

An Investigation of User Costs and Benefits of Winter Road Closures

Final Report—June 2005

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AN INVESTIGATION OF USER COSTS AND BENEFITS OF WINTER ROAD CLOSURES

**Final Report
June 2005**

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EXECUTIVE SUMMARY

Although mountainous states have historically closed roads when severe winter weather makes roads unsafe, in the last twenty years, non-mountainous, Snow Belt states have developed road closure policies. Some of these Snow Belt states have also gated entrances to freeways when travel is believed to be unsafe. A survey of the majority of Snow Belt states revealed that some have no policy for closing roads due to winter weather, but those states with weather closure policies generally base decisions to close roads on the subjective evaluations of field personnel who feel that the roadway is no longer safe for travel. Although field personnel may have an excellent understanding of the safety performance of the roadway under current conditions, it places travelers in the position of not knowing whether the road will be closed until unsafe conditions are observed, resulting in unexpected delays.

Severe winter weather makes travel unsafe and dramatically increases crash rates. When conditions become unsafe due to winter weather, road closures should allow users to avoid crash costs and eliminate costs associated with rescuing stranded motorists. Therefore, the benefits of road closures are the avoided safety costs. The costs of road closures are the delays that are imposed on motorists and motor carriers who would have made the trip had the road not been closed. This project investigated the costs and benefits of road closures and found that evaluating the benefits and costs is not as simple as it appears.

To better understand the costs and benefits of road closures, this project investigates the literature, conducts interviews with shippers and motor carriers, and conducts case studies of road closures to determine what actually occurred on closed roadways before and during closures. The project also estimates a statistical model that relates weather severity to crash rates. Although the statistical model is intended to illustrate the possibility of quantitatively relating measurable and predictable weather conditions to the safety performance of a roadway, use of this type of statistical model will allow weather conditions (such as snow fall intensity and visibility) to be used to make objective measures of the safety performance of a roadway in the future.

The literature review and interviews illustrate that not all delays (increased travel time) are valued equally. Expected delays (routine delays) are valued at the generalized costs (value of the driver's time, fuel, insurance, wear and tear on the vehicle, etc.), but unexpected delays are valued much higher because they result in interruption of synchronous activities at the trip's destination. To reduce the costs of delays resulting from road closures, public agencies should communicate as early as possible the likelihood of a road closure. Much to the surprise of the research team, the motor carriers interviewed would appreciate having early notification of likely road closures and unambiguous notice of actual road closures.

This report makes several specific recommendations to State Transportation Agencies (STA) responsible for winter weather-related road closure decisions and specifically to the Iowa Department of Transportation:

1. STAs and State Police need to accurately communicate road conditions and the likelihood of future weather resulting in conditions that may lead to a closure. Information provided to the public regarding road conditions needs to be completely accurate to maintain credibility with the public.
2. The importance of travel time reliability is not very well understood and further research is needed. Understanding the value of reliable travel time can help to place a value on the benefits derived from winter maintenance. Therefore, it is recommended that the winter maintenance community should become engaged in and support research efforts to better understand the value of travel time reliability.
3. Further work is needed to relate safety performance to measurable and predictable weather parameters. These relationships can help highway managers to make closure decisions based on objective information.
4. The Iowa Department of Transportation and the Iowa State Patrol should develop policies to more aggressively evacuate and close roadways once a closure decision is reached.

1. INTRODUCTION

This report investigates issues related to the costs and benefits of road closure due to winter storms. In Iowa and Minnesota and in other states in the region, state transportation agencies (STAs) have started erecting gates to physically close sections of rural freeways during severe winter storms. The purpose of these closures is to keep vehicles off the interstate because the roadway is deemed unsafe and to keep motorists from being stranded if they do become stuck in a remote location. At least in Iowa and Minnesota, these gates are used very sparingly, and both states have closed and gated freeway segments a few times per year.

Road closures have been implemented without any analysis of the benefits and costs or examination of the unintended consequences of a road closure. For example, as a result of a freeway closure, some drivers will divert to lower functional class roadways (e.g., two-lane roads) to continue their trip. These roadways have lower design standards and poor safety performance. Thus, traffic diverted to other routes is at greater risk than if they had continued on the freeway, given that both are exposed to the same severe weather conditions. The purpose of the research reported here is to examine the benefits and costs of winter weather road closure and develop a framework for their analysis.

Initially, our team of researchers believed that we could develop a methodology to evaluate the benefits and costs of road closures. However, we discovered that the problem is more complex than it initially appeared. Although this report provides insights into the costs and benefits of road closure through case studies, it does not provide a methodology that can be used to determine under what conditions a road should be closed. The benefit side of the analysis focuses on the safety issues related to road closures and is covered in sufficient detail. However, the cost of a road closure is much more complex as it is concerned with the value of travel time and the value of travel time reliability.

Issues of travel times and travel time reliability due to severe weather will be addressed by projects identified in the Future Strategic Highway Research Program (F-SHRP) plan for research in transportation system reliability. A plan for F-SHRP was requested by the U.S. Congress in the last Federal Transportation Authorization bill and subsequently developed by the Transportation Research Board (TRB). Currently, the TRB is waiting for Congress to authorize the necessary funds in the next Federal Transportation Authorization bill. The F-SHRP plan developed by TRB identified four research programs that will each require funding at the 75 million dollar level. The project planned in the F-SHRP plan to determine the cost associated with weather-related travel time unreliability and travel time increases is 15 times larger than our project (1). Funding for the F-SHRP is expected as part of the Federal Transportation Reauthorization bill being considered by Congress in the 2005–2006 session.

Background

Many of the mountainous states have always had policies that allow road closures and restrictions when winter weather conditions make roadways impassible. However, STAs in non-mountainous states have not had a heritage of road closures. All states have the authority to declare an emergency and close a roadway for public safety purposes, but it was not until the 1980s and 1990s that several Midwestern states began adopting policies and procedures for the systematic closure of roads due to snow and ice. For example, in the early 1980s, South Dakota adopted policies for roadway closures and began erecting gates to physically close roads (2). In the mid-1990s, Iowa and Minnesota adopted similar policies and erected gates on the entrances to specific freeway routes to prevent motorists from becoming stranded or operating vehicles on unsafe, slippery roads.

A typical ramp closure gate used by the Iowa Department of Transportation (Iowa DOT) is shown in Figures 1.1 and 1.2. This is a simple fence gate that must be manually closed by Iowa DOT maintenance personnel on I-35 north of Ames. This gate is located on the northbound entrance ramp of I-35 at an interchange with Hamilton County Road D20.



Figure 1.1. Iowa entrance ramp gates



Figure 1.2. Left Iowa ramp gate

The Minnesota Department of Transportation (MnDOT) uses an entrance ramp closure gate and a flip-down “Ramp Closed” sign (the sign is not flipped down in the figure), as shown in Figures 1.3 and 1.4. Although MnDOT maintenance personnel make decisions about whether to close the gates and gate operation is coordinated by the MnDOT, the manually operated gates are closed by Highway Patrol and county sheriffs (3). The MnDOT has a few gates on I-90 around Jackson, Minnesota that operate automatically (lowered and raised remotely).

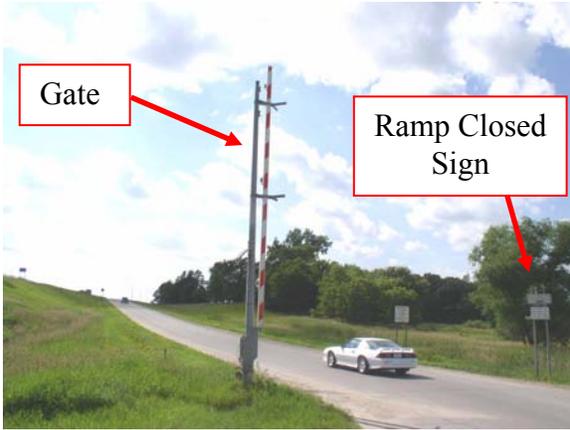


Figure 1.3. Minnesota entrance ramp gate



Figure 1.4. Minnesota flip-down ramp closure sign

Minnesota fines gate violators, while Iowa does not have any specific legal sanction for gate violators. Figure 1.5 shows a mainline gate that can be used to barricade the mainline. This picture was taken on westbound I-90 immediately after the exit ramp to southbound I-35, north east of Albert Lea, Minnesota.

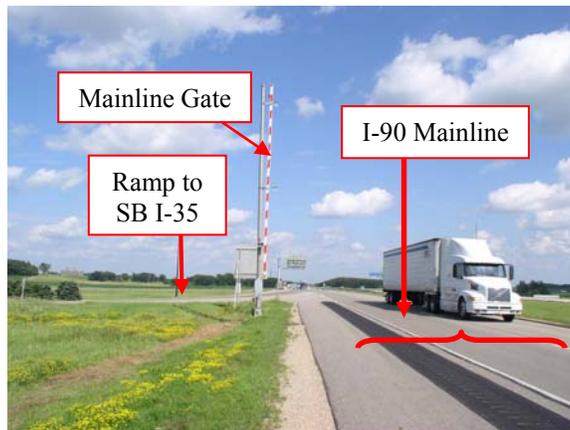


Figure 1.5. Minnesota mainline gate closure

In Iowa, the decision to close a roadway due to winter weather is usually made by the officer-in-charge at the respective Iowa State Highway patrol district office in consultation with the Iowa DOT and is generally dependent on when the highway is judged to be unsafe. The decision that a highway is unsafe is often triggered by a surge of crashes and by the road conditions observed by field staff. In Minnesota, the decision is made by the respective Minnesota DOT area maintenance engineer based on input from field personnel and in consultation with district State Highway Patrol. Although both

would trigger a road closure: when winds reach 45 mile per hour, visibility is reduced to the point where closures are warranted.

Without measurable and objective criteria to determine when a roadway is unsafe, inconsistent decisions are made and the likelihood of a roadway reaching a condition warranting closure cannot be predicted. Road users can clearly determine when weather is severe, but they are given no or minimal advanced warning of a road closure.

Safety Risks of Winter Weather

One of the overwhelming findings of this research is that snowy and icy roadways create conditions that are far more hazardous than we had thought. Typically, in the upper Midwest, we tend to think of brutal winter weather and slippery driving conditions as part of life in the Snow Belt. The average Midwesterner has experienced severe winter weather and recognizes the need to drive more cautiously during snowy and icy conditions. Regardless of the winter driving skill of Midwestern drivers, historical Iowa crash records show that crash rates on interstate highways increase by 13 times during common snowstorms (storms where more than 0.2 inches of snow fall per hour), putting the average driver at roughly 13 times greater risk of being in a crash (4). In extreme winter events (low visibility and blowing snow), the risk of being in a crash can be 20–30 times greater than during clear conditions.

To put this in perspective, Compton et al. studied the relative risk of being in a crash at varying blood alcohol content (BAC) and found that the risk of having a crash was elevated by 2.69 times when the driver had a BAC of 0.08 (the legal limit in most states), by 4.79 times when the driver had a BAC of 0.10 (the legal limit in most states prior to 1998), and by 13 times when the driver had a BAC of 0.13 (5, p. 42). Admittedly, this comparison must be qualified. Compton et al. conducted their study in urban areas and, although the authors do not mention the location of their samples, the majority of BAC involved crashes were on city streets. Our information for elevated winter crash rates is for rural interstate highways—the lowest crash risk highways. However, if all things remain equal, driving in a snowstorm elevates your risk of a crash far more than driving legally impaired. Although the crash risk is the same, we tend to treat driving in wintry weather as an unavoidable consequence of living in the Snow Belt, while we treat driving alcohol impaired as a civil and sometimes a criminal offence. The tolerance of drivers in unsafe wintry conditions suggests that drivers and policy makers really don't understand the risk of winter driving.

In Iowa, winter weather conditions exist on the state's roadway for a small proportion of the year. Generally, a storm will cross the state and pavements will be bare again within 24 hours. Of course, it may take much longer to recover from some storms, but for most storms, the time until bare pavement is much shorter than 24 hours. Using Ames as representative location for the entire state, over a 20-year period, Ames experienced an average of 18.6 snow events of over 0.1 inches per year (6). Using 24 hours as the average length of time a roadway is impacted by a storm and average of 18.6 storms per

year, on the average, snow impacts traffic for about 450 hours per year, or around 5% of the year.

Table 1.1 shows a summary of 5 years of Iowa crash records for crashes on all Iowa public roads. The table compares the number of crashes, the severity of crashes, and economic losses due to crashes during the entire 5-year period to periods of the same years when winter weather condition existed. Winter weather-related crashes are considered to be those where the reporting officer noted the surface conditions as ice or snow covered or the weather conditions were snow or sleet. Over the 5-year period (1996–2000), 19% of all crashes occurred during winter weather. Therefore, 19% of the crashes took place during snowy and icy conditions that only existed 5% of the time. To further emphasize the relative hazards of winter weather, we also know that during winter storms, traffic volumes subside while prudent drivers postpone trips to other times or cancel trips. The percentage of commercial vehicle crashes that occur during winter weather (23%) is higher than the average, which is partly because trucks are less likely to differ their travel during winter weather, as we will see in the analysis portion of this report.

The severity of crashes decreases during winter weather. Traffic is traveling at slower speeds and, as a result, crashes become less severe than they would be under clear conditions. To some extent, the reduction in severity counteracts the increase in crash frequency during winter storms to minimize the overall severity of winter weather related crashes. In Table 1.1, we have calculated the average severity of crashes and winter weather-related crashes using the Iowa DOT’s crash severity index (fatality = 200, major injury = 100, minor injury = 10, and possible injury and PDO = 1), and the average severity is reduced by only 18% during winter weather (from 9.4 to 7.7 average severity per crash). Similarly, we have calculated the average economic loss per crash using the Iowa DOT’s loss values (fatal = \$1,000,000, major injury = \$150,000, minor injury = \$10,000, possible injury = \$2,500, and PDO = reported value), and the average economic loss is also reduced by 18% (\$19,374 to \$15,866 average loss per crash). The modest reduction in crash severity is hardly a compensation for the increased crash frequency.

Table 1.1. Comparison of winter weather-related crashes to all crashes, 1996–2000

	All crashes		Winter weather crashes				
	Average Crashes	Average severity	Average loss	Crashes	Percent of total crashes	Average severity	Average loss
Commercial vehicles	22,048	13.6	\$ 39,103	4,962	23%	11.5	\$ 33,860
All vehicles	342,732	9.4	\$ 19,374	64,410	19%	7.7	\$ 15,866

By closing roadways during the most severe winter storms, STAs can avoid elevated crash costs and the costs associated with rescuing injured and stranded motorists. On the other hand, closing the roadway creates productivity losses for the freight and people that would have moved along a corridor had the corridor not been closed. A simplistic method for calculating the cost of a closure would be to treat a road closure like the travel time

costs in an engineering economic evaluation of a highway improvement. The economic analysis of a highway improvement calculates the travel time savings associated with the improvement. Conversely, a road closure would simply make travel time longer. We could simply apply the same costs coefficient to determine the cost of making a trip longer. However, a road closure cannot be treated so simply, and the road closure problem has many more dimensions. They include the following:

- Depending on the weather conditions (snow fall intensity, wind speed, visibility, temperature, etc.), some drivers decide to avoid winter weather driving risks and many trips will be postponed and/or cancelled. Given that trips would have been cancelled due to weather, independent of a road closure, the loss of these trips can hardly be defined as a cost due to the road closure.
- There may be synchronous activities that are dependent on a freight delivery and, when a freight shipment is delayed, activities at the destination may be impacted. Delaying crews or assembly lines due to a failure to make a delivery on time may result in a cost penalty far greater than the shipment itself.
- Regardless of whether the road is closed, some freight shipments and some travelers will continue using the route or parallel routes. For example, even though road closures on I-35 north of Ames are implemented with positioning a gate across entrance ramps, the Automatic Traffic Recorders (ATRs) on I-35 almost never recorded fewer than 20 vehicles per hour and typically there were volume of 50 to 150 vehicles per hour even though the roadway was closed.

Without doing extensive analysis of traveler tolerance of winter weather driving risks and the dependence of activities at the receiving location on freight shipments, it is difficult to estimate the costs associated with a road closure. However, it is clear that advanced warning of the potential of a road closure will significantly reduce the associated costs. With advanced warning, travelers can adjust their schedules to accommodate the road closure and shippers and receivers can adjust the schedule of synchronous activities.

