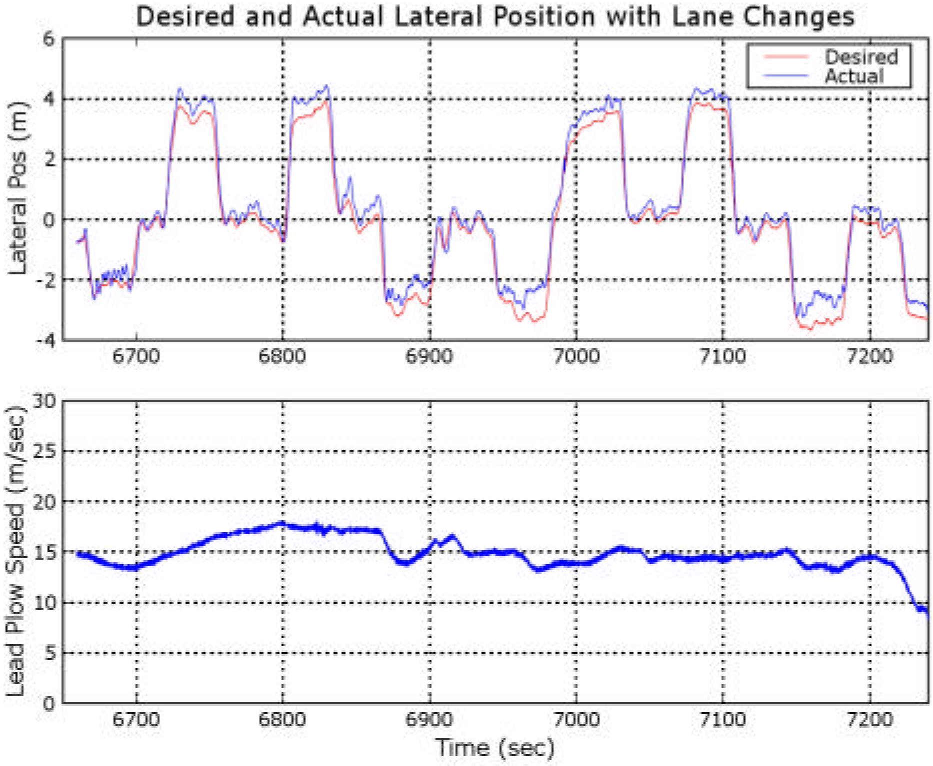


Figure 3-13. Weaving performance. "Zero" is the center of the right lane of the two lane northbound leg of Minnesota TH 101 north of Rogers, MN.

In this experiment, the lead plow performed a number of lane change maneuvers. In Figure 3-13, at approximately 6700 seconds, the lead plow moves from the right shoulder into the right lane of traffic, remaining in the right lane for approximately 20 seconds. At 6720 seconds, the lead vehicle moves to the left lane, and remains in the left lane for 25 seconds. At 6750 seconds, the lead plow returns to the right lane, where it remains for 50 seconds before moving to the left lane at 6800 seconds. Similar patterns repeat, and are shown through 7225 seconds. All of these maneuvers occur at a speed of approximately 15 m/s (33 mph).

Examination of the upper graph shows that the lateral controller shows good performance at this speed. The following vehicle does exhibit some undershoot when changing to the shoulder, particularly at 6975 and 7150 seconds. The system also exhibits overshoot when moving to the left lane from the right lane. This indicates that the lateral offset chosen by the driver of the following vehicle was not zero, but shifted to the left of the lead vehicle by an amount not exceeding 0.5 meter.

Chapter 4
Extension to a Three-Vehicle Gang

Heavy traffic conditions and multi-lane roads in metropolitan areas greatly complicate the snow removal process. Mn/DOT is under significant public pressure to clear roads as quickly as possible after a snowfall. To expedite the snow removal process, Mn/DOT operates snowplow gangs with as many as three, four, or five vehicles.

Using a large number of vehicles adds to the difficulties faced by snowplow operators. First, the localized snow cloud produced by the gang increases significantly. The third vehicle in the gang, for instance, has to deal with snow thrown up by two plows instead of just one. This forces the spacing between the second and third plows to be greater than the spacing between the first and second plows. Matters become worse the further back in the gang.

Second, with heavy snows, momentum plays an important role. The volume of snow moved by a snowplow increases with the relative position in the gang. The third snowplow in the gang moves the snow from the first and second plows as well as its own. If a tight formation is maintained, the snow continuously moves from plow to plow. As long as the snow moves with the gang, plows down the line are able to move it.

