Risk Analysis of Freeway Lane Closure During Peak Period

Jake Kononov and Zane Znamenacek

This paper examines risks associated with peak period lane closure during construction or maintenance work on urban freeways. In accordance with recently implemented policy by the Colorado Department of Transportation, lane closure would be allowed if reserve capacity were available. A relatively minor accident in the work zone caused substantial delays during the peak period that virtually paralyzed traffic in the Denver, Colorado, metropolitan area. This occurrence caused reexamination of the existing lane closure policy. Generally speaking, if a contractor is allowed greater flexibility in establishing work schedules, including the ability to work through peak periods, a lower bid can be expected. This paper compares savings in the cost of construction related to allowing lane closure during peak periods with the cost of potential incident-related delays in the framework of a quantitative risk analysis.

Probabilities direct the conduct of the wise man.

—Cicero, *De Natura Deorum*

A lane closure decision support analysis model was developed and implemented for the Greater Denver Metropolitan Area by the Colorado Department of Transportation (*1*). It was conceived as an expert system intended to improve the quality of lane closure decisions, simplify the decision-making process for the end user, and reduce uncertainty associated with handling traffic during construction and maintenance. It established uniform criteria and authoritative guidance for scheduling lane closures in the metropolitan area. The lane closure strategy was conceived as a knowledge-based expert system that can be calibrated and adapted to other metropolitan areas around the country. Development of the lane closure strategy was motivated by the need to strike appropriate balance between delays to the traveling public in the work zone and the cost of construction and maintenance. A decision support analysis system was developed on the basis of extensive data collection and analytical procedures that estimate the queues and delays expected during lane closures. This decision support system forms the analytical framework behind the lane closure strategy implemented by the Colorado Department of Transportation (DOT) in the Denver metropolitan area.

Historically, lane closure decisions were made primarily on the basis of field observations, previous experience, and engineering judgment. Project-specific decisions were required to determine an appropriate lane closure schedule. This comprehensive strategy bases lane closure schedules on actual data, accounting for the spatial and temporal variations in traffic patterns that typically occur throughout a large urban area. The results of the analyses are lane closure schedules covering more than 500 mi of freeway and arterial roadways and reflecting traffic operations for more than 16,000 different lane closure scenarios possible in the Denver area. The schedules have been summarized in a graphical format and entered into lane closure schedule databases that may be queried by Colorado DOT personnel to develop appropriate lane closure schedules for individual projects or maintenance operations. Figure 1 and Table 1 represent a sample of the information contained in the lane closure report. This report was also made available to the contractor community to assist with planning roadwork in the Denver metropolitan area.

The lane closure strategy had been in effect in the Denver metropolitan area for approximately 2 years when a relatively minor accident in the work zone involving a truck breakdown resulted in substantial delays during the peak period, which virtually paralyzed traffic in the area. This site-specific occurrence prompted a general reexamination of the existing regionwide lane closure strategy affecting freeways during the peak period. Before this incident, lane closure during the peak period would be allowed if reserve capacity were available. Generally, if the contractor is allowed greater flexibility in establishing work schedules, including the ability to work during peak periods, a lower bid can be expected. This paper compares savings in the cost of construction with the cost of potential incident-related delays in the framework of a quantitative risk analysis.

LITERATURE REVIEW

Much has been written on the subject of work zone safety. The emphasis appears to be focused on compliance with reduced speed limits in the work zones and the expected reduction in safety due to the presence of a work zone and capacity reduction in work zones.

In "Safety Implications of Freeway Work Zone Lane Closures," Zhu and Saccomanno discussed the safety implications of left-lane and right-lane closures (*2*). Wang et al. observed that accident rates on highways are 7% to 119% higher during construction than during times without construction (*3*). Such a broad range of change in accident rates in the work zone suggests that the question is not well understood.

Huebschman et al. stated that accident rates increase about 30% on Interstates in work zones (*4*). The remainder of their study focused on the evaluation of a product's effectiveness on reducing speed in the work zone.

Rister and Graves conducted extensive research in estimating reasonable delay costs (*5*). They found that the various delay costs for cars used throughout the United States ranged from about \$9/h to about \$15/h in 1998 dollars.

J. Kononov, Colorado Department of Transportation, 2000 South Holly, Denver, CO 80222. Z. Znamenacek, Safety Engineering and Analysis Group, Colorado Department of Transportation, 4201 East Arkansas, Denver, CO 80222.

Transportation Research Record: Journal of the Transportation Research Board, No. 1908, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 80–87.