Report Organization

This report is organized into six chapters:

Chapter 1: Establishment of the complexity inherent to understanding the benefits and costs of road closure and identifying the issues associated with road closures.

Chapter 2: Review of available literature. Although there is currently little literature that addresses road closures due to winter weather, there are analogous situations that can help illustrate the issues related to closures.

Chapter 3: Collection of interviews with shippers and carriers to obtain their perspectives about issues related to road closures and winter storms.

Chapter 4: Discussion of case studies of actual closures of I-35 in Iowa and I-90 in Minnesota.

Chapter 5: Discussion of development of a statistical model that relates weather conditions to crash rates on I-35 in northern Iowa. Although this model is just a prototype, it provides a framework for the development of a model which could be used to correlate related or actual weather conditions to the expected safety (as measured by crashes) of a roadway, thereby providing an agency with objective and predictable measures for determining whether a roadway is unsafe and a closure is necessary.

Chapter 6: Conclusions and recommendation for future research.

2. LITERATURE REVIEW

The following chapter documents some of the relevant literature related to winter weather road closures. The only literature we found regarding winter road closure were documents produced by State Transportation Agencies (STAs) that document their processes and procedures for closing roads, but not the benefits and costs of road closures.

This chapter is divided into five sections:

- A discussion of studies that document the benefits and costs of winter maintenance
- A discussion of road user costs due to road closures in an attempt to put the discussion of road user costs into the context of the road closure issue.
- Costs of delay to travelers
- Costs of delay to freight shipments
- Conclusions

Studies That Document the Cost of Winter Maintenance

Measuring the benefits of snow and ice removal is much like the measurement of any other road user benefit. The direct benefits are those that are accrued by the user and indirect benefits are those that are accrued as a result of the direct benefits. A fairly common transportation example of direct benefits and indirect benefits is the relationship between new or improved transportation facilities and property values. When a new or improved roadway provides better access to land, travel costs for accessing the land decrease and property values increase. In this example, the primary benefits are the reduced road user costs and the secondary benefits are increased property values. The benefits of the road can either be measured through the primary benefits or secondary benefits, but not both. To count both would be inappropriate and is known as “double counting.”

Typically, the primary benefits of snow and ice removal include improved safety, reduced travel time, and improved travel time reliabilities. A few studies have tried to evaluate the benefits through secondary effects. For example, Igarashi attempted to measure the benefits of snow removal and the quality of snow removal based on the variations in property values in Japan (7, 8). In other words, the researchers believed that properties located on or near roadways with a higher level of winter maintenance would have higher market values. Unfortunately, the myriad of characteristics associated with land value makes it very difficult to isolate the impact of the quality of snow removal.

One of the most widely referenced and quoted studies concerning the benefits of snow and ice removal through secondary impacts was conducted by the Salt Institute. This report estimated the statewide financial impact a winter storm would have if it crippled

the transportation system of an entire state (9). The study assumes that a storm causes almost all transportation to cease operation for one day. The researchers assume that without snow and ice clearing services during a severe winter storm, all movement of workers from home to work and shoppers to stores would cease. The authors of the report assume that some essential services will continue (such as health care services), but at a reduced level. The authors forecast the income losses, tax revenue losses, retail trade losses, and the ripple effect of those losses from such a storm. The Salt Institute study provides estimates for Iowa and eleven other states and two Canadian provinces. In Iowa, for example, the authors estimate that the cost of statewide shutdown would cost about \$60 million per day. The authors note that with a state the size of Iowa, such a statewide shut-down is extremely unlikely and that the purpose for the estimate is to provide an order of magnitude estimate of the cost of a major snow storm when “remedial actions” are not undertaken (clearing snow and ice).

These numbers provide a nice estimate of the worst case scenario, but are not indicative of a real-world situation, which the authors acknowledge. In reality, the costs imposed on a state by a severe storm would be some fraction of the Salt Institute estimate because it is unlikely that a storm would cover an entire state and cause a shutdown of all government offices, schools and university, industries, and businesses.

Most other benefit studies do not assume that traffic ceases completely and instead assume that although traffic continues to move, quality of service declines. For example, Kuemmel and Hanbali studied the benefits of the application of salt to de-ice roadways. Their assumption is that without de-icing salt, travelers will be delayed and roadways will become more hazardous. Kuemmel and Hanbali found that during the first four hours following the application of salt during a winter storm, the direct road user benefits were \$6.50 for every \$1.00 spent on maintenance operations (10). In addition, crash costs were found to decline by 88% following the application of deicing salt.

Morisugi et.al. measured the benefits of snow removal as function of travel time (11). Their methodology assumes that the quality (and cost) of winter maintenance is a function of the ability to keep the pavement as close to bare as possible. The authors also assume that the relative speed that a vehicle is able to travel is a function of the amount of snow and ice that covers the pavement, where bare is ideal and not plowing at all creates the worst condition. In other words, the researchers believe the benefit of snow removal is travel time savings (in comparison to the travel time without snow removal) and the cost is the cost of winter maintenance activity.

Perhaps, the most comprehensive benefit study was a Federal Highway Administration (FHWA) pooled fund study lead by the Utah Department of Transportation, where eleven Snow Belt states pooled their funds to create a comprehensive system to examine both the benefits of snow removal and the direct costs of winter maintenance, including the costs of externalities of winter maintenance (e.g., environment damage done by deicing chemicals) (12). The objective of the project was to develop a computer program that defines the optimal level of effort (number of trucks for a given set of highways) during a snowstorm of a specific intensity.

In developing such a computer program, the researchers' intentions were to comprehensively gather the user costs from winter storms. They concluded that winter weather has impacts on several traffic characteristics and they attempted to quantify the impacts of snowy weather on crash rates, user delay, traffic volumes, and vehicle speeds. The computer program was to be developed in five modules. The modules were to be used to estimate the maintenance cost, the traffic and safety costs, environmental costs, and the costs of structural deterioration (bridge corrosion) and vehicle corrosion when achieving a given level of service on the highway.

The researchers calculated the additional delay as the difference between the speeds at the assumed level of winter maintenance service and the normal speed multiplied by the distance traveled. Speed was estimated using data from the member states for varying levels of snow covering the roadway (winter maintenance level of service). This was then multiplied by a cost for comfort and convenience, operating costs to cars and trucks, and the wages lost through tardiness and absenteeism. The only operating costs included were the additional fuel consumed due to the greater wheel resistance from the snow.

Perceived personal discomfort by motorists was assumed to be equal to what they would pay to avoid a delay. The researcher uses a value of willingness to pay derived by another study. What motorists were willing to pay to avoid a delay was multiplied by the delay time to arrive at an estimate of the value of delay. The cost of tardiness (lost wages) was the delay time multiplied by an average wage rate.

The researchers attempted to link crash rates to level of service but the analysis failed because there were not sufficient data to perform the analysis. For this reason, crash costs were not included in the final economic analysis. Also not included in the economic analysis were environmental costs, structural deterioration, and corrosion, since these costs were hard to evaluate on a storm-by-storm basis as they are the result of long-term application of deicing chemicals.

All the models provide input to arrive at incremental benefits and incremental costs of increasing levels of winter maintenance. The incremental benefits of winter maintenance are reduced crashes and reduced delay. The benefits are the reduced road user costs. The incremental costs are the costs of increased levels of maintenance needed to provide better levels of service. The incremental costs are the added costs associated with maintaining the facility.

Although these studies are insightful, they are addressing a problem that is very different than the one we face in this project: the closure of the roadway to all traffic. In the case of a road closure, the issue is not necessarily a trade-off between additional maintenance costs and road user costs. It is a trade-off between two types of road user costs. If a roadway is closed when it is unsafe due to winter weather conditions, road user costs are reduced because there are fewer crashes. However, a road closure will delay road users that would have traveled during inclement weather and complete the trip to their destination without incident. This delay is the cost of a road closure. Thus, the decision to close a road is really a trade-off between safety costs and imposed travel delays costs.

Road User Costs Due to Road Closures

There are essentially two types of road user costs that must be considered when closing a road: safety costs and travel delays. Crash rates have been found to increase dramatically as winter weather conditions become more severe. As the rate of crashes increases during inclement conditions, safety costs increase correspondingly.

Imposed travel delay costs consist of two parts: expected delay and unexpected delay. To illustrate this, suppose a traveler is making a trip between Des Moines, Iowa and Minneapolis, Minnesota, which normally takes four hours. Also, suppose on the traveler's next trip she is delayed because a road is closed due to high winds and blowing and drifting snow just north of Des Moines. The roadway remains closed for three hours until the winds subside. When the road is re-opened, travel is resumed north of Des Moines, but the snowy conditions slow traffic and the trip's travel time is now seven hours. Thus the door-to-door travel time is ten hours (three hours delay plus seven hours travel time). We could assume that the cost of travel to this traveler was ten hours of unproductive time, as opposed to the normal cost of four hours of unproductive time. A six-hour increase in unproductive time is caused by the road closure and the poor driving condition. This analysis illustrates the generalized costs of delay. Generalized costs are the hourly travel time costs (e.g., we might assume that this equals the hourly wage of a traveler on a business trip) and the direct costs (e.g., fuel, automobile ownership costs, insurance). If this were a trip with no synchronous activities waiting for the traveler's arrival in Minneapolis, for example a trip to visit the Art Institute in Minneapolis, the only costs associated with this delay might only be the generalized costs.

However, in a more realistic situation, if the traveler knew that the conditions were likely to warrant a road closure, the traveler would probably stay in Des Moines and find something productive to do; for example, visit the Des Moines Art Center. However, if the trip is one where synchronous activities are going to take place once the traveler arrives in Minneapolis, the delay will impact more than just the traveler. The delay will impact those activities that must be postponed until after the traveler's arrival. For example, suppose the traveler is a professor at the University of Minnesota and a failure to arrive at class on time will cause all of her students to spend unproductive time traveling to class only to find that class is cancelled and that the information not covered by this class has to be covered during a different class or not covered at all. In this case, the road closure has not only resulted in costing the professor several unproductive hours but has resulted in the secondary costs of unproductive time accrued by the entire class.

The above example makes the rather naive assumption that the professor's travel has only two outcomes: either she arrives on time and the class meets as planned or she is delayed and the class is canceled. In reality, the professor would likely call a colleague or a graduate student and ask them to take the class and the class would meet regardless of whether the professor arrives on time or not. The professor, recognizing that she/he was not going to make it to Minneapolis in time for the class, might stop and share research results with a peer at Iowa State University. Thus, the professor has found a way to adjust and minimize the costs of travel interruption. The ability to adjust is something we

intuitively understand but is difficult to quantify. We also intuitively understand that given more advanced warning of a delay, travelers have a greater ability to adjust and accommodate a delay. It is an unexpected delay that provides the traveler the least opportunity to adjust synchronous activities and results in the highest costs.

When we examine freight transportation, we find similar relationships with synchronous activities at the trip's destination. The costs of a delay will be greater for shipments with synchronous activities that will take place when the shipment arrives than for shipments without synchronous activities. For example, a delay of a just-in-time delivery may stop work for entire manufacturing facility and result in substantial secondary costs, but a delay for a commodity that is stockpiled at the destination (e.g., grain) may only result in a loss of the generalized costs associate with truck and the driver.

From these examples, we can see that the cost of delay for a traveler is very dependent on characteristics related to the trip and the trip maker, such as the flexibility of the arrival time, the type of trip (business or social), the income of the traveler, distance of the trip, etc. The costs associated with the delay of a shipment depend on the value of synchronous activities at the destination, the value of the shipment, the quantity shipped, the perishability of the shipment, and other shipment attributes. Another key variable in calculating the cost of delay is the amount of advanced notice given that a closure of a roadway is likely to occur. With advance notice, the traveler is more likely to be able to make alternative arrangements and the shipper can reduce the costs associated with missing delivery schedule. To understand this further, we investigated literature addressing service disruptions and unexpected delays for both travelers and freight.

Cost of Traveler Delays

Most studies of the cost of traveler delay concern situations with incremental changes in travel time or delay. For example, a typical study would be an investigation of the reduction in travel time (traveler benefits) resulting from grade separating the intersection of two busy highways. In this case, the new alternative (grade separation) reduces travel time in comparison to the existing condition. In a winter maintenance example, we could assume that the benefits of a higher level of winter maintenance service include vehicles being able to travel faster, reducing travel times. Therefore, the user cost reductions (user benefits) are spending less time traveling. However, in the case of a closure, the traveler is not traveling and there are likely to be other options for the use of this time. For example, if a driver is forced to stop due to a road closure they might find some place to stay and continue to work on a laptop computer or read a book. These are activities that the driver could not engage in more typical analysis. Therefore, even if the traveler has no advanced warning of the closure, it is not the same as conventional change in travel time.

Assuming a traveler is not given information in advance of the closure (at their trip origin) and simply heads into the road closure and waits for the road to be re-opened, the costs of delay can be broken into two parts. The generalized cost per hour and the cost per hour of travel time unreliability (unexpected delay). Most situations where

researchers have tried to evaluate travel time unreliability have dealt with incidents in congested traffic where unexpected delays might be a few minutes to 30 minutes. However, in the case of a road closure, the delay will be from a few hours to as much as one or two days. Therefore, applying the results of existing travel time studies to a road closure may be inappropriate because of the difference of the context.

A recent study by Small, Winston, and Yan identified the value of travel time and travel time reliability through the use of revealed preference (RP) and stated preference (SP) data (13). RP is where choices are observed and the researcher uses these data to determine the relative importance (value) of the attributes the decision maker considered in making a choice. In this case, the researchers studied State Route 91 in California where drivers have a choice between taking the free lanes which are often congested or a tolled lane that is less congested and usually provides more reliable travel times. By knowing whether the driver chose to pay the toll and the relative travel time performance of the free-lanes versus the toll lanes, the researcher can estimate the value of travel time and travel time reliability with the use of a discrete choice model. SP uses a simulated situation where a driver has to make the trade-offs between the toll and travel time reliability. SP is generally considered a less robust technique than RP because SP illustrates what a driver thinks she/he will do, while RP illustrates what a driver has actually done.

Small, Winston, and Yan found that based on RP data, the median value commuters placed on travel time was \$20.36 per hour. The median value on travel time reliability (the median value that a driver would pay to avoid an unexpected delay) was \$19.31 per hour. Although the numbers may not be entirely applicable to the circumstances involved in a winter weather road closure, it is clear that the most undesirable case is one where travel time is lengthened and the added travel time is unexpected—almost doubling the cost of an expected increase in travel time.

To further understand traveler behavior when facilities are closed, we looked for impact studies conducted on transportation systems disruptions resulting from construction projects, natural disasters, and other events that would cause the total closure of a roadway. There are many such studies of land slides knocking out roads in New Zealand, earthquakes collapsing freeways in California, and transit workers striking in large urban cores (14). However, the most comprehensive and widely cited study is one by Cairns, Hass-Klau, and Goodwin conducted for the London Transport and the Department of Environment (15). This study set out to answer the questions “what really happens to traffic conditions when road capacity is reduced or relocated?” and “what are the underlying changes in travel choices and behavior that cause these effects?”

Cairns et al. collected over 150 sources of information from 100 locations and included more than 60 case studies. Capacity reductions examined included road maintenance, bridge collapses, natural disasters, labor strikes, etc. In their case studies, the authors found that the unweighted average number of trips was reduced on the treated area or in the area by 41%. On average, less than half of this traffic then reappears on alternative

roads at the same or different time of day. This suggests that quite a few trips are naturally dissipated due to road closures.

The authors examined different conditions where roads are reduced in capacity or closed. The authors determined that the response (reduction in traffic) is a result of the number of alternative routes, the duration of the capacity reduction, and the availability of alternative modes of travel. However, in studying even short-term closures due to railroad worker strikes, users seemed to be able to accommodate capacity reductions very quickly. This is due in part to the availability of information regarding the capacity reduction that allows the public to adjust trip-making behavior. The authors found that in some cases, even on the first day of the disruption there was no substantial traffic chaos, and the lack of chaos was often greeted with the bemusement of the press and transportation professionals. They also found that the extent of publicity and information before the change might itself influence expectations and outcomes.