When the separation between plows increases, the freshly plowed snow can stop. In this situation, the next plow to approach the snow encounters a large mass with lower momentum which it may not be able to move. If this situation occurs, the gang is broken, and the advantages of gang plowing are lost.

Architecture.

To overcome this inefficiency, an architecture which should lead to improved gang plowing operations was developed. This architecture facilitates communication between all vehicles in the gang, so that any vehicle in the gang can determine the position of all vehicles ahead. The longitudinal control algorithm in a given plow uses speed information from the lead plow and position information from the plow directly ahead to maintain a tight snowplow formation. A tight snowplow formation preserves the momentum of the snow being moved, facilitating efficient, large scale gangs.

The architecture is represented graphically in Figure 4-1. Each plow is equipped with DGPS and a wireless communication transceiver. Each vehicle is identified by its position in the gang. Each vehicle broadcasts its position and speed to every vehicle behind it in the formation. Information regarding the position and speed of each preceding vehicle allows the formation to avoid instability caused by the propagation of error down the gang (often called the “accordion” effect), facilitating a tighter formation than otherwise possible.

Both lateral and longitudinal controllers are used in the multi-vehicle gang. The lateral controller for all following vehicles is identical to the lateral controller whose configuration is described in [1] and whose performance is described in the preceding chapter. The lateral offset reference for each trailing vehicle is set from the lead vehicle. This approach allows each following vehicle to independently adjust its lateral position in the gang without affecting the lateral position of any other plow in the gang. This minimizes the need for a trailing vehicle operator to react to all lateral changes made ahead.