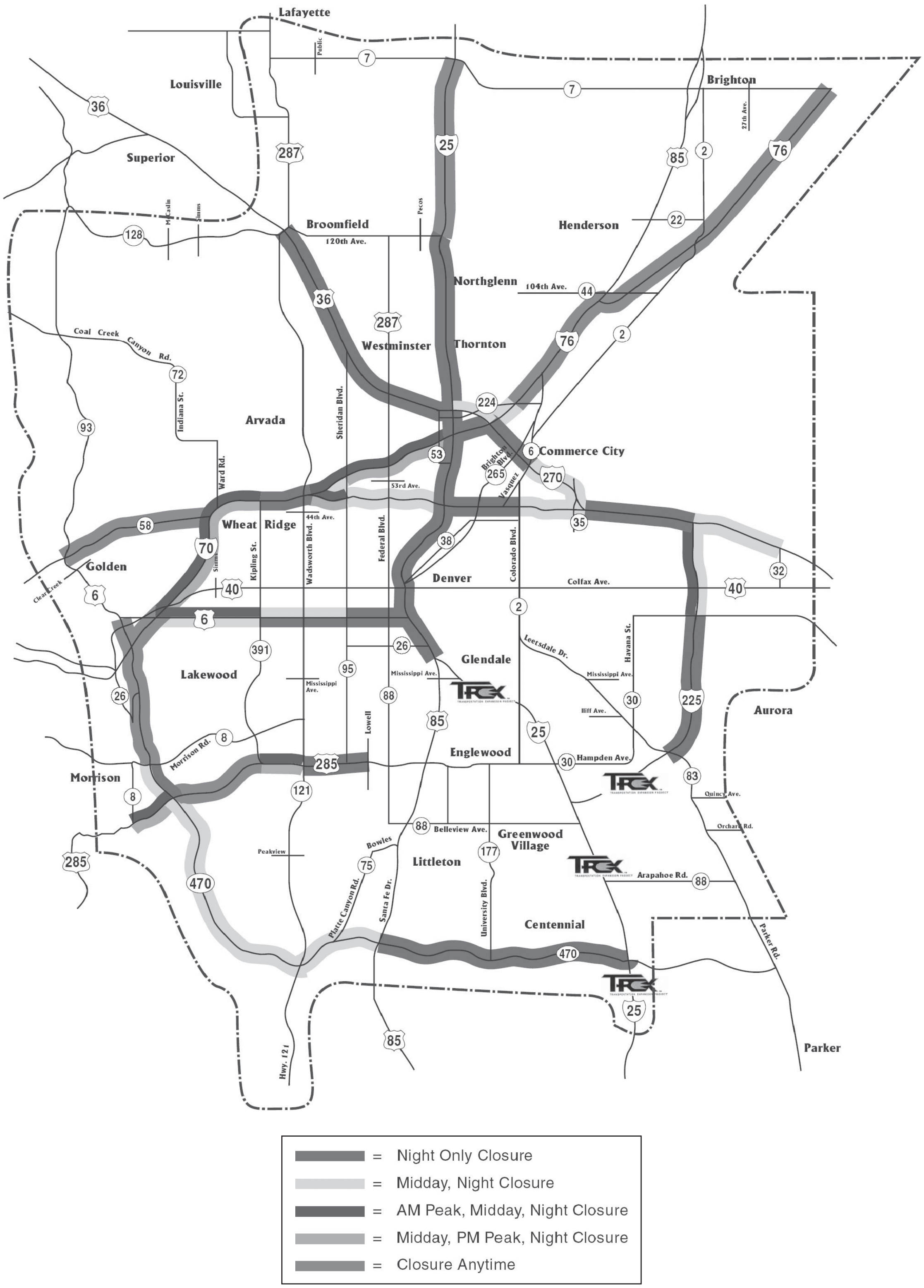

FIGURE 1 Map of six-lane closures.