From the work by Cairns, Hass-Klau, and Goodwin we can see that travelers are amazingly resilient in working their way through a closure or a reduction in capacity. Travelers are finding other activities to remain productive and the issue is not so simple as to assume that if a traveler does not make a specific trip that productive activities cease.

Several studies have found that traffic volumes decrease during winter storms even when roads are not closed (16, 17, 18, 19). This may be due to several reasons, including travelers diverting trips to other modes or other paths, canceling trips, and taking trips at other times before or after the storm. Hanbali and Kuemmel investigated volume reductions due to winter storms across varied intensity of snow fall, time of day, day of the week, and roadway type (20). Overall, they found that reductions ranged from 7% to 56%, depending on the type and severity of the winter event. Hanbali and Kuemmel conclude that volume decreases with the total volume of snow, and volume decreases are smaller during the peak travel periods (work trips) and on weekdays than during off-peak hours and on weekends (discretionary trips). This means, depending on type of trip (work versus discretionary trips), a number of travelers will prudently decide not to travel when the weather conditions are adverse. Travelers who decide not to travel when weather conditions result in poor driving condition make the road closure decision irrelevant to this portion of the traveling population because they weren't going to travel anyway.

Cost to Freight Transportation Delays

A few researchers have tried to estimate a value for travel time and travel time reliability for truck freight in the U.S., but far more examples exist in studies conducted in Western Europe. However, two U.S. studies completed in the late 1990s were based on surveys of motor carriers. Small, Noland, and Lewis attempted to estimate the value travelers and motor carriers based on travel time saving during congested periods and on value they placed on travel time predictability (21). The authors must have been running out of resources because they attempted to estimate the value motor carriers place on travel time and on travel time predictability with stated preference samples from only 20 motor

carriers. However, based on the small sample, motor carriers valued transit travel time at \$144.22 to \$192.83 per hour (expected delay) and savings in late schedule delays at \$371.33 per hour (unexpected delay).

A second U.S. study was conducted by Kawamura. His database consisted of 70 carriers, of which about half were truckload carriers and half were less-than-truckload carriers (22). Each carrier representative was interviewed, and during the interview, the carrier's representative was asked stated preference questions where the carrier decision maker had to make trade-offs between travel time and tolls on a routes with faster travel times. No estimates of value were made for travel time predictability. The value per hour tended to vary by carrier type (truck load versus less than truck load), but the average travel value was \$23.40 per hour.

The problem with both of the above studies is that they interviewed the carrier and not the shipper and/or receiver. The shipper and/or receiver are the ones that will have to suffer the consequences of a late delivery. Although, to some extent, carriers should reflect the interests of their customers, their perspectives are not the same. In addition, it is the attributes of the goods carried that are important in determining a value for time, particularly when determining the value an unexpected delay.

In the *Handbook on Transportation Modeling*, De Jong reviews the state of the art of Value of Freight Travel-Time Savings. The studies and results he presents are from Western European studies that use factor-costs based modeling approaches and discrete decision making modeling approaches based on RP and SP methods. Factor-cost approaches attempt to calculate the costs per hour through estimates of the inputs to transportation (e.g., fuel, driver's wage, opportunity costs of cargo). In general, the RP and SP surveys are surveys of shippers as opposed to motor carriers that better reflect the costs of a delayed shipment. The RP and SP studies result in value of travel time per hour per truckload ranging from almost nothing to \$71 per hour; the author believes a realistic average value of a truckload travel time is about \$40 per hour. De Jong points out that this is about twice the value that is typically arrived at using factor costs models. He interprets this to mean that the cost imposed on industry by delays in transit is about double the direct costs (the factor costs).

Kurri, J., Sirkia, A., and Mikola, J., conducted a similar stated preference study in Finland, and they were successful at isolating the expected travel time costs and unexpected travel time costs with a data set that included 103 shippers shipping 236 commodities. They found that on average, an hour of travel time (expected delay) was valued about \$1.53 per metric ton or \$11.03 per shipment, and unexpected delay was valued at \$47.47 per metric ton or \$350.96 per shipment (the authors do not say if a shipment is the same as a truckload). In other words, the cost of an unexpected delay is more than 30 times greater than an expected delay of the same amount of time. The difference between the value of expected travel time and unexpected delay is even greater for perishable goods. The authors note that their estimates of the value of freight travel time are much less than De Jong's estimate, but what is important is the difference between values of expected travel time and unexpected delay.

The relationship between costs of unexpected and expected delay is shown in Figure 2.1. With enough advanced warning of an unexpected delay, it is no longer unexpected and becomes expected. In Figure 2.1, the decrease in cost is shown as a line representing the declining cost to the cost of an expected delay over some time after notification which reduces costs down to the cost of an expected delay. The issue is to provide enough advanced warning so that the delay due to inclement weather is only valued at the cost imposed by an expected delay.

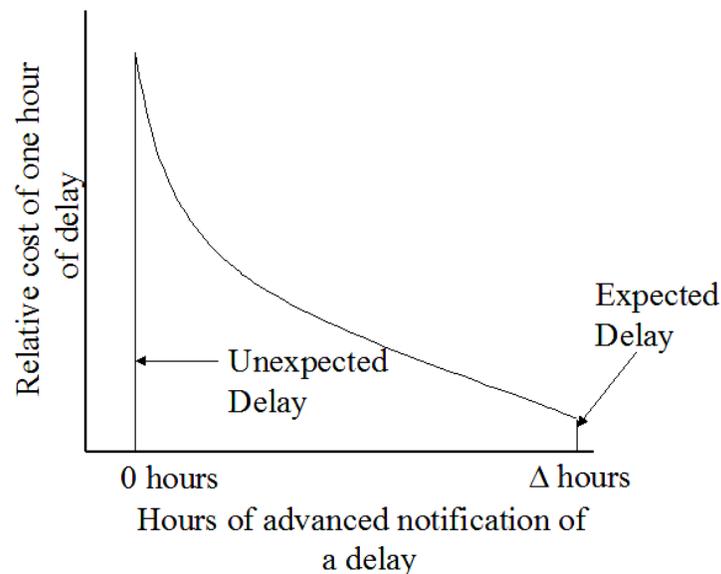


Figure 2.1. Relative cost of a delay

Literature Review Conclusions

We found no literature dealing directly with the benefits and costs of road closure during severe winter storms. We found studies that provided insight into the problem and those that researched the outcomes of transportation capacity reduction and restrictions and studies of delay costs. However, because none of these studies were in the context of a winter road closure, the results are not likely to be directly transferable.

Some of the issues that were made clear through the literature review included the following:

- Although researchers differ on the exact value of travel time reliability, the common finding is that unexpected delay is much more costly than expected delay, and the difference between the value of expected delay and unexpected delay is greater for freight than it is for travelers and is greatest for perishable goods.

- Availability of information describing a transportation system disruption or the likelihood of a future disruption allows travelers and freight shippers to adjust the synchronous activities that will take place at their destination. The more warning the traveler or shipper has before the disruption occurs, the greater the opportunity to adjust and the lower the costs.

Because the literature tells us that an unexpected delay is greater for freight shippers than it is for travelers, and that there tends to be a lot of heterogeneity in the value of travel time reliability between different types of freight, the next chapter explores the cost of a disruption of transportation services due to road closure through interviews with shippers/receivers and motor carriers.

3. CARRIER AND SHIPPER/RECEIVER INTERVIEWS

The impact of highway closings varies widely among trucking companies and shippers and receivers of freight. The research team conducted interviews with six companies (three trucking firms and three shipper/receiver firms) to gather information on the types and magnitudes of costs associated with highway closings and how companies cope with these closings. Though one cannot generalize the findings from a limited number of company interviews, the information gathered from the interviews is insightful nonetheless.

The primary objective of the interviews was to obtain a broad range of perspectives on the impacts of highway closings in Iowa and Minnesota. Two criteria were used for selecting the companies to interview. First, each company must have facilities in either Iowa or Minnesota or in both states. Second, because the costs of transit delay depend upon a number of product and operating characteristics, there had to be differences among the companies in terms of their operations and the products/services they provide. For example, for the trucking company interviews, a general freight truckload carrier, a flatbed carrier, and a less-than-truckload carrier were selected because their operations, customer requirements, and cost structures are quite different from each other.

Selected companies were contacted to solicit their voluntary participation. Each company was provided with a brief overview of the project and its objectives and was promised confidentiality (anonymity). To provide consistency in the information gathering process, a set of questions was developed and faxed to the companies before the interview, allowing each interviewee adequate time to prepare for the interview. The interview questions are provided in the Appendix. The interviews were conducted by telephone or in person and tape-recorded for reporting accuracy purposes. At least two members of the research team participated in each interview.

The key findings from each interview are presented in the following sections. A summary and conclusions derived from the interviews are then discussed.

Trucking Company Interviews

Company A

Company A is a truckload carrier that operates approximately 800 dry vans and hauls general freight. Some of its key customers are in the food, consumer durable goods, and equipment manufacturing industries. The interviewee is the director of expedited services.

Expedited freight comprises a substantial percentage of the company's business. More than 45% of its shipments are considered to be just-in-time (JIT) deliveries and many customers have very tight delivery schedules. For example, nearly 25% of the company's loads involve "dedicated" runs with tightly and regularly scheduled pick-ups and

deliveries. Vehicle delays have a ripple effect—they affect not only the immediate load, but subsequent loads as well. Road closings are a large factor in these types of operations. Furthermore, because of the tight profit margins in the trucking industry, a bad month, especially in the winter, can make or break a trucking company.

Financial Impacts

When a vehicle is delayed due to a winter road closing, Company A estimates it costs \$25 per hour, or a total operating and financial cost of \$600 per day (\$1,150 if it is a team driving situation). This includes the cost of fuel consumption while the vehicle is idling, capital costs for the equipment, lost opportunity cost (i.e., missed revenue opportunities), etc. Additionally, the company may be subject to penalties from its customers for late shipments. The company usually avoids these penalties, however, because it can document the severity of the bad weather and/or convince its customers that the delay was due to safety considerations.

The company's customers may incur even greater costs due to delayed shipments. For example, one key manufacturing customer reports a cost of \$1,000 per hour when shipments of parts arrive late. Another JIT customer is a make-to-order company. That is, the company does not fabricate a product until it has received an order for it. This customer, therefore, puts tremendous emphasis on fast, dependable transportation both for inbound and outbound movements. Though Company A cannot cite a cost for delayed shipments for this customer, it estimates it is in the thousands of dollars per hour for inbound shipments.

Coping with Road Closings and Bad Weather

At Company A, unless the public authority closes the road, the decision to delay a trip due to severe weather conditions resides with the driver. In terms of anticipating weather-related delays, Company A uses the internet, the Weather Channel, and in-truck satellite information to assess each situation. When asked about the possibility of better road weather prediction through Roadway Weather Information Systems (RWIS), Company A thought that RWIS data would help them to document for their customers the condition of the road when a shipment is delayed due to severe weather conditions (i.e., road closed, snow/ice accumulation, visibility) after the fact to avoid late shipment penalties.

Company A notes that it is very difficult to prepare for or circumvent weather-related delays. It is often not possible or practical to make route adjustments because either alternative routes are also affected by the same weather conditions or alternative routes are too lengthy (i.e., less time and cost are incurred by waiting until the road re-opens).

The company stresses communications with customers as the primary means of coping with or adjusting to weather-related delays. Informed customers can then make alternative plans (e.g., sourcing the inbound products from other vendors, changing production schedules). Once a delay is predicted or occurs, Company A contacts its key

customers (such as those on JIT or dedicated systems). Currently, all customers receive either verbal or electronic shipment updates every hour, but they do not have real-time access to Company A's AVL and GPS location data. These communications efforts create additional costs for the company, as employees are often required to stay late or arrive early to keep customers informed.

Public Policy and Other Issues

When asked about best practices in public road management, the interviewee expressed a preference for forced closures. Shutting down the roadway leaves little doubt about what the driver and company should be doing. The company's most problematic route for severe weather is I-80 through Wyoming. The interstate is gated and no entry is allowed during windy or poor conditions. Closures on this portion of highway seem to occur more frequently than on other roadways that Company A uses, and the delays can be quite lengthy (a day or more).

An issue that will exacerbate the costs and operational problems associated with road closings and delays are the new hours-of-service regulations that became effective on January 4, 2004. Truck drivers can no longer log weather delays as "off-duty" time. Thus, delays will now have a greater effect on the number of hours that drivers can work and drive.

Company B

Company B is a flatbed trucking company that operates nationwide. This interview was conducted with both the vice president of operations and the vice president of safety.

More than 50% of Company B's business involves delivering materials to construction and building job sites. All of their loads are handled on a just-in-time basis. The interviewees estimate that 50%–60% of loads have a delivery window of one to two hours.

Financial Impacts

Company B's estimates of delay costs, \$575–\$600 per truck per day, are similar to that of Company A. Company B provided a breakdown of costs as well, estimating that total fixed costs are \$26 per hour and total variable costs are \$0.45 per mile.

The costs of a late delivery can be substantial for Company B's customers. The interviewees were aware of delay costs of thousands of dollars. For example, cranes are often needed to unload building materials from the flatbed trailers at the job site. These cranes are leased on an hourly basis, and the customer pays for the period of time the cranes are at the site, regardless of whether or not they are used. Lease costs of up to \$1,000 per day are not uncommon. Also, many of Company B's equipment manufacturing customers make-to-order and carry lean inventories, often moving

finished product directly from the production line onto the flatbed trailer. Therefore, the penalties for late delivery are substantial.

Coping with Road Closings and Bad Weather

Company B gains valuable weather information from a number of sources, including the Weather Channel, Internet, state road condition web sites, and feedback from the drivers themselves. Unless the public authority closes the road, the driver decides when it is unsafe to proceed. Drivers are told to continue only when the route is acceptable for his or her driving abilities.

When there is an advanced warning of serious weather conditions, alternatives considered include shipping that day and incurring the delay, keeping drivers at the terminal and shipping late, and shipping early (with customer's permission) and beating the weather. Use of alternate routes is usually not a feasible option for reasons mentioned by Company A. However, when the company is expecting a storm, Company B will try to avoid the affected area to maximize productivity.

Company B tries to be proactive in communicating their delays. With effective communication, nine out of ten customers understand the reason for the delay. The biggest problem with respect to customer relations and assignment of fault or liability occurs when the bad weather is not at the origin or destination point. For instance, a Texas consignee is less aware and understanding when bad weather in Iowa causes the delay than if the weather problem was in Texas. Thus, the ability to document road closings and driving conditions nationwide is important to the carrier.

Public Policy and Other Issues

The interviewees cited a problem with lack of advance information about road closings and travel delays. They emphasized the need for state and local governments to communicate with each other and the public.

Company B, like Company A, is concerned about the impact of the new hours-of-service regulations. The interviewees believe the new rules will make it very difficult to "work through" road closures. Because of the inability to log off-duty time, they are also concerned that the new rules will put pressure on drivers to continue driving when they should be shutting down for safety reasons (e.g., weather, fatigue)

Company C

Company C is one of the largest less-than-truckload (LTL) carriers in the country. It provides regional, national, and international transportation to over 400,000 customers. The interview was conducted with a branch (i.e., terminal) manager.

Financial Impacts

Company C reports that delay costs for LTL carriers' over-the-road equipment should be similar to those of truckload carriers. However, travel delays create much greater operating costs at the LTL carriers' terminal facilities where shipments are consolidated for the line-haul move and de-consolidated for local distribution.

Employees and assets in the terminals represent a fixed cost (i.e., a "committed" resource). Almost 90% of Company C's cost would be classified as fixed. Shipment delays disrupt operations planning and cost performance. For example, the company plans its weekly workloads far in advance, using historic data and recent freight orders, and schedules dock workers one day prior. When a truck is delayed in getting to the terminal, the result is excess labor during the delay and a shortage of labor during the "catch up" period (when the delayed and regularly-scheduled shipments arrive). The company incurs non-productive downtime costs during the slack period, and higher labor costs due to overtime pay and congestion during the catch up period.