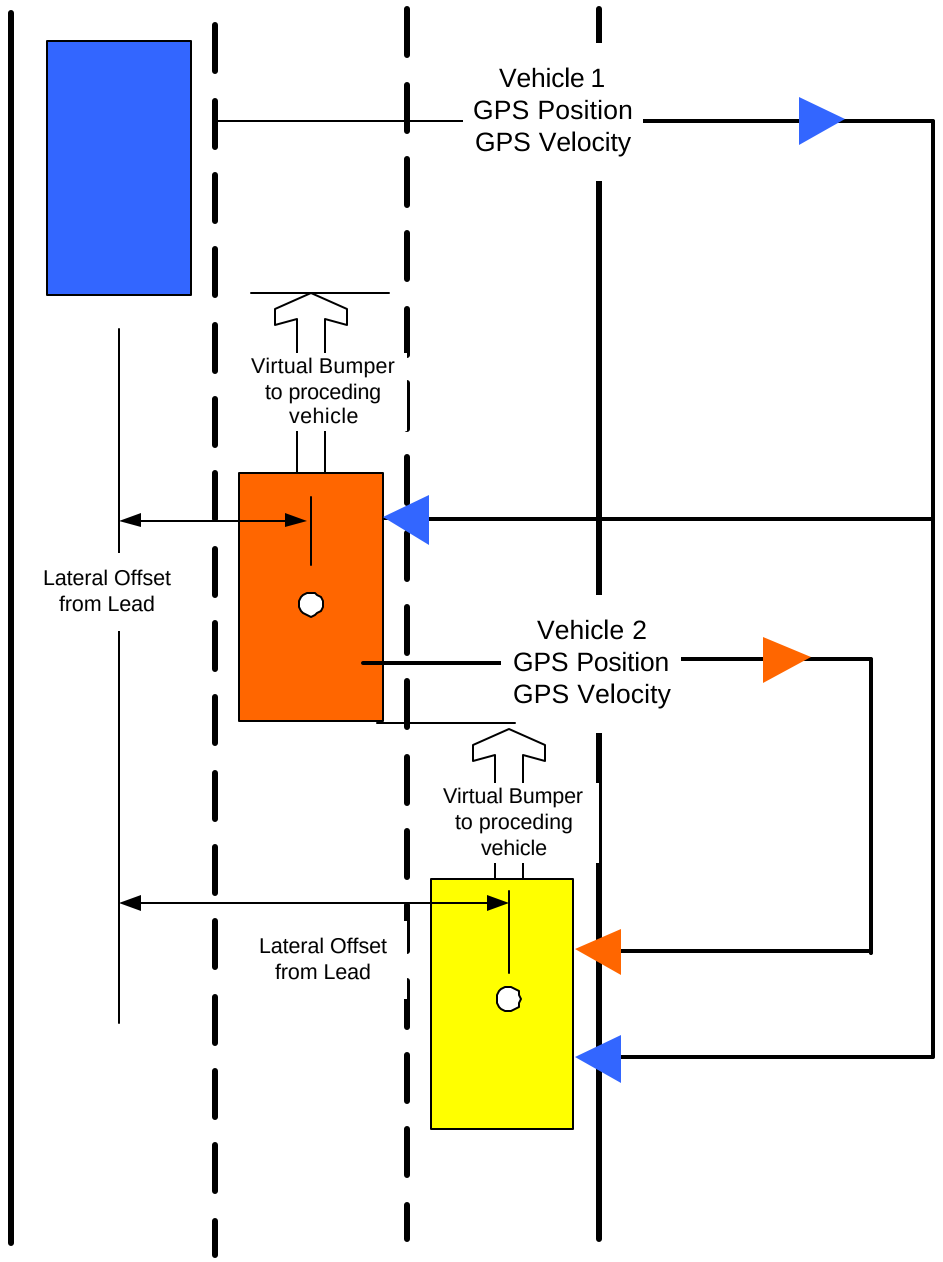


Figure 4-1. Architecture of multi-vehicle gang plow system. Each plow is equipped with DGPS and a wireless communication transceiver. Each vehicle is identified by its position in the gang. Each vehicle broadcasts its position and speed to every vehicle behind it in the formation.

To minimize the accordion effect typically associated with long platoons of vehicle, an inner/outer loop approach to longitudinal control is applied. The outer loop uses the lead vehicle speed as a system reference signal. Each vehicle in the gang receives the lead vehicle's speed, and establishes this as its control reference. The outer control loop adjusts vehicle speed to match the speed of the lead plow. This speed information provides a global control reference for each plow in the gang, allowing each plow to react with a minimum delay to speed changes and to avoid speed error propagation of the gang as a whole.

The inner loop uses the virtual bumper concept [4] [5] is used to achieve the desired headway for each vehicle in the gang. The desired headway time to the vehicle directly ahead is set by the driver as described in previous sections; the desired speed differential between the proceeding vehicle and the following vehicle is optimized to achieve the desired headway. The virtual bumper minimizes range and range-rate errors to the vehicle ahead.

Control throughout the gang is maintained because each vehicle following the lead plow uses the same control structure. By using a single control strategy, variations in system performance are minimized. This will become evident in the following section.

Performance.

The performance of a three-vehicle gang operating under this common communication architecture was evaluated simulation. The basis of the simulation was the dynamic model of the Safeplow research vehicle developed in [1]. This dynamic model of the Safeplow research vehicle includes both lateral and longitudinal components, and has been validated to show good fidelity.

Both lateral and longitudinal performance were investigated in the simulation experiment. Figure 4-2 illustrates ability of this architecture to maintain a desired lateral offset for both the second and third vehicles in the gang. To better illustrate differences in lateral control performance, an offset of zero was specified for both the second and third vehicles in the gang.

The experiment begins with three vehicles at zero lateral offset and zero speed. The lead vehicle longitudinal controller is given a command to accelerate to a speed of 15 m/s; steady state speed is reached at approximately 37 seconds with an assumed maximum acceleration of 0.7m/s/s.

In simulation, the lead vehicle maintains its lane position perfectly until 35 seconds at which point the lead vehicle moves to the left approximately 1.5 meters. Vehicles two and three, however, show some oscillatory behavior up to the 35 second mark. This oscillation is relatively small amplitude (10 cm maximum excursion), and is likely round off and integration errors associated with integrating the closed loop equations of motion for the lateral controller.

The response of the second and third vehicles to the lateral excursion of the lead vehicle does show a bit of delay and some overshoot. It is important to note, however, that the overshoot is relatively slight, with a maximum error of approximately 16 cm. This simulated performance is similar to the performance exhibited by the two-vehicle gang as shown in Figure 3-4 above.

As would be expected, vehicle two and vehicle three exhibit similar lateral control system performance. This is not unexpected because in this architecture, the lead vehicle serves as the source lateral position reference for all vehicles in the gang. The lateral position information received by vehicle two and vehicle three differs by only a small amount of time delay, so the error between vehicles two and three should be small. This is shown in Figure 4-2.