Coping with Road Closings and Bad Weather

Company C receives weather information from three sources:

- Central dispatch (at corporate headquarters) produces weekly and daily reports that are sent directly to the terminals and drivers
- Driver feedback to gain current, up-to-the-minute data
- In its safety department, Company C employs former drivers to drive to the problem to experience the conditions first-hand

Company C's central dispatch makes all decisions on closing routes, changing routes, and monitoring the weather in Canada, Mexico, and the United States. The interviewee noted that to alter a route, the movement must be substantial enough to allow the driver to bypass a large portion of the U.S. It is difficult to make those types of adjustments on shorter trips.

Communicating delays to customers is a major challenge for Company C. It has so many customers that it is difficult to contact each of them. Shippers and receivers can check their shipments' status via Company C's website, however, and the largest customers are often contacted directly when delays occur. However, because the LTL industry is not organized to provide delivery of time-sensitive freight, weather related delays are not significant issues for customers, but they are a serious issue for scheduling and managing terminal labor and can result in significant costs. With advanced information regarding a road closure, labor scheduling can be adjusted.

Public Policy and Other Issues

The interviewee did not identify any best practices from local or state governments. Nevertheless, he suggested that an improved information flow between the company and local/state authorities would greatly benefit the safety and operational planning of the company.

Company D

Company D is a manufacturer of consumer and industrial durable goods and is the country's largest producer in its primary industry. All products are made-to-order rather than made-to-stock, and very lean inventories are kept. The company receives and delivers 80% of its products on a JIT basis. Delivery windows range from 1 to 4 hours, and carriers must make appointments for loading and unloading shipments.

Financial Impacts

Because of the integrated nature of its plant operations and the use of JIT systems, late deliveries of inbound materials create huge costs for Company D. Delays of basic materials can shut down an entire plant. The downtime cost at one of its mid-size plants is \$6,000/hour.

Company D's customers assess a \$500 penalty if the shipment is more than 30 minutes late. Carriers also assess a penalty of \$600 per truck per day when an appointment is missed and must be rescheduled.

Coping with Road Closings and Bad Weather

Like the other companies that we have interviewed, Company D stressed that communication is the key to mitigating the effects of delays. Early communication of potential or impending delays allows Company D and its customers to make adjustments. For example, Company D does have some flexibility in its manufacturing facilities to switch over production lines to alternative products. Typically, 12- to 24-hour advance notice is adequate. The company monitors the Internet and the weather channel for climate information.

In the event of bad weather and potential road closings or delays, Company D occasionally makes an effort to receive a shipment earlier or possibly reroute the shipment. Also, it is relatively easy to switch modes to avoid the delay or to make up lost time. For instance, the company has used airfreight carriers; though, it usually costs four times the amount of truck transportation. The company allows more time for shipments in the winter because of the possibility of transit delays due to weather. Its transportation management software implements this by adjusting the average miles per hour for road transport during the winter period.

Public Policy and Other Issues

The interviewee mentioned that it would be helpful if state transportation agencies (STAs) archived road closure information. This would enable shippers and carriers to document such closures and avoid penalties for late deliveries.

Company E

Company E produces non-perishable food products. For its primary product, its central Iowa facility is the largest such facility in the world. Company E is generally not a JIT company. It does, however, expedite about 3% of its shipments to meet the needs of customers. One example of a JIT product is plastic containers, which are used in finished goods packaging. Plastic containers affect all product lines and have a delivery window of plus or minus one hour.

Most of its deliveries to customers are “live unload” and are made by appointment. Missing an appointment time causes the company to lose an entire day before the shipment is unloaded (because the customer pushes the shipment to the next day). Company E only receives shipments during its day shift. If a shipment is late, the company must change the duties of an entire shift, resulting in productivity loss and a delay in producing the originally scheduled product. The company utilizes “drop trailers” for the majority of its inbound freight (i.e., the carrier drops the loaded trailer at Company E’s facility, allowing Company E to unload at a convenient time).

Financial Impacts

Company E’s costs due to shipment delays are similar to those of Company D, but the magnitudes are different. For example, the cost of shutting down a production line is \$90-100 per hour. If a shipment of packaging is late and shuts down the plant (i.e., all six production lines), the cost is \$600 per hour.

The interviewee noted that road closings may prevent its workers as well as its carrier’s drivers from getting to the plant, thus resulting in delayed outbound loads. Company E’s customers assess a penalty up to \$500 for missed delivery appointments.

Coping with Road Closings and Bad Weather

Company E relies mainly on its carriers and their information. Decisions about shutting down or continuing to drive during inclement weather are left to the carriers.

With respect to operating practices during winter storms, the company occasionally attempts to have loads ready earlier or will unload at non-regular times. Company E will also carry extra inventory or may preorder product in anticipation of delays. In critical situations, the company will expedite shipments to get them there on time, which costs the company 70%–100% more than regular shipping. The company also uses airfreight

carriage, but the cost is generally 3 times the price of the regular truck service. Changing the sources of a product and changing routes are not practical options for the company.

Company E stresses the importance of communicating delays to its customers. Customers tend to focus on local weather and are not aware of regional or national weather patterns. If the local weather is good, the customer does not expect any shipment delivery problems.

The interviewee pointed out that in most situations, road closures last fewer than six hours and the carrier is able to make the delivery on time. However, when a delay persists for an entire day, the customer generally becomes impatient.

Public Policy and Other Issues

Company E is concerned about the potential impacts of the new truck driver hours-of-service regulations.

Company F

Company F is a producer of perishable, temperature-controlled food products. It is the world's leading processor and marketer of its primary product lines. The interviewee is the director of distribution and is responsible for transportation and distribution. The company manufactures more than 1,300 different products, comprising more than a billion pounds of product annually, and distributes its products throughout North America and Asia.

More than 50% of Company F's freight is considered JIT. Delivery windows range from 2 to 24 hours. Perishability is a key dimension of the product, as some product's retail shelf life is only 10 days. Some product is delivered to customers that provide further processing.

Financial Impacts

The interviewee noted that inbound shipment delays of three hours or more have the potential to shut down a plant. The cost of a full plant shut-down could range from \$5,000 to \$10,000 per hour depending on which plant is impacted. A partial shut-down would cost in the range of \$1,000 to \$5,000 per hour.

On the customer delivery side, late delivery penalties range from \$250 to \$500 per delivery. Since Company F averages 6 deliveries per truck, one delayed truck can result in customer penalties ranging from \$1,500 to \$3,000.

The average customer reports a cost of \$600 per late shipment due to lost sales, lost productivity, etc. Also, customers such as major grocery chains advertise sales on certain items. If one of these product shipments is delayed, one of three things could happen:

- The shipment is delayed further due to the lack of employees to unload the product (possible loss of 24 hours)
- The shipment is refused and returned to the company (cost of \$2,000)
- The shipment is refused and a customer is lost (very large cost)

Company F may incur other costs when shipments are delayed. For example, in one instance the company added roughly 5–6 hours to each of its transportation employees' schedules to cope with a delay situation. The cost of these extra hours was \$600–\$700.

Coping with Road Closings and Bad Weather

When anticipating a storm, Company F allows the carrier to analyze the weather and route. However, Company F pays close attention to large shipments and tends to use the Internet, including STA road condition Internet sites, to identify problem areas and alternate routes.

In the event of a delay, it is imperative that the company is proactive and communicates with its customers. If customers are aware of the problems, a majority of the delay penalty costs can be avoided. The relatively short shelf-life of the product, however, allows very little leeway for lost time.

The interviewee observed that if the bad weather occurs in the state they are delivering to, a penalty is usually not added. If the event occurs in a different state, delay penalties usually will be added.

Public Policy and Other Issues

Company F is very concerned about the new truck driver hours-of-service regulations. The company has general concerns about the impact of the new rules on day-to-day operations and costs, but pointed out that road closings and other delay-causing events will have even greater impacts when the new rules are in effect.

Summary and Conclusions

Road closings due to weather create shipment delays that have impact on both motor carriers and the customers they serve. The interviewed carriers cited immediate operating costs (e.g., fuel while idling) and capital costs of equipment (e.g., finance and depreciation costs) while the truck waits. Estimates of these costs by the interviewed carriers are not insignificant. The carriers also suffer a lost revenue opportunity (i.e., during waiting time the equipment is not generating revenue).

Road closings may also have long-term impacts as the synchronization of future shipments is disrupted. That is, the delay caused by a road closing may result in a truckload carrier missing a delivery appointment and having to wait an extra day to unload. The next scheduled shipment for that driver and equipment is therefore affected. The impact LTL carriers experience may be even more substantial given that each vehicle is transporting several shipments for different customers, and the human and capital resources used at the LTL carrier's terminal facility may be affected.

Furthermore, the carriers' customers may assess penalties for late deliveries or late pick-ups; though, carriers may be able to avoid these if the delay is due to winter weather. The magnitude of these penalties and the costs incurred by customers for shipment delays depend in large part on the nature of the customers' operations (e.g., JIT, integrated assembly line operations) and characteristics of the products being transported (e.g., perishable vs. non-perishable, high value vs. low value). Both the interviewed carriers and shippers/receivers reported tight delivery windows for a large percentage of their business. Not surprisingly, the interviewed shipper of temperature-controlled, perishable food products reported the largest shipment delay costs and customer penalties. Similarly, the JIT manufacturer indicated substantial productivity costs arising from delayed shipments.

Each of the interviewed parties made reference to the new truck driver hours-of-service regulations. These new rules are expected to exacerbate the operational problems and costs associated with any delays in the supply chain, regardless of type or cause.

The carriers acknowledged that they have few effective or practical operational alternatives for avoiding or mitigating the effects of road closings due to winter weather. There is little opportunity for alternative routing because the additional time it takes to circumvent the affected area usually exceeds the wait time for the road to re-open.

With respect to gathering information about weather and road conditions, the interviewed carriers primarily tend to use the Internet, the Weather Channel, and in-truck satellite information from drivers. The shippers/receivers tend to rely on the carriers for this information, though the interviewed perishable goods producer monitors the Internet and STA road condition websites for large shipment areas and for key customers. With more advanced warning, carriers may be able (with customers' permission) to alter some shipment times to beat the weather or to wait it out. Thus, there is value in more accurate and timely weather and road condition forecasts.

The carriers expressed a desire to having government agencies archive information about road closings and driving conditions so they can document why shipment delays occurred (i.e., to relieve carriers of liability for late shipment pick-ups and deliveries).

Each interviewed carrier and shipper/receiver stressed the importance of keeping customers informed about potential and actual shipment delays because customers are often in a better position than the carriers to exercise some options. As noted earlier, proactive measures by carriers are rather limited, so their focus is on communicating

delays as early as possible so customers can alter their operations. For instance, customers may utilize expedited transportation service, though at a greater cost. They may also carry extra inventory and allow for longer transit times during the bad weather season. Alternative sourcing may also be possible, though this was not feasible for the interviewed shippers/receivers.

When asked about best government agency practices outside of Iowa, none of the interviewees reported any uniquely good practices in other states (with respect to methods of communicating with carriers and drivers, available information and information technology, monitoring or policing traffic, regulations and penalties, etc.). One carrier interviewee did express a preference for the STAs to make decisions to close roads rather than leaving it to carriers and drivers to use their own judgment. This same person preferred gating to restrict entrance to closed interstates.

4. CLOSURE CASE STUDIES

To better understand what takes place during a road closure, the research team analyzed what actually occurred during road closures with respect to traffic volumes and crashes. Initially, and rather naively, the team expected that on these gated highways, when the roads were closed, no traffic would be traveling and no crashes would be occurring. In reality, even with the gates, traffic continued to flow on the closed highway, albeit at a lower level than without the closure, and travelers continued to be involved in crashes. This chapter presents case studies of each of the road closure on Interstate 35 and Interstate 90 between 2000 and 2003.

This chapter also presents a study of Commercial Truck traffic during winter storms. We assumed that trucks were less likely than other traffic to defer trips during winter weather, and our analysis shows that our assumption is correct.

To conduct our closure case studies, we collected crash and traffic volume information during past winter storms that resulted in a closure of interstate highways in Iowa and Minnesota. The corridors investigated were Interstate 35 (I-35) in Iowa from Ames to the Minnesota border (113 miles) and Interstate 90 (I-90) in Minnesota from the South Dakota Border to Albert Lea (159 miles).

During the 3-year period from 2000 to 2003, there were 6 road closures on I-35 and I-90: 4 on I-35 in Iowa and 2 on I-90 in Minnesota. The 2 Minnesota closures were at roughly the same time as closures on I-35 in Iowa. Using data from both states, the average road closure duration was 12 hours. The typical weather conditions involved low visibility and high winds. Even though the roads were officially closed, the traffic volumes on the closed roads averaged about 30% of the expected traffic during a normal day. It surprised the research team that there was still a good deal of traffic on roads even after they were closed. Minnesota has a more aggressive program for evacuating I-90 than Iowa and volumes, expressed as a percent of the expected traffic, were lower than those in Iowa. Minnesota law makes it a misdemeanor for anyone to “drive over, through, or around any barricade, fence, or obstruction erected for the purpose of preventing traffic from passing over a portion of a highway closed to public travel...” In addition, there is a \$700 fine associated with being cited for this misdemeanor (23). Further, Minnesota law makes the individual who violates a road closure liable for any costs associated with their rescue should they become stranded or crash.

In both Minnesota and Iowa, the volume of traffic on the facility during a closure was higher than we expected. We expected very few vehicles to be on the road and that the vehicles still on the road would be maintenance and emergency vehicles. However, this was not the case since we observed, in most cases, over 100 vehicles per hour during road closures in Iowa. In Minnesota, the observed volumes were much lower, but throughout the storm there still was some traffic. In both states, vehicles, driving on the closed roadway, continued to experience crashes.

Iowa Closure Experience

The Iowa Department of Transportation (Iowa DOT) closure policy makes the closure decision and the execution of a closure a joint operation between the Iowa State Highway Patrol and the Iowa DOT. The policy mainly outlines how traffic will be properly diverted from the route in the event of a closure. During road closures, the Iowa State Patrol and the Iowa DOT divert traffic to major cities, while the Iowa DOT physically closes the gates on the I-35 entrance ramps. In practice, the closure decision is driven by safety concerns, and the closure decision is made by the Patrol based on roadway conditions and the number of crashes that have already occurred. A standard gate on an entrance ramp to I-35 is shown in Figure 4.1 and Figure 4.2.



Figure 4.1. Gates on entrance ramp to I-35



Figure 4.2. Left-side swing gate on entrance to I-35

I-35 from Ames, Iowa north to the Minnesota border was closed four times between November 2000 and March 2003. Traffic volume and crash data were gathered for each closure. Traffic volumes are collected in Iowa by a network of automatic traffic recorders (ATRs). ATRs vary in capability, but all ATRs record volumes. Some ATRs record speed and some report volume, speed, and vehicle classification. For our analysis of I-35 conditions, we used data from the ATRs located at Hanlontown, on the northern end of the corridor, and Jewell, at the southern end of the corridor. For purposes of this study, only information on volumes during days when road closures occurred and on clear days was extracted from the ATR database. The location of the Jewell and Hanlontown ATRs are shown on the Iowa map in Figure 4.3.

Additional volume data were collected from ATRs on primary highways that run perpendicular or parallel to Interstate 35. These sites are on roadways that remained open through the weather event and include sites on U.S. 30 at Boone, U.S. 20 at Webster City, U.S. 65 at Hampton, and U.S. 18 at Clear Lake. These sites are also shown on the map in Figure 4.3. Data were collected from these sites for two purposes. The first was an

attempt to determine if travel was being diverted off of the interstate during the closure to the primary system. The second reason was to help understand how much of the reduction in trip making was due to the closure and how much was due to the inclement weather (none of the non-interstates were closed, although travel was not advised). If the volumes on the primary highways declined to the same degree as on the closed interstate, then the weather, not the interstate closure, caused the reduction. Unfortunately, the network of traffic counting stations is not sufficiently dense to allow the measurement of diverted vehicles per hour. Data were also collected on routes far enough away from the interstate that they would largely remain unaffected by the interstate's closure. These sites were considered control sites and were located on U.S. 18 at Algona, on IA 9 at Armstrong, on U.S. 7 at Fostoria, and on U.S. 18 at Sheldon. These sites were also not closed and are not on the map shown in Figure 4.2, but they did observe weather conditions similar to those observed along I-35.

Hourly volume counts from each ATR are reported before, during, and after the closure. Rather than reporting actual traffic volume, we reported the traffic reduction during that day. We selected a typical day with clear weather to serve as a control day for comparison. The control days were days (and hours) during the same day of the week and during the same month and year when there were low winds, no precipitation, and high visibility.

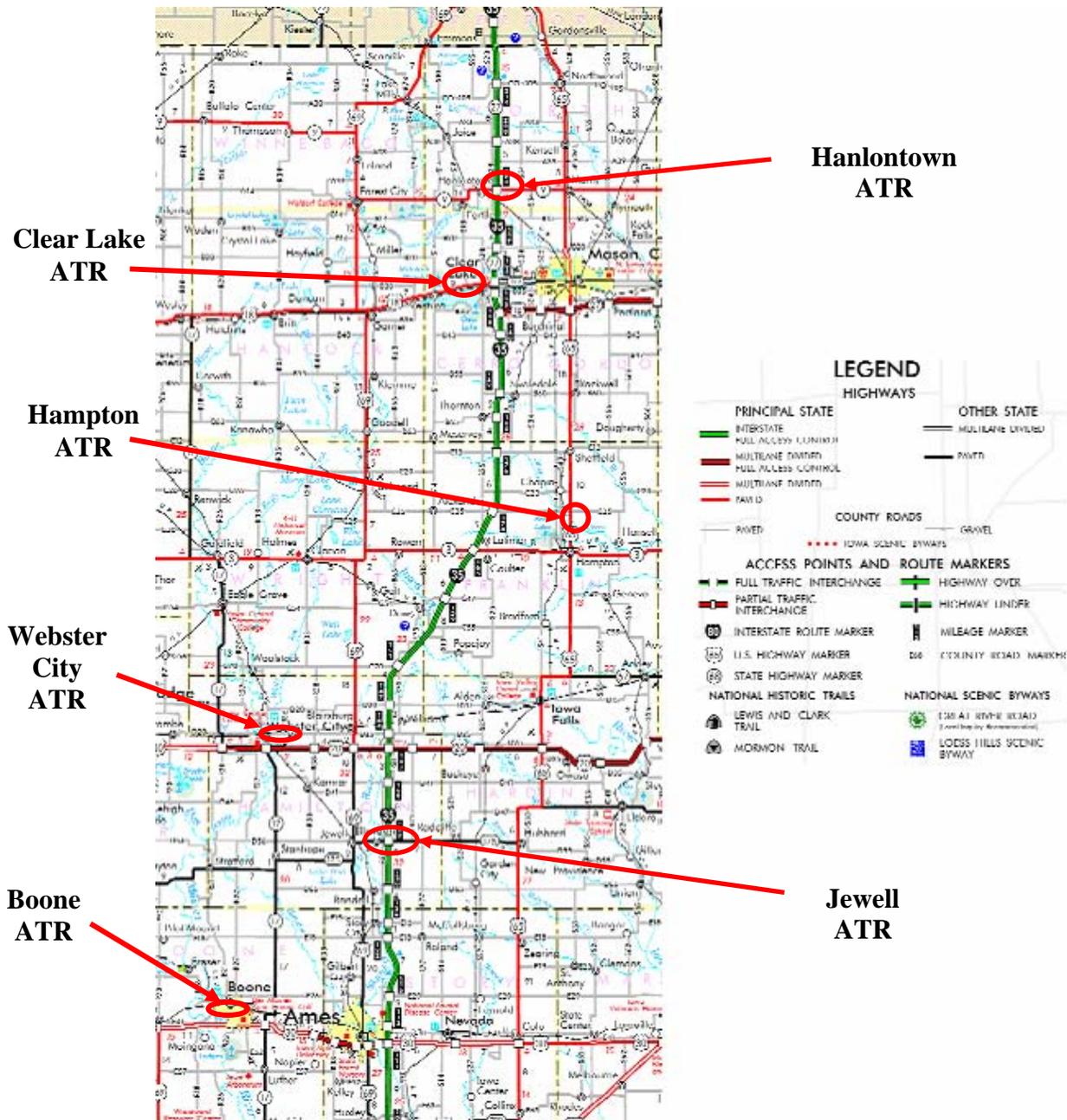


Figure 4.3. Location of ATRs in Iowa from Ames to the Minnesota border used in study (23)

Iowa Road Closure Dates

The list below indicates the date of each I-35 road closure north of Ames to the Minnesota border.

- Saturday, December 16, 2000
- Friday, February 9, 2001
- Sunday, February 25, 2001
- Saturday, March 9, 2002

Iowa 12/16/2000

On Saturday, December 16, 2000, I-35 was closed from 1:00pm until 9:00pm. The weather conditions included blowing snow and ice covered road surfaces. The Iowa DOT closed I-35 from Ames to the Minnesota Border due to increasingly poor weather conditions and a large number of crashes. At roughly the same time, the Minnesota DOT closed I-90 between Albert Lee, Minnesota and the South Dakota boarder.

Traffic Count Data

The control day used for comparison of traffic volume counts was December 9, 2000. December 9 was chosen as the control day because it is the same day of the week, the same month of the year, and the same year. On December 9, 2000, there was no precipitation, the visibility was high, and the winds were low.

Table 4.1 contains the percent of the expected traffic (the traffic volumes during the control day) remaining on the road. During the road closure event at the Jewell site, the traffic decreased by 83% (or we observed 17% of the traffic we would expect if the weather were clear). The Hanlontown site experienced an average decrease of 69%.

Table 4.1. Percentage of traffic during road closure event on 12/16/2000

	Jewell	Hanlontown	Boone	Hampton	Clear Lake	Armstrong	Forstoria	Sheldon	Algona
13:00	40.28%	42.89%	32.01%	21.63%	30.02%	5.05%	10.51%	9.22%	11.76%
14:00	38.78%	28.73%	20.38%	17.91%	30.09%	10.23%	8.45%	1.79%	10.87%
15:00	24.15%	33.04%	23.78%	21.78%	26.68%	5.08%	6.55%	6.86%	10.27%
16:00	20.20%	22.31%	33.79%	28.94%	27.15%	10.89%	8.24%	4.98%	15.03%
17:00	10.12%	14.89%	55.44%	30.81%	24.83%	3.77%	6.41%	5.36%	12.66%
18:00	8.56%	7.40%	28.59%	19.66%	16.53%	10.20%	4.39%	7.11%	10.00%
19:00	5.94%	9.52%	17.19%	6.40%	12.72%	1.33%	5.37%	3.20%	4.92%
20:00	2.08%	10.36%	43.08%	12.66%	13.11%	3.28%	4.95%	5.22%	5.49%
21:00	3.59%	7.67%	34.38%	9.38%	14.75%	7.84%	6.30%	6.00%	4.76%
Total	17.08%	19.65%	32.07%	18.80%	21.76%	6.41%	6.80%	5.53%	9.53%

In addition to the decrease in traffic observed on I-35, the traffic at the count locations on the primary system around I-35 declined as well (Boone, Hampton, and Clear Lake).

However, the control locations (Armstrong, Forstoria, Sheldon, and Algona) experienced even greater declines in traffic. The greater reduction at the control sites may be related to their remote rural locations, while the Boone and Clear Lake ATRs are located very near to these cities. The reduction of traffic on the primary system follows roughly the same pattern of traffic reduction as on the closed I-35.

Event Crash Experience

Crash data were collected on I-35 for both the event and control date. A crash rate was calculated by assuming that the total traffic volume on the segment between Ames and the Minnesota boarder was the average of the counts at the Jewell and the Hanlontown ATRs. This segment includes the 113 miles of Interstate between Ames and the Minnesota border.

During the closure, a crash rate of 13.81 crashes per million vehicle miles (MVM) was observed. For the control date, the crash rate was 1.10 per MVM. Using 5 years of crash records, the Iowa DOT estimates the average crash rate for a rural Iowa interstate at 0.51 per MVM (24). In other words, vehicles driving on I-35 were roughly 27 times more likely to be in a crash than they would be under normal conditions ($13.81/0.51 \approx 27$). Table 4.2 presents data on the crashes that occurred on the day of the event (12/16/2000) and on the control day (12/09/2000). The crashes that occurred on I-35 when the highway was closed are shaded in gray. No fatalities were observed in any of these crashes.

Table 4.2. Crash data during road closure event and control day

Event Crash Data (12/16/00)								
#	Date	Time	Crash location/mile marker	Vehicle	Major cause	Surface conditions	Weather conditions	Injury accidents
1	12/16/00	08:00	186 (Mason City)	Pickup truck	Unknown	Ice	Sleet/hail	2
2	12/16/00	09:45	187 (Mason City)	Pickup truck	Loss of control	Ice	Sleet/hail	0
3	12/16/00	13:30	171 (Alexander)	Pickup truck	Unknown	Snow	Snow	0
4	12/16/00	13:30	171 (Alexander)	Pickup truck	Vision obstructed	Other	Other	2
5	12/16/00	03:00	121 (Story City)	Pickup/trailer	Unknown	Ice	Snow	0
6	12/16/00	07:40	114 (Ames)	SUV	Loss of control	Ice	Sleet/hail	2
7	12/16/00	08:00	114 (Ames)	Truck tractor (semi)	Unknown	Ice	Snow	1
8	12/16/00	09:30	143 (Webster City)	Pickup truck	Unknown	Ice	Sleet/hail	0
9	12/16/00	10:45	116 (Ames)	Passenger car	Unknown	Ice	Sleet/hail	0
10	12/16/00	13:15	158 (Dows)	Passenger car	Unknown	Ice	Sleet/hail	1
11	12/17/00	16:47	194 (Clear Lake)	Passenger car	FTY	Snow	Strong wind	0
Control Crash Data (12/9/00)								
#	Date	Time	Mile marker	Vehicle	Major cause	Surface conditions	Weather conditions	Fatalities
1	12/9/00	20:00	119	Passenger car	Animal	Dry	Snow	0

Iowa 2/9/2001

On Friday, February 9, 2001, I-35 was closed from 1:00pm until 6:00am the following morning. The weather conditions included blowing snow (poor visibility) and ice-covered road surfaces. The Iowa DOT closed I-35 from Ames to the Minnesota border due to zero visibility and safety concerns.

Traffic Count Data

For this road closure event, a control date of Friday, February 16, 2001, was selected. When comparing the event traffic count to the control count, the ATR at Jewell observed an average hourly decrease in traffic of 70% over the course of the closure. The ATR at Hanlontown observed an average decrease of 66%. Table 4.3 shows the level of reduction when the percentages are the portion of the traffic remaining on the roadway in comparison to the control date. The percentage of traffic remaining on the closed portion

of I-35 were fairly similar to the percentage remaining on the primary system in the vicinity of I-35, but the reduction in sites to the northwest experienced a more modest reduction, which probably indicates that the storm was less severe than it was along the I-35 corridor.

Table 4.3. Percentage of traffic during road closure event on 2/9/2001

	Jewell	Hanlontown	Boone	Webster City	Hampton	Clear Lake	Armstrong	Forstoria	Sheldon	Algona
13:00	27.63%	41.97%	25.83%	16.81%	37.13%	56.54%	41.51%	54.47%	67.77%	27.27%
14:00	27.08%	37.07%	23.46%	23.83%	34.85%	59.67%	35.10%	50.36%	86.75%	34.08%
15:00	13.75%	23.85%	27.19%	19.85%	44.10%	61.96%	35.14%	60.56%	65.33%	20.32%
16:00	4.40%	25.13%	20.77%	20.60%	30.68%	43.10%	38.27%	72.98%	63.93%	12.95%
17:00	4.82%	16.39%	16.78%	11.55%	25.45%	31.04%	24.54%	63.66%	105.99%	14.46%
18:00	3.13%	10.05%	15.17%	18.60%	27.12%	31.83%	40.57%	66.06%	94.64%	26.61%
19:00	1.76%	8.76%	15.56%	18.91%	29.90%	30.66%	50.63%	59.20%	77.69%	21.34%
20:00	5.04%	7.45%	22.20%	16.61%	39.53%	2.61%	39.66%	69.78%	126.02%	45.74%
21:00	2.40%	7.85%	17.76%	13.07%	40.00%	26.03%	47.83%	81.19%	82.35%	37.10%
22:00	6.28%	9.85%	17.26%	22.22%	83.72%	33.52%	32.50%	50.00%	56.67%	35.82%
23:00	10.34%	24.65%	18.47%	16.15%	84.00%	32.66%	41.03%	87.40%	112.75%	16.98%
0:00	45.00%	28.48%	18.79%	25.00%	52.17%	17.38%	68.00%	78.57%	56.76%	22.45%
1:00	52.78%	57.92%	17.31%	43.08%	57.89%	25.79%	47.06%	95.74%	129.03%	18.42%
2:00	52.26%	48.08%	26.67%	34.69%	75.00%	43.10%	83.33%	48.39%	68.18%	81.25%
3:00	70.31%	57.85%	31.03%	46.15%	133.33%	37.23%	87.50%	79.31%	100.00%	128.57%
4:00	70.59%	63.30%	60.00%	55.17%	22.22%	38.78%	150.00%	119.05%	52.63%	45.45%
5:00	71.13%	60.77%	68.18%	96.77%	36.84%	86.21%	75.00%	134.15%	52.94%	60.00%
6:00	76.40%	83.10%	88.33%	86.96%	116.00%	84.75%	103.85%	160.00%	31.58%	64.00%
Percentage total	30.28%	34.03%	29.49%	32.56%	53.89%	41.27%	57.86%	79.49%	79.50%	39.60%

Event Crash Experience

The crash data were collected on I-35 for both the event and control dates. A crash rate was calculated assuming that average traffic volume along this segment was the average of the volumes counted at the Jewell and the Hanlontown ATRs. During the closure itself, a crash rate of 17.07 crashes per MVM was observed. For the control date, a crash rate of 0.32 crashes per MVM was observed. However, the long term average on rural Iowa interstate highways is 0.51 crashes per MVM. In other words, vehicles driving on I-35 during this closure were roughly 33 times more likely to be in a crash than they would be under normal conditions (17.07/0.51=33). Table 4.4 reports crashes that occurred during the event day and during the control day. The shaded portion of the chart is the period of the closure. No fatalities were observed in any of these crashes.

Table 4.4. Crash data during road closure event and control day

Event Crash Data (2/9/01)							
#	Date	Time	Vehicle	Major cause	Surface conditions	Weather conditions	Accident injuries
1	2/9/01	8:00	Passenger car	Lost control	Ice	Severe winds	0
2	2/9/01	9:40	Truck tractor (semi)	Run off road	Ice	Blowing snow	0
3	2/9/01	10:10	Passenger car	Too fast for conditions	Ice	Snow	0
4	2/9/01	10:45	Passenger car	Lost control	Ice	Sleet/hail	1
5	2/9/01	11:30	Passenger car	Unknown	Ice	Severe winds	0
6	2/9/01	12:00	SUV	Too fast for conditions	Ice	Snow	0
7	2/9/01	12:30	Passenger car	Too fast for conditions	Ice	Severe winds	2
8	2/9/01	14:03	Pickup truck	Evasive action	Ice	Severe winds	0
9	2/9/01	15:30	Passenger car	Evasive action	Ice	Sleet/hail	0
10	2/9/01	23:55	Pickup truck	Too fast for conditions	Ice	Sleet/hail	0
Control Crash Data (2/16/01)							
#	Date	Time	Vehicle	Major cause	Surface conditions	Weather conditions	Accident injuries
1	2/16/01	6:00	Passenger car	Animal	Dry	Clear	1

Iowa 2/25/2001

On Sunday, February 25, 2001, the Iowa DOT closed I-35 from Ames to the Minnesota border between 8:00am until 4:00pm due to zero visibility.

Traffic Count Data

For this event, a control date of Sunday, February 18, 2001, was selected. When comparing the event traffic volume to the control volumes, the traffic recorder at Jewell observed an average hourly decrease in traffic of 68% over the course of the closure, as shown in Table 4.5. The ATR at Hanlontown observed an average decrease of 87%.