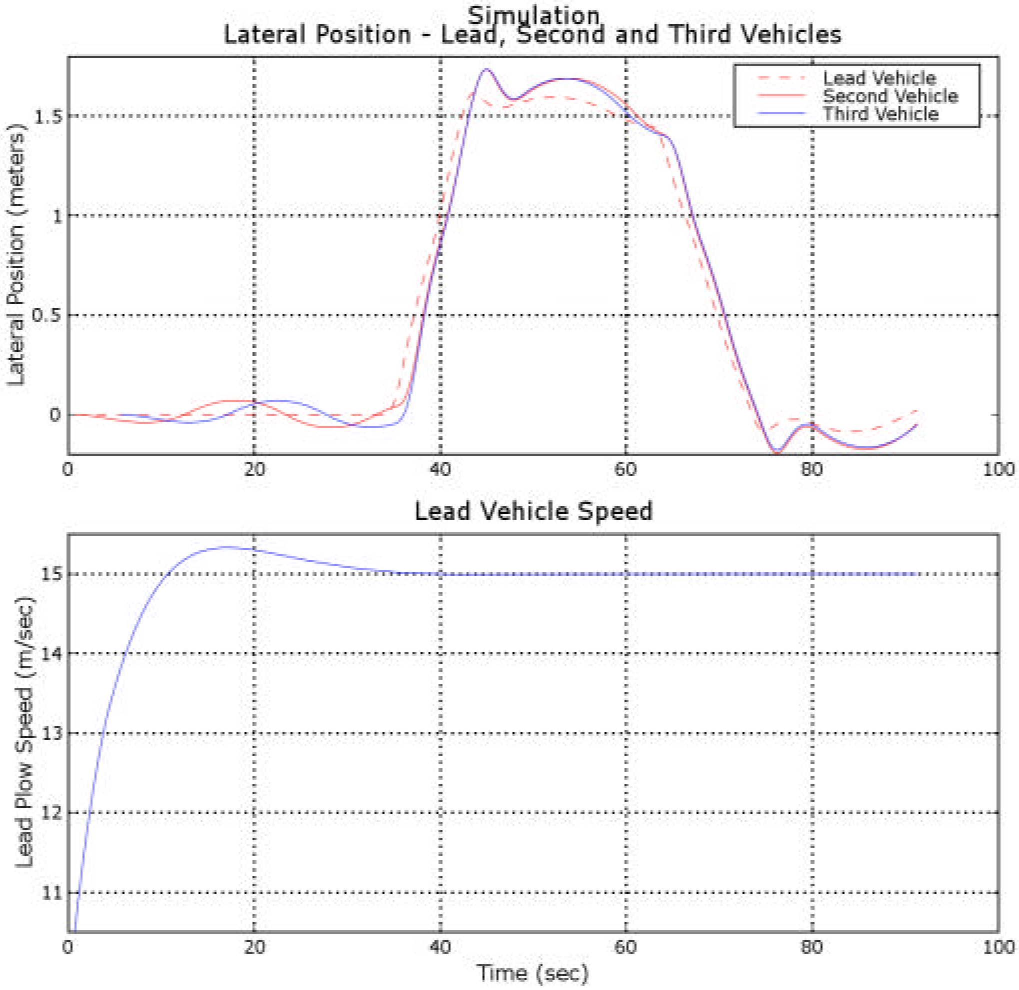


Figure 4-2. Simulated lateral performance of a three-vehicle gang. Lateral and longitudinal models are based on the Safeplow model developed in [1].

The longitudinal performance of the three-vehicle gang is shown in Figure 4-3 and Figure 4-4 below; Figure 4-3 illustrates time headway performance, and Figure 4-4 shows distance headway performance.

The longitudinal control law for the gang plowing system is based on time headway. Figure 4-3 shows that time headway performance for vehicle two is similar to vehicle three. With this control structure, the accordion problem has been effectively dealt with. Figure 4-3 also illustrates that for both vehicle 2 and vehicle 3, the actual headway does not converge to the desired headway. This lack of convergence is due to the incorporation of the safety buffer built into the time headway controller.

Figure 4-3 shows the longitudinal control in terms of distance headway. The effect of the safety buffer is readily apparent between 60 and 80 seconds when the lead vehicle is stopped. Vehicle two and vehicle three are no closer than 18 meters to the vehicle ahead.