Table 4.5. Percentage of traffic during road closure event on 2/25/2001

	Jewell	Hanlontown	Boone	Webster City	Hampton	Clear Lake	Armstrong	Fostoria	Sheldon	Algona
8:00	48.97%	24.77%	58.45%	39.78%	37.84%	39.62%	0.00%	17.44%	17.86%	12.00%
9:00	48.60%	19.63%	66.49%	41.51%	24.19%	32.34%	4.00%	25.73%	7.94%	6.35%
10:00	39.00%	14.19%	64.77%	48.86%	19.00%	30.79%	3.39%	35.58%	24.32%	21.10%
11:00	38.31%	6.06%	74.87%	48.55%	68.38%	34.52%	14.04%	28.62%	35.71%	21.97%
12:00	41.22%	8.35%	76.13%	54.74%	70.55%	30.88%	25.86%	20.75%	23.30%	21.94%
13:00	43.19%	8.95%	77.33%	65.56%	88.76%	33.76%	23.26%	30.77%	36.81%	19.38%
14:00	41.99%	10.65%	75.60%	61.22%	136.49%	37.47%	53.01%	41.03%	53.70%	32.24%
15:00	41.47%	14.76%	79.55%	64.47%	126.76%	45.95%	71.91%	55.43%	83.03%	39.15%
16:00	40.49%	15.26%	79.88%	57.29%	112.71%	51.73%	59.09%	51.03%	59.16%	50.80%
Percentage total	42.58%	13.62%	72.56%	53.55%	76.07%	37.45%	28.28%	34.04%	37.98%	24.99%

Also, as shown in Table 4.5, each of the primary routes nearby I-35 (Boone, Webster City, Hampton, and Clear Lake) observed an average total decrease of 40% in traffic counts. The control ATRs in northwest Iowa observed a decrease of 69%. In this case, the lower volumes on the interstate illustrate that the closure in this case had an impact on reducing traffic.

On the day prior to the Iowa closure, the Minnesota DOT closed I-90, which may have impacted the traffic volume on the northern end of I-35 and could partially explain the precipitous reduction in traffic at the Hanlontown ATR.

Event Crash Experience

The crash data were collected on I-35 for both the event and control dates. A crash rate was calculated using the assumption that the average traffic on the entire section was an average of the hourly volumes at the Jewell and Hanlontown ATRs.

During the closure, a crash rate of 3.41 crashes per MVM was observed. For the control date, a crash rate of 0.32 crashes per MVM was observed. Typically, the crash rate on a rural Iowa interstate is 0.51 crashes per MVM. In other words, vehicles driving on I-35 during this closure were roughly 7 times more likely to be in a crash than they would be under normal conditions (3.41/0.51 \approx 7). Table 4.6 includes data for each crash during the event day and control day. The crashes shaded in gray took place during the closure. No fatalities occurred in any of these crashes.

Table 4.6. Crash data during road closure event and control day

Event Crash Data (2/25/01)							
#	Date	Time	Vehicle	Major Cause	Surface Conditions	Weather Conditions	Accident Injuries
1	2/25/01	1:00	Passenger Car	Too Fast for Conditions	Ice	Severe Winds	0
2	2/25/01	1:40	Passenger Car	Run Off Road	Ice	Blowing Snow	1
3	2/25/01	6:30	Truck Tractor (semi)	Evasive Action	Ice	Severe Winds	1
4	2/25/01	7:55	Truck Tractor (semi)	Evasive Action	Ice	Blowing Snow	2
5	2/25/01	8:00	Truck Tractor (semi)	Lost Control	Ice	Blowing Snow	1
6	2/25/01	18:50	Passenger Car	Too Fast for Conditions	Ice	Blowing Snow	0
7	2/25/01	23:48	Passenger Car	Run Off Road	Ice	Blowing Snow	3
Control Crash Data (2/18/01)							
#	Date	Time	Vehicle	Major Cause	Surface Conditions	Weather Conditions	Accident Injuries
1	2/18/01	2:10	Pickup Truck	Collision	Dry	Clear	2

Iowa 3/9/2002

On Saturday, March 9, 2002, the closure of I-35 ran from 8:00am to 4:00pm. The weather conditions included blowing snow, poor visibility, and heavy drifting. The Iowa DOT closed I-35 from Ames to the Minnesota border due to zero visibility.

Traffic Count Data

For this event, a “control date” of Saturday, March 16, 2002, was selected. When comparing the event traffic counts to the control counts, the traffic recorder at Jewell observed an average hourly decrease in traffic of 80% over the course of the closure, as shown in Table 4.7. The ATR at Hanlontown also observed an average decrease of 80%.

Table 4.7. Percentage of traffic during road closure event on 3/9/2002

				Webster		Clear					
	Jewell	Hanlontown	Boone	City	Hampton	Lake	Armstrong	Forstoria	Sheldon	Algona	
Time / traffic counts	8:00	37.75%	37.74%	48.76%	29.25%	55.84%	64.69%	3.13%	16.43%	13.59%	13.98%
	9:00	17.94%	26.88%	40.39%	21.75%	38.64%	52.92%	5.88%	15.70%	8.77%	4.76%
	10:00	4.08%	17.71%	28.75%	11.86%	29.57%	39.53%	5.10%	8.30%	11.11%	7.22%
	11:00	3.23%	11.08%	36.69%	9.70%	31.68%	27.26%	1.74%	13.41%	12.83%	6.54%
	12:00	6.05%	8.71%	50.59%	17.74%	35.20%	24.65%	4.63%	15.64%	13.31%	9.58%
	13:00	9.96%	11.27%	56.21%	29.46%	47.54%	26.12%	8.94%	15.05%	15.89%	20.00%
	14:00	17.09%	13.88%	48.93%	35.70%	48.33%	30.05%	10.26%	20.85%	24.52%	29.15%
	15:00	43.61%	20.83%	53.80%	44.93%	67.02%	37.46%	14.06%	15.87%	27.41%	22.84%
	16:00	40.34%	40.39%	55.88%	41.49%	50.90%	42.50%	18.33%	20.68%	36.00%	42.29%
Percentage total	20.01%	20.94%	46.67%	26.88%	44.97%	38.35%	8.01%	15.77%	18.16%	17.37%	

The traffic on all primary routes and the control routes also decreased, but it did not decrease as much as on the interstate, showing that the closures on I-35 discouraged some traffic from using I-35. As shown in Table 4.7, each of the primary routes (Boone, Webster City, Hampton, and Clear Lake) observed an average total decrease of 60% in traffic counts. The control ATRs in northwest Iowa observed a decrease of 85%. This may be related to the remoteness of the northwestern Iowa locations and to the increase in severity of the weather at these locations.

Event Crash Data

The crash data were collected on I-35 for both the event and control dates. Assuming that the average of the hourly traffic counts at the Jewell and Hanlontown ATRs was the average hourly volume on the segment of I-35 from Ames to the Minnesota boarder, crash rates were calculated during the day of the closure and on the control day.

During the road closure, the crash rate was 4.55 crashes per MVM. On the control date, no crashes were reported, but we can use the long-term rural interstate average for Iowa of 0.51 crashes per MVM for comparison. In other words, vehicles driving on I-35 during this closure were roughly 9 times more likely to be in a crash than they would be under normal conditions (4.55/0.51φ9). The actual crash data for the day of the closure and for the control data are shown in Table 4.8. The crash that occurred on I-35 during the closure is shaded in gray. Unfortunately, all the crashes recorded on the event day resulted in injuries and one resulted in a fatality. The last crash before the closure accounted for eight injuries.

Table 4.8. Crash data during road closure event and control day

Event Crash Data (3/9/2002)							
#	Date	Time	Vehicle	Major cause	Surface conditions	Weather conditions	Accident injuries
1	3/9/02	1:50	SUV	Too fast for conditions	Ice	Sleet/hail	2
3	3/9/02	2:14	Pickup truck	Too fast for conditions	Ice	Severe winds	1 fatality
2	3/9/02	7:30	Passenger car	Too fast for conditions	Snow	Severe winds	8
4	3/9/02	8:00	Tractor trailer (semi)	Vision obstructed	Snow	Snow	2
Control Crash Data (3/16/02)							
#	Date	Time	Vehicle	Major cause	Surface conditions	Weather conditions	Accident injuries
No collisions were reported							

Iowa Data Conclusions

Although not shown in any of the tables, the traffic counts on I-35 during the closures were rarely under 20 vehicles per hour and average during the closure was between 50 and 150 vehicles per hour on I-35. This demonstrates that Iowa’s closure practices on I-35 are not having the desired effect of evacuating the roadway. Vehicles are still getting on I-35, and, once they are on I-35 during the closure, they are still managing to crash. All closures averaged a length of 12 hours and involved severe weather and poor road conditions.

Traffic volumes on I-35 experienced an average decrease of 70% during the closure, while nearby primary routes reduced in traffic volume during the same period by roughly 60%. The decrease on the opened primary system seems to indicate that most of the reduction on the closed primary system is a result of a natural decline in the number of drivers that continue to travel during unsafe conditions rather than being dissuaded by the road closure, although there is some evidence that some drivers may be diverting trips on I-35 due to the closure.

Minnesota Closure Experience

Further analysis was conducted in Minnesota to assess the impact of the differences in road closures policies between Iowa and Minnesota and to confirm some of the conclusions regarding the Iowa closure experience. The analysis involved all winter weather road closures of I-90 from the I-90/I-35 intersection at Albert Lea, Minnesota, west to the South Dakota border. The Minnesota DOT has stricter policies than Iowa regarding the enforcement of road closures. Drivers found on I-90 after a closure are fined \$700 and face the potential of a jail sentence. In addition, Minnesota law makes the motorist responsible for any costs associated with rescuing a stranded motorist during a road closure. A decision to close the road in Minnesota is made by the Minnesota DOT.

A map of the gate system on I-90 is shown in Figure 4.4. There are 27 interchanges along I-90: 12 are low-traffic volume interchanges that have no ramp gates or signs, 8 interchanges have gates on the ramps only, and 7 have gates on the ramps and the mainline. Figures 4.5 and 4.6 contain pictures of a mainline and ramp gate, respectively. Figure 4.7 contains a picture of a sign mounted at all gates announcing a fine for violating the gate.

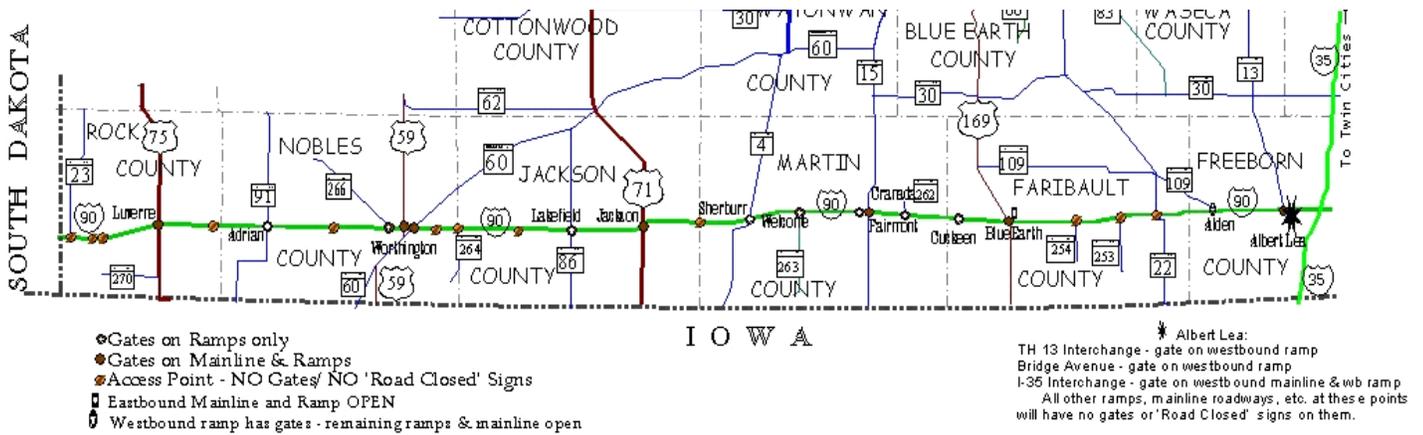


Figure 4.4. I-90 gate locations (25)

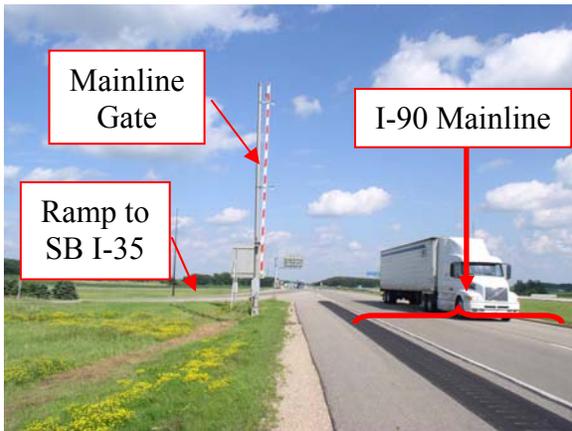


Figure 4.5. Minnesota mainline gate

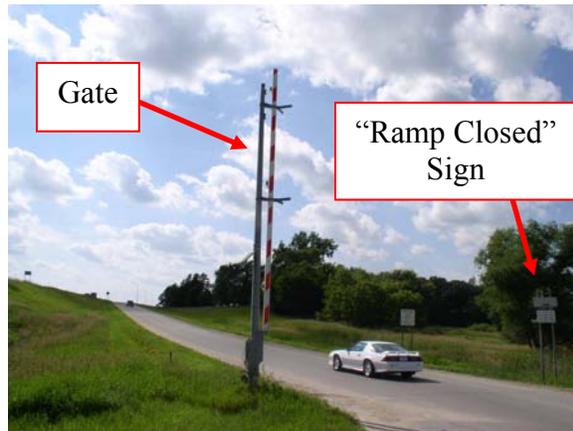


Figure 4.6. Minnesota ramp gate



Figure 4.7. Minnesota sign warning motorists of fine

I-90 from Albert Lea, Minnesota, west to the South Dakota boarder has been closed two times during the period between November 2000 and March 2003. I-90 was closed on December 16, 2000 (I-35 was also closed), and on February 24, 2001 (I-35 remained open, but was closed on February 25). For each closure, traffic volume was collected from ATRs. The traffic volumes were recorded by ATRs at 2 locations. The first ATR is located near Alden, Minnesota (8 miles west of Albert Lea), while the second one is located at the South Dakota border (near Monley, Minnesota). It is important to note that the ATR located on the border is actually on the South Dakota side. Furthermore, it was observed that South Dakota did not close their interstate at the same time as Minnesota. Therefore, traffic continued to travel into Minnesota and the ATR volumes reflected that

traffic. For this summary, all count data will be broken into the date of the closure and the location of the ATR.

Minnesota 12/16/2000

On Saturday, December 16, 2000, I-90 was closed from 4:00pm to 7:00am the following morning. The weather conditions during this closure included heavy and blowing snow. No crashes were reported during this closure.

Traffic Count Data

In order to compare the traffic counts during the event, a control date was selected. For this road closure event, the control date was Saturday, December 9, 2000. Traffic volume data on the control date were compared to the volumes reported at each ATR during the closure. These data are reported by the Minnesota Office of Transportation Data and Analysis.

When comparing the event traffic count to the control count, the traffic recorder at Alden observed an average hourly decrease in traffic of 92% over the course of the closure, as shown in Table 4.9. The ATR at the South Dakota border observed an average decrease of 48%. However, given the location of the ATR at the South Dakota boarder, we are not sure that these data are meaningful. The table contains the percentage of event traffic compared to the control traffic: when a number reads 21%, the actual decrease in traffic is 79%.

Table 4.9. Percentage of traffic during road closure event on 12/16/2000

Time/traffic counts	Alden	MN/SD Border
17:00	17.50%	105.67%
18:00	4.65%	93.81%
19:00	1.39%	100.71%
20:00	0.44%	95.24%
21:00	0.39%	108.16%
22:00	3.52%	101.54%
23:00	0.00%	103.64%
0:00	2.36%	100.50%
1:00	1.25%	0.68%
2:00	2.50%	2.08%
3:00	2.44%	3.13%
4:00	6.45%	6.49%
5:00	12.12%	11.67%
6:00	14.29%	19.39%
7:00	26.67%	25.63%
Average	7.59%	61.64%

Minnesota 2/24/2001

On Saturday, February 24, 2001, I-90 was closed from 10:00am to 1:00pm the following afternoon (February 25). The weather during this closure was reported to include blowing snow and icy road surfaces.

Traffic Count Data

In order to compare the traffic counts during the event, a control date was selected. For this event, the control date selected was Saturday, February 17, 2001. In Table 4.10, the hourly traffic counts during the event are compared to the same hours during the control day. At Alden and on the average, the traffic volume was reduced by 65%. At the South Dakota border, the average decrease was 85%. The low volumes at the South Dakota border, in comparison to the previous closure, must indicate that there should be coordination between the Minnesota and South Dakota DOTs in the future.

Table 4.10. Percentage of traffic during road closure event on 2/24/2001

Time/traffic counts	Alden	MN/SD Border
10:00	21.48%	29.33%
11:00	38.68%	33.20%
12:00	36.29%	32.97%
13:00	47.83%	33.33%
14:00	52.35%	39.59%
15:00	45.72%	37.42%
16:00	43.51%	38.71%
17:00	56.54%	43.44%
18:00	60.23%	27.40%
19:00	43.37%	22.19%
20:00	53.92%	17.07%
21:00	48.79%	18.67%
22:00	35.98%	16.28%
23:00	35.25%	10.14%
0:00	27.12%	5.61%
1:00	48.65%	8.51%
2:00	37.25%	2.56%
3:00	48.48%	1.75%
4:00	37.93%	0.00%
5:00	69.23%	0.00%
6:00	36.84%	0.00%
7:00	19.64%	0.00%
8:00	21.88%	0.00%
9:00	9.20%	0.47%
10:00	7.35%	3.13%
11:00	6.01%	1.38%
12:00	4.35%	3.48%
13:00	7.54%	4.14%
14:00	9.88%	5.04%
Percentage average	34.87%	15.03%

Event Crash Experience

The crash data were collected on I-90 for both the event and control dates. To calculate the average hourly traffic volumes, we took the average of the volumes reported by the two ATRs. By using the volumes counted at the South Dakota ATR, the traffic volumes are likely over-estimated, and the volumes were probably the lowest in the middle of the segment rather than on the ends of the segment (the locations of the Alden and the South Dakota ATRs). The segment length of I-90 from the South Dakota border to the interchange with I-35 at Albert Lee, Minnesota, is 159 miles.

For the closure period, a crash rate of 1.41 crashes per MVM was estimated, which we believe underestimates the actual crash rate. No crashes were observed during the control date. Table 4.11 shows detailed information pertaining to the crashes that occurred during the closure.

Table 4.11. Crash data during road closure event on 2/24/2001

#	Date	Time	County	Vehicle	Major cause	Surface conditions	Weather conditions	Injury accidents
1	12/24/2001	12:00	Feebom	Truck tractor w/semi trailer	Unsafe speed	Ice/packed snow	Blowing snow	0
2	2/24/2001	13:00	Nobles	Passenger car	Unclear	Wet	Cloudy	0

Comparison of Iowa to Minnesota Closure Experience

Minnesota has more restrictive policies regarding a roadway closure than Iowa; they have the authority to enforce and complete evacuation of the interstate. Although the ATRs we had access to in Minnesota were not ideally located to determine the volume of traffic on I-90, during the course of the closures, there were periods where there were either no or nearly no vehicles recorded at our two ATRs. In Iowa, during closures, the ATRs rarely experienced as few as 20 vehicles per hour, and, during most closures, the ATRs experienced between 50 and 150 vehicles per hour or more. These vehicles were 7 to 33 times more likely to be in a crash than under clear weather conditions. Given increased crash risk under severe weather conditions, it would seem reasonable that Iowa needs to develop more aggressive policies to evacuate the roadway. On the other hand, even though Minnesota is more aggressive when it comes to evacuating the highway, there are still some vehicles traveling on I-90 when the road is closed.

Truck Traffic Analysis

Intuitively, we would suspect that during severe weather, commercial vehicles would be less likely to cancel trips. Commercial trips are not discretionary, and as we saw in the literature review and the carrier interviews, the costs of unexpected delays can be quite significant. However, using an ATR just south of Ames on I-35 that has the capability to classify vehicles, we captured data on the number of commercial and passenger vehicles traveling during three storms to validate our intuition.

We started with dates in which more than one inch of snow fell and also dates where all weather conditions were normal (control days). Each date analyzed occurred on a Saturday of the same month and year, except for one event on March 1, 2002, which was on a Friday. On March 1, 2002, snow was falling from 3:00pm to midnight; on March 2, 2002, snow was falling from midnight to noon; on March 9, 2002, snow was falling from midnight to 7:00pm, and I-35 north of Ames was closed from 8:00am to 2:00pm. The control day was March 16, 2002. On this day, the sky was clear, wind speeds were low, and traffic counts were determined to be at normal levels for that month and year.

The Iowa DOT defines a “commercial truck” as any commercial vehicle with 2 or more axles and having a Gross Vehicle Weight (GVW) over 10,000 pounds (5 tons). This does not include pickup trucks, but does include heavier vehicles such as straight trucks. Using

hourly counts of commercial vehicles and non-commercial vehicles, we calculated the percentage of the total traffic stream that consisted of commercial trucks. The results are shown in Table 4.12. In this table, the periods when snow was falling are shaded.

As each of the events progressed, the percentage of commercial truck traffic increased. This is largely because non-commercial truck trips declined and the trucks remaining on the road become a larger percent of the total. This trend is also illustrated in Figure 4.8, which is a plot of the data in Table 4.12. The red line (usually the line on the bottom) is the control day. The lines represent the percentage of the traffic stream that consists of trucks during that hour. In only a couple of cases, the snowy day percentages are not above those of the control day. Over the entire day, the percentage of the traffic stream consisting of trucks increased over the control day by 38%–70%. This increase verifies our theory that commercial truck trips are less likely to be deferred than non-commercial truck trips.

Table 4.12. Percentage of total hourly traffic volume consisting of commercial trucks

Time	Control	3/1/2002	3/2/2002	3/9/2002
1:00	30%	53%	42%	45%
2:00	41%	60%	39%	45%
3:00	42%	62%	59%	39%
4:00	55%	73%	65%	52%
5:00	51%	69%	59%	56%
6:00	38%	51%	47%	38%
7:00	32%	44%	52%	34%
8:00	20%	32%	44%	32%
9:00	14%	27%	40%	23%
10:00	11%	27%	29%	36%
11:00	10%	26%	23%	19%
12:00	10%	27%	24%	8%
13:00	11%	23%	24%	10%
14:00	10%	20%	21%	25%
15:00	11%	19%	20%	20%
16:00	12%	19%	20%	18%
17:00	12%	18%	21%	19%
18:00	11%	18%	20%	24%
19:00	12%	20%	23%	25%
20:00	13%	25%	23%	31%
21:00	12%	28%	27%	28%
22:00	16%	32%	25%	23%
23:00	16%	38%	23%	33%
24:00	11%	42%	21%	22%
Day average	21%	36%	33%	29%

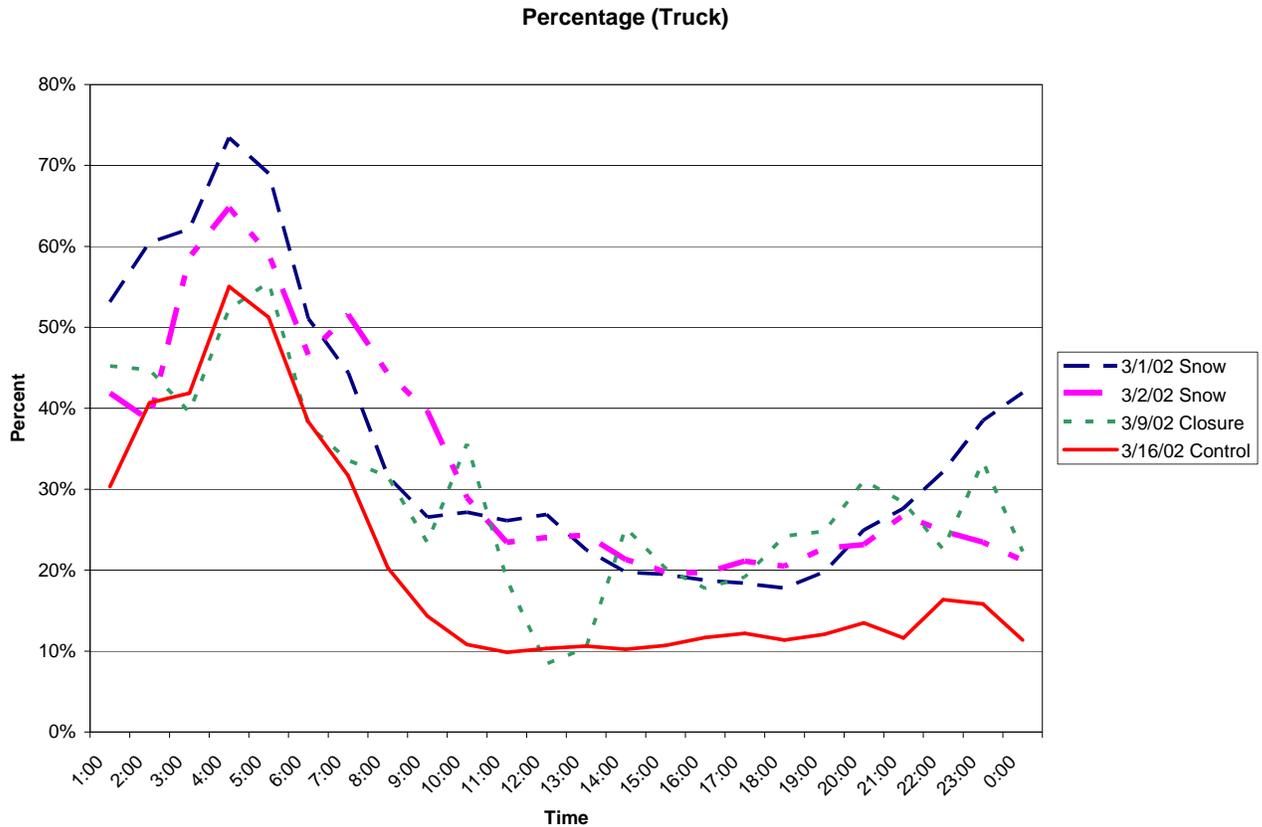


Figure 4.8. Commercial truck traffic as a percentage of the total hourly volume

Conclusions

In this chapter, we reported on case studies of all of the road closures on I-90 (in Minnesota) and I-35 (in Iowa) between 2000 and 2003. Minnesota has more restrictive laws regarding the enforcement of road closures, while Iowa’s policy is to encourage travelers to go to the nearest large city and get off the road. Minnesota uses ramp and mainline gates, while Iowa only gates the ramps. Minnesota’s closure practices seem to be more effective in evacuating closed roads. However, even with Minnesota’s more restrictive laws, some motorists are using the road and are having crashes.

In Iowa during closures, traffic volumes remained between 20% and 30% of the volume we would normally expect during clear weather. Traffic remaining on the closed road crashes 7 to 27 times more frequently than traffic on the same road during clear conditions.

We also analyzed the proportion of commercial trucks traveling on a closed road relative to the entire traffic stream. From this analysis, we learned that commercial trucks are much less likely to defer trips than other types of vehicles.

5. MODELING SAFETY IMPACTS OF WINTER WEATHER

Introduction

As we saw in the literature review and through the carrier/shipper interviews, the more notice an STA can provide travelers, shippers, and carriers about the potential of a road closure, the lower the road user cost. Also, with more advance warning, an STA can close a road more orderly and methodically. Waiting for conditions to evolve and then closing the road with no advance warning results in the most costly set of conditions. We have speculated that the reason that so many drivers violate closures in Iowa on I-35 is partly that they are not given advance warning of the closure and see no other option than to continue their trip regardless of the road conditions.

In the survey of STAs, we found that most states close roadways based on conditions reported by field staff or by deeming the road unsafe as a result of a recent spate of weather related crashes. Only one state reported a measurable weather parameter indicating a threshold for determining when the roadway is no longer safe.

To understand how conditions impact the relative safety of a road, safety analysts often develop a Safety Performance Function (SPF). Typically, the analyst uses the SPF to understand the relationship between safety and design aspects of a roadway or an intersection (e.g., presence of deceleration lanes, shoulder width, lane width, grade, curve radius) and characteristics of the traffic (e.g., traffic volume, speed variance, average speed, percentage of trucks in the traffic stream, percentage of traffic turning left). Typically, an SPF will consist of one or more of these measurable variables as independent variables, and the dependent variable will be crash density as measured by crashes per some distance measure over a time period (e.g., crashes per mile per year) or crashes at a location over a time period (e.g., crashes per intersection per year). The dependent variable is the number of crashes and, therefore, the dependent variable is a positive integer. A statistical model where the dependent variable is a non-negative integer is known as a count model.

In our case, we are dealing with a relatively homogeneous roadway environment—rural interstate highways. The traffic volumes are low enough so that interactions between vehicles are not causing safety problems. Assuming that during winter storms the level of maintenance remains consistent and driver behavior remains consistent from storm-to-storm, the primary variable impacting the relative safety are weather parameters (e.g., intensity of snow fall, wind speed, visibility). Therefore, we can model the relative crash density as a function of winter weather parameters. The results of our modeling (an SPF) provides insight into two issues:

1. The resulting SPF can provide insight into how measurable properties of winter weather impact safety. Assuming that we can identify the number of crashes that make a segment unsafe, we can then identify the thresholds of each weather

parameter, or weather parameters in combination, that result in an unsafe highway.

2. With predictions of future weather, the STA can identify in advance when the roadway is likely to become unsafe. As our knowledge of the weather condition becomes more certain, our prediction of the safety performance of the roadway will become more certain. Sharing knowledge of the likelihood of a closure will help the road users and the STA to prepare for a road closure.

Analysis

This analysis was conducted to show that it is possible to create an SPF using weather parameters as the independent variables. We had hoped that the road weather information system (RWIS) operated by the Iowa DOT would provide the weather parameters needed to estimate an SPF, but important weather parameters, such as visibility and snow fall intensity, were not available through the Iowa DOT RWIS. Ultimately, we relied on weather information from a nearby airport and had only one data reporting point for 113 miles of freeway. Therefore, we consider our model a prototype for future models.

The estimation of the prototype model involved two steps. First, since travel declines during winter storms, we needed to develop a model that relates weather conditions to traffic volumes. Second, we needed to develop a model that relates weather conditions to crash frequency. In other words, the second model would estimate the safety performance of a roadway during a storm.

We used data from I-35 in northern Iowa as our case study. The entire segment is considered rural, with flat or slightly rolling terrain. We used weather data collected at Mason City's commercial airport (about one mile from I-35 and roughly one-third of the length of the segment south of the Minnesota border). The airport maintains an automated weather observing system (AWOS) that provides information on weather conditions, including visibility and snow fall intensity.

Because we were only interested in the impact of winter storms, we first found days during 2000 and 2001 (years when we had crash, traffic counts, and weather data) when more than 1 inch of snow fell during a 24-hour period. We determined hourly traffic counts during these time periods on non-snow days to develop baseline average hourly traffic volumes. Average hourly traffic volumes were then compared to hourly traffic volumes during snowy days to arrive at a percentage of traffic reduction during that hour due to snowy conditions. We correlated the traffic volume reductions with visibility measurements and wind speed measurements from the Mason City airport. Our data included 27 days and a wide range in visibility—from 1/4- to 10-mile visibility. Wind speeds varied from no wind to winds over 30 miles per hour.