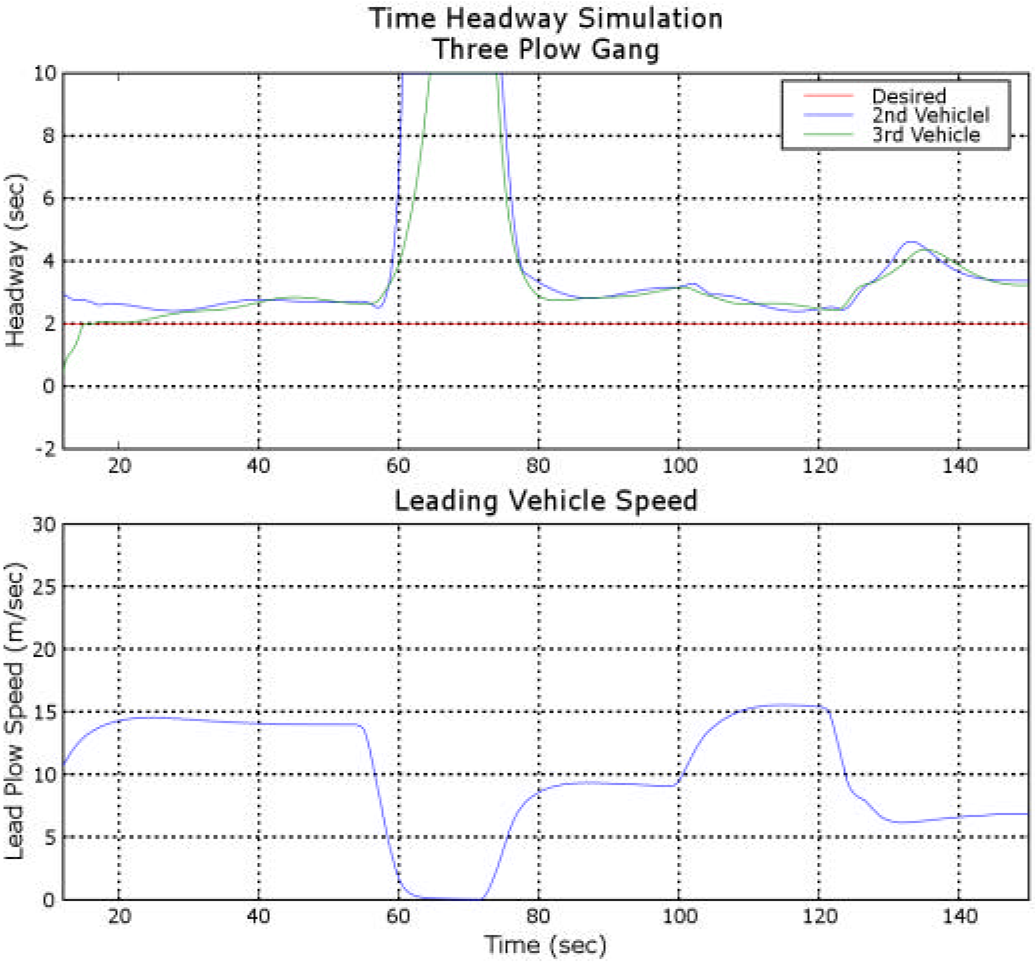


Figure 4-3. Simulated time headway performance for a three-vehicle gang. Headway is measured to vehicle directly ahead (i.e., vehicle two to vehicle one, vehicle three to vehicle two) and is set at 2 seconds. The safety buffer is responsible for the offset between actual and desired headway.

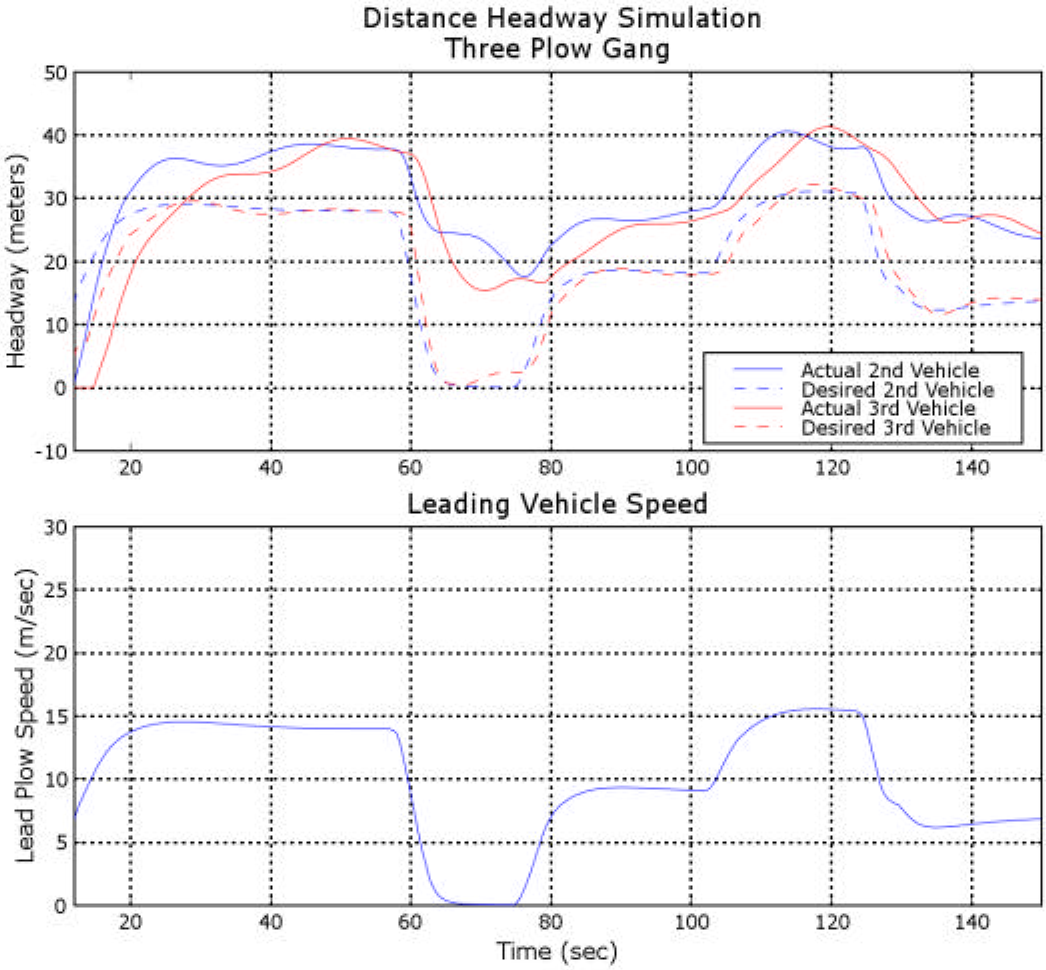


Figure 4-4. Simulated distance headway performance for a three-vehicle gang. Headway is measured to vehicle directly ahead (i.e., vehicle two to vehicle one, vehicle three to vehicle two). Safety buffer is shown between 60 and 80 seconds; the safety buffer maintains a prescribed minimum distance between vehicles. Errors here appear more pronounced than in the time headway case; this is expected as time headway is the parameter upon which the longitudinal controller is based, and distance headway is a surrogate measure of performance.

Clearly, this architecture has minimized the accordion effect suffered by typical vehicle platoons with limited sensing and communication capability. An extension to a larger number of vehicles, provided the communications channels have sufficient bandwidth to minimize time delay, is technically feasible.

Chapter 5
Conclusions and Recommendations

An operational gang plowing system has been demonstrated to work on a Minnesota Trunk Highway. Although the ultimate goal was to perform operational tests in poor weather and low-visibility conditions, mild winter weather, combined with a shortage of Mn/DOT snowplowing staff, rendered poor weather testing impossible. However, on road testing in good weather did show that the system was sufficiently developed for operational gang plowing. Had more resources been available, that testing could have taken place.

Also important is the development of an architecture to support longer gangs. The simulator effort indicates that the architecture would support a much larger gang provided timely, robust communications can be provided. Modern wireless technology (802.11b, g, and Mesh Networks) provides the robust, high bandwidth wireless communication needed by large vehicle gangs.

One application in particular which would benefit greatly from this large vehicle gang capability is winter airport runway maintenance. Airport personnel have only a short time to clear a runway during periods of heavy snow. For example, at MSP International, a gang of up to 24 vehicles will be used to clear a runway. The first wave of vehicles are trucks which use a conventional plow blade; the distance between the blade and the runway is maintained between three and five centimeters. This is done to prevent damage to the tarmac. Behind the snowplows are snow brushes; the job of the snow brush is to remove the last three to five centimeters of snow from the tarmac. Finally, two large snowblowers follow the main gang to blow the snow moved by the plows and brushes up to 150 meters from the runway.

As one can imagine, this is a difficult task, and one which is ripe for automation. The IV Lab intends to continue its dialogue with MSP, with a goal of developing a gang plow system for airport runway maintenance.

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