Linear regression was used to relate visibility and wind speed to percent reduction in volume for each hour. The regressions in the mid-afternoon hours (1:00pm–4:00pm)

resulted in a best fit, but our independent variables (visibility and wind speed) were always highly statistically significant regardless of the hour. The model for 3:00pm is shown below. The numbers in parenthesis are the statistical significance of the regression parameters (p-values). The R-squared for the model is 0.46. When we apply fairly severe condition to this equation (WS = 40 mph and Vis = 0.25) we arrive at almost an 80% reduction in hourly traffic volume.

$$\text{PRTC} = 0.200 + 0.015(\text{WS}) - 0.036(\text{Vis})$$

(0.08)
(0.014)
(0.004)

Where: PRTC = Percentage reduction in hourly traffic count
 WS = Wind speed in miles per hour
 Vis = Visibility in miles

The next step was to create a model relating our weather parameters to crash frequency along the 113-mile segment of I-35. Since the dependent variable is a count variable, we used Poisson regression to model our dependent variable (crashes per hour). We used all hours in our data set in one regression, giving us 288 data cases. Again, our parameter estimates for our variables are very statistically significant. The best fit resulted is shown below:

$$\text{ECFreq} = -\exp(-1.4943 - 0.1445(\text{VIS}) + 0.0101(\text{INTER}))$$

(0.0001)
(0.010)
(0.032)

Where: ECFreq = Expected Crash Frequency
 VIS = Visibility
 INTER = Visibility x Wind Speed

Wind speeds and visibility are highly correlated, and the INTER term in the equation expresses this interaction. Combining the two equations and using the visibility and wind data shown in Table 5.1, we get the crash rate plot shown in Figure 5.1. The visibility and wind are fabricated based on our experience with these data. We assumed an average hourly volume of 1,000 vehicles, which is typical for this stretch of highway mid-day on a day with clear weather. At the best visibility and lowest wind speed, the equation estimates a crash rate of 0.54 crashes per million vehicle miles (MVM). A crash rate of about 0.51 crashes per MVM is what we would expect on a rural interstate highway under good conditions (26). Under our most severe weather conditions, we estimated a crash rate of 13 crashes per MVM—an increase of 25 times, which is quite similar to the crash rate we observed during I-35 road closure.

Table 5.1. Visibility (in miles) and wind speed (in mph)

Visibility	Wind
10	2.5
9	5
8	7.5
7	10
6	12.5
5	15
4	17.5
3	20
2	22.5
1	25
0.5	27.5
0.25	40

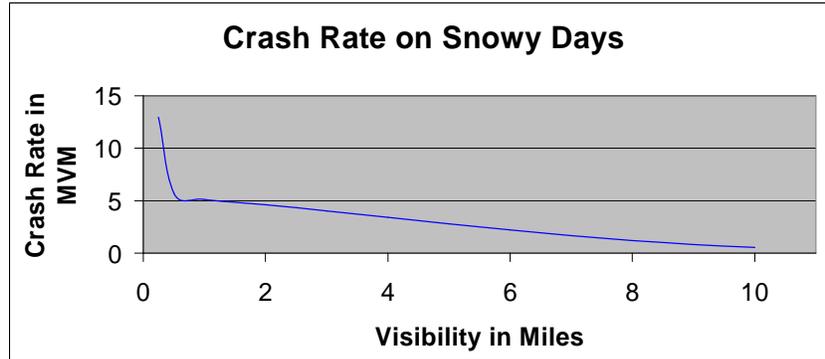


Figure 5.1. Modeled crash rate versus visibility during snowy conditions

Implications of the Analysis and Conclusions

The above analysis is only one example of what could be done to model the relationship between measurable weather parameters and safety. Additional research is needed before a real-time working prototype system is deployed. We did find, however, a strong statistical relationship between visibility and traffic volume and traffic crashes. Ideally, we would have preferred using measurements of visibility at the roadside instead of at a nearby airport. Further, there are probably other variables that should be included in the models to improve reliability and predictability, such as road surface friction, snowfall intensity, and intensity of winter maintenance activity. Nevertheless, the analysis does show that weather condition information collected at the roadside can be used to estimate current relative safety of the highway. Using forecasted weather condition data, we can estimate the relative probability that highway environmental conditions will reach a level that makes travel unsafe and possibly predict when a road closure will be necessary. Forecasts of roadway conditions and possible road closures would allow freight shippers and travelers to adjust their schedules and dramatically reduce user costs and anxiety.

6. CONCLUSIONS AND RECOMMENDATIONS

This report investigated issues related to the costs and benefits of road closures due to winter storms and found that the issues related to determining the benefits and costs of road closures were far more complex than the research team had initially suspected. The benefits of a road closure are related to user costs (mostly costs associated with crashes) that would have occurred had traffic been allowed to proceed on the roadway. The costs are the costs incurred by shippers and travelers that would have successfully traversed the roadway had it remained open. Through our research, we learned quite a bit about the benefits of road closures, but found that the cost side is a complicated issue.

Conclusions

Very clearly, there are significant costs associated with driving during severe winter weather conditions. Driving during snowy weather increases the risk of being in a crash, and driving during the most severe weather elevates the crash risk by several times. As we saw in our safety performance function model, and as exhibited in case studies of I-35 closures, crashes during the worst weather conditions can increase a driver's crash risk by 25 or more times in comparison to the risk during clear conditions.

On the cost side, the costs of delays are difficult to quantify due to several reasons. The reasons include the following:

1. When the weather is severe, many travelers will simply choose not to travel. For example, on rural I-35, during a snow day we can expect an 80% reduction in traffic volumes when the wind speed increases to 40 mph and visibility drops to 0.25 miles. Many drivers will choose not to travel when conditions are severe, and, therefore, the decision to defer the trip is made independently of the STA's decision to close the roadway.
2. Traditional models of road user delay deal with small increments of time where the driver and passengers are assumed to have no alternative use for their time. However, typical road closures last for a minimum of several hours and possibly days. Depending on conditions, drivers may have alternative uses for their time, and shippers, receivers, and motor carriers may be able to adjust their schedules and routing to accommodate or avoid a delay. Observation studies of many types of transportation service disruptions have shown that, given information about the disruptions, many travelers are able to make adjustments to avoid the cost consequences of a disruption.
3. Traditional models of road user delay take into account generalized and direct costs—the costs associated with making the trip itself (value of the driver's time, capital costs of the vehicle, fuel, insurance, wear and tear on the vehicle, etc.). The problem with these types of models is that travelers and commercial shipments will often have synchronous activities at the destination. As was seen

in the interview with perishable shipper in Chapter 3, the costs of unexpected delay can be quite significant. As we saw in our review of Western European freight travel time studies, the value of 1 hour of unexpected delay can cost 30 times or more the value of an expected hour of delay.

Until we can better understand the cost side of winter weather-related delays, we can only construct naive models of road user costs. To bridge the knowledge gap, research needs to be conducted on travel time reliability and on the way advance information impacts costs. A first step in understanding the value of travel time reliability is to follow the lead of our European counterparts and conduct revealed preference to stated preference studies to determine the value of expected and unexpected travel time delay to travels and commercial shipments. The Future Strategic Highway Research Program (F-SHRP) plans to tackle the issues of travel time reliability and, assuming congress funds F-SHRP, we should have much better information on the value of travel time reliability within the next five years.

Although we already know a good deal about the added risk that winter weather presents to highway travel, we really have not yet quantified what attributes of winter weather make roadways unsafe, what the relative safety is under varying levels of these attributes, and how the level of winter maintenance service impacts relative roadway safety. In Chapter 5 of this report, we built a model that illustrates how a model can be used to quantify the relationship between weather conditions and relative road safety. Models, like the one proposed, can be used to understand the relationship between measurable and predictable road weather attributes. Measurable attributes can then be used to estimate the relative safety of a roadway. Once the present or future road safety is known, road management decisions on the likelihood of a road closure or an actual road closure can be made on objective information rather than depending solely on subjective input from field staff and experience of road managers or, worst of all, waiting for spate of crashes to make a decision to close a roadway.

Many state transportation agencies (STAs) in Snow Belt states are building road weather information systems to provide roadway specific weather information, and groups such as the AURORA are working to improve and expand the capabilities of these systems.(25) However, if these system are going to provide weather information that is important for understanding road safety, useful to road safety decision-making, and of assistance in supporting traffic management decisions, these system need to accurately collect weather attributes that are important to traffic safety and traffic management. These include attributes like visibility, pavement friction, precipitation type, and precipitation intensity.

Recommendations

The following are specific recommendations for authorities responsible for making road closure decisions (specifically the Iowa DOT):

1. *STAs and state police need to accurately communicate weather-related road conditions.* Information on road conditions has improved greatly through several state-level road condition reporting systems and through state-level 511 systems (see <http://www.fhwa.dot.gov/trafficinfo/index.htm> for several examples). The more can be done to communicate likely future road conditions and the likelihood of a road closure, the more travelers and shippers and receivers of commercial goods can adjust their activities and schedules to accommodate an unexpected delay.
2. *The importance of travel time reliability is not well understood and should be studied further.* Understanding travel time reliability is the key to determining the value of maintaining roads during winter weather. Without knowing the value of travel time reliability, it is impossible to understand the value of maintaining roads during winter storms. Therefore, we recommend that the winter maintenance community become engaged and supportive of efforts by F-SHRP and other programs that fund research to better understand travel time reliability.
3. *An SPF model should be developed to relate the relative safety of a roadway to measurable weather parameters.* An example of such an SPF is presented in Chapter 5. These models can quantify the present and future safety of a roadway based on measurable weather attributes and provide highway managers with objective measures of the relative safety rather than subjective measures. Therefore, we recommend the funding of research to quantify the relationship between measurable severe weather parameters and safety.
4. *The Iowa DOT and the Iowa Highway Patrol should develop policies that more aggressively evacuate and close roadways once a closure decision is reached.* We were surprised that during our interviews with motor carriers, two suggested that it would help their business if STAs would close the road when it was unsafe to travel and provide public notice that the road had been closed to traffic. This would take the decision to stop due to severe weather out of the hands of their drivers and provide proof to their customers that shipments are late due to official actions. Possibly, the Iowa DOT and the Iowa Department of Public Safety can work with the legislature to adopt laws similar to those of Minnesota that allow for sanctions for those that violate closures.

APPENDIX

Trucking Company Interview Questions

I. Impacts of Closed Roads

1. What types of operational and financial costs do you incur when a vehicle is delayed due to road closures arising from winter storms?
2. What is the total cost to your firm on a per hour basis?
3. What other operating and service problems or challenges are presented by such road closures?
4. What are the primary types of products you haul on I-35 and I-80 in Iowa?
5. What percentage of your shipments is for customers on just-in-time systems? What are the typical delivery windows for these JIT shipments?
6. Do you know the level of costs your customers incur when shipments are not delivered on time? (Please cite some examples.)
7. Do you have contractual agreements with your customers that include penalties for late deliveries? If so, are you still held to these standards (a) when public authorities close roads? (b) when your company decides that travel is not safe?

II. Planning for Road Closures

1. Other than public authorities deciding to close a route, how does your firm decide whether it's safe for the driver to continue during a winter storm?
2. What type of information and information sources do you utilize in your decisions related to road closures and travel safety?
3. Please describe your firm's contingency planning for and responses to road closure situations (e.g., alternative routes, using alternative/partner carriers, interactions with customers).

4. What are the “best practices” of your customers with respect to planning and responses to transportation delays and shutdowns due to weather?

III. Road Closure Experiences Outside of Iowa

1. Please describe best practices of other states with respect to road closures (or keeping roads open) during winter storms (e.g., methods of communicating with carriers and drivers, available information and information technology, monitoring or policing traffic, regulations and penalties).

REFERENCES

1. Cambridge Systematics, Inc., Texas Transportation Institute, the University of Washington, and Dowling, Associates. *Providing a Highway Systems with Reliable Travel Times: Study 3–Reliability*. Prepared for the Future Strategic Highway Research Program, Transportation Research Board, Prepared by 2003.
2. Johnson, D.L. *Automated Road Closure Gate Needs Assessment and I-90, Exit 67 Electric Actuator Project*. Study SD2001-08. Pierre, South Dakota: South Dakota Department of Transportation, July 2003.
3. Minnesota Department of Transportation. *I-90 Gate Closure Operations Manual*. November 2000.
4. Khattak, A.J., K.K. Knapp, K.L. Giese, and L.D. Smithson. *Safety Implications of Snowstorms on Interstate Highways*. Preprint, presented at the Annual Meeting of the Transportation Research Board, Washington, D.C., January 2000.
5. Compton, R.P., R.D. Blomberg, H. Moskowitz, M. Burns, R.C. Peck, and D. Fiorentino. Crash Risk of Alcohol Impaired Driving. In *Proceedings of the 16th International Conference on Alcohol, Drugs, and Traffic Safety*. International Council on Alcohol, Drugs, and Traffic Safety, Montreal, Canada, August 4–9, 2002. [http://www.saaq.gouv.qc.ca/t2002/actes/pdf/\(06a\).pdf](http://www.saaq.gouv.qc.ca/t2002/actes/pdf/(06a).pdf)
6. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. *United State Snow Climatology*. 2002. <http://lwf.ncdc.noaa.gov/oa/climate/monitoring/snowclim/mainpage.html>
7. Igarashi, H. A. Tentative Essay on the Economic Effect of Snow Removal on the Street Network. *Proceedings of the Japan Society of Civil Engineers*, No. 196, pp. 87–93, 1971.
8. Chiba, H., K. Sato, K. Taniguchi, and H. Igarashi. Effects on Industry of the Winter Traffic Environment—the Example of Supporo City. *Proceedings of the Third Cold Region Technology Conference*, 1987, pp. 113–118.
9. Salt Institute. Billion\$ at Risk During Snow Emergencies, Snowfighting Investment Pays Big Dividends. Prepared for the Salt Institute by Standard and Poor’s DRI, Alexandria, VA, 1999, <http://www.saltinstitute.org/emergency.html>
10. Kuemmel, D.A., and R.M. Hanbali. *Traffic Accident Analysis of Ice Control Operation*. Presented at the 3rd International Symposium on Snow and Ice Control

-
- Technology, Transportation Research Board Conference, Minneapolis, MN, 1992, pp. 14–18.
11. Morisugi, H., Y. Hayashiyama, M. Saito, and C. Sato. *Benefit Evaluation of Road Snow Removal in the Tohoku Region*. Presented at Xith International Winter Road Congress World Road Association, PIARC, Sapporo, Japan, January, 2002.
 12. McBride, JC, “Economic Impact of Highway Snow and Ice Control,” Transportation Research Record 674, 1978, pp. 58-63
 13. Small, K.A., C. Winston, and Y. Yan. *Uncovering the Distribution of Motorists’ Preferences for Travel Time Reliability: Implications and Road Pricing*. Berkeley, CA: University of California Transportation Center, paper number 546, 2003, <http://www.uctc.net/papers/546.pdf>
 14. Dalzeill, E. and A. Nicholson. Risk and Impact of Natural Hazards on a Road Network. *Journal of Transportation Engineering*, Vol. 127, Issue 2, 2001, pp. 159–165.
 15. Cairns, S., C. Hass-Klau, and P. Goodwin. Traffic Impact of Highway Capacity Reductions: Assessment of the Evidence. Prepared for London Transport and the Department of the Environment, Transportation and the Regions, London, England, 1998.
 16. Knapp, K.K. Investigation of Volume, Safety, and Vehicle Speeds During Winter Storm Events. Presented at the Ninth AASHTO/TRB Maintenance Management Conference, Juneau, Alaska, August, 2000, pp. 57–64.
 17. McBride, J.C., M.C. Benlangie, W.J. Kennedy, F.R. McCornkie, R.M. Steward, C.C. Sy, and J.H. Thuet. Economic Impacts of Highway Snow and Ice Control. National Pool Fund Study Report FHWA-RD-77-95, Federal Highway Administration, U.S. Department of Transportation, 1977.
 18. Hanbali, R.M. *Economic Impact of Winter Road Maintenance on Road Users*. Transportation Research Record 1442, Transportation Research Board, Washington, DC, 1994, pp. 151–161.
 19. Nixon, W. *The Potential of Friction as a Tool for Winter Maintenance*. Iowa City, IA: Iowa Institute of Hydraulic Research, Report No. 392, College of Engineering, University of Iowa, February, 1998.
 20. Hanbali, R.M. and D.A. Kuemmel. Traffic Volume Reductions Due to Winter Storm Conditions. Washington, DC: Transportation Research Record 1387, Transportation Research Board, 1993, pp. 159–164 .

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21. Small, K.A., R. Noland, and D. Lewis. *Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway Users-Cost Estimation*. National Cooperative Highway Research Program Report 431. Washington, D.C.: Transportation Research Board, 1999.
 22. Kawamura, K. Perceived Value of Time for Truck Operations. *Transportation Research Record* 1725, 2000, pp. 31–36.
 23. Minnesota Department of Transportation. *I-90 Gate Closure Operations Manual*. February, 2000.
 24. Iowa Department of Transportation, Department of Traffic and Safety. *2000 Iowa Crash Facts*. Ames, IA: October 15, 2002.
 25. See <http://www.aurora-program.org/>