TABLE 1 Region 6 Lane Closure Policy

State Highway Number	Facility Name	Direction	From	To	Beginning of Section (MP#)	End of Section (MP#)	Facility Type	Weekday Closure Window #1	Weekday Closure Window #2	Weekend Closure Window
030A	6th Avenue	EB	Billings Street	Airport Blvd.	10.168	12.585	Arterial	7:00 p.m. to 9:00 a.m.		6:00 p.m. to 11:00 a.m.
030A	6th Avenue	WB	Airport Blvd.	Billings Street	12.585	10.168	Arterial	6:00 p.m. to 8:00 a.m.		5:00 p.m. to 11:00 a.m.
035A	Quebec	NB	I-70	I-270	8.553	8.898	Arterial	Anytime		Anytime
035A	Quebec	SB	I-270	I-70	8.898	8.553	Arterial	Anytime		Anytime
035A	Quebec	NB	I-270	End SH 35	8.898	9.57	Arterial	Anytime		Anytime
035A	Quebec	SB	End SH 35	I-270	9.57	8.898	Arterial	Anytime		Anytime
036B	US 36	EB	Wadsworth	Sheridan Blvd.	48.035	52.479	Freeway	7:00 p.m. to 5:30 a.m.		8:00 p.m. to 9:00 a.m.
036B	US 36	WB	Sheridan Blvd.	Wadsworth	52.479	48.035	Freeway	8:00 p.m. to 5:30 a.m.		8:00 p.m. to 10:00 a.m.
036B	US 36	EB	Sheridan Blvd.	Federal Blvd.	52.479	54.858	Freeway	9:30 p.m. to 5:30 a.m.		10:00 p.m. to 8:00 a.m.
036B	US 36	WB	Federal Blvd.	Sheridan Blvd.	54.858	52.479	Freeway	8:00 p.m. to 5:30 a.m.		11:00 p.m. to 8:00 a.m.
036B	US 36	EB	Federal Blvd.	I-25	54.858	56.999	Freeway	9:30 p.m. to 5:30 a.m.		11:00 p.m. to 8:00 a.m.
036B	US 36	WB	I-25	Federal Blvd.	56.999	54.858	Freeway	9:30 p.m. to 5:30 a.m.		11:00 p.m. to 8:00 a.m.

EB = eastbound, WB = westbound, SB = southbound, NB = northbound.

Most studies indicate that the introduction of work zones leads to an increase in accident rates, although this increase is highly dependent on traffic and geometric conditions, traffic control devices, and other aspects of the work zone environment. According to Venugopal and Tarko, the increase in crash rate at work zones may be due to several reasons, including "the general disruption of traffic due to closed lanes, improper lane merging maneuvers by drivers, and inappropriate use of traffic control devices" (*6*).

Work zones appear to be especially difficult for trucks because of their dimensions and operating characteristics. Benekohal and Shim surveyed 930 truck drivers and found that 90% of those surveyed considered traveling through work zones to be more hazardous than traveling through road sections not affected by construction (*7*). Safety in work zones continues to remain a high-priority issue for highway agencies, in part because of limited understanding of the causes of the crashes. According to the National Work Zone Safety Information Clearinghouse, in 1 year, work zones in the United States are associated with more than 700 fatalities, 24,000 injury crashes, and 52,000 property-damage-only crashes, and the estimated cost of these crashes exceeds $4 billion per year. One could argue that the work zones are likely to increase in number because of the emphasis on repair and reconstruction. Hence, it can be expected that the number of accidents in work zones will increase correspondingly.

Traffic control devices were found to reduce the frequency of crashes in the work zone. For example, Garber and Srinivasan found that variable message signs with radar could reduce the possibility of speeding at work zones and hence reduce the frequency and severity of crashes (*8*). In another study, orange rumble strips, because of their high visibility, were found to have a significant effect on vehicle speeds (*9*). However, in some cases, these traffic devices may themselves be a safety hazard to drivers, passengers, and the workers and must be studied carefully (*10, 11*). Rear-end crashes have consistently been the most predominant type of crash. This has been found to be true for work zones as well. Between 30% and 40% of crashes at work zones are rear-end crashes (*3*). Few published studies have analyzed the causes and the factors associated with rear-end crashes in work zones. A possible reason is the lack of detailed data. According to the study by FHWA (*12*), which was based on data from Illinois, Maine, and Michigan, the percentage of work zone accidents involving a rear-end collision was significantly higher than that of non–work zone accidents. This may suggest that speed differential among vehicles traveling through work zones may be a primary contributor to work zone accidents. It was also found from all three states' distributions that the percentage of sideswipe collisions in work zones is higher than the percentage of sideswipe collisions in non–work zones. Many work zones typically include narrower lanes and shoulder or lane closures, which increase the chance of lane-change maneuvers. This may account for the difference in the percentage of sideswipe accidents.

Questions remain regarding the safety of work zones. It is believed that major obstacles to answering these questions are the lack of quality data related to the characteristics and conditions existing at the time of the accident and the lack of reliable work zone inventories. Past studies about work zone safety were mostly based on limited data. Few studies attempted to explicitly consider exposure to work zone activities or to develop work zone accident rates that account for differences in exposure. A key need is to determine an appropriate exposure measure to calculate the work zone crash rate.

The prevailing majority opinion among researchers of work zone safety appears to be that the phenomenon of accident occurrence in the work zone is complex, dependent on many factors, and not well understood.

ANALYTICAL FRAMEWORK OF RISK ANALYSIS

This study accepts uncertainty related to the increase of accidents related to work zones and still provides decision support analysis for freeway lane closure during the peak period. This methodology will help transportation professionals with lane closure decision making in a climate of uncertainty by estimating accident risk and resulting delays. Crash cost (i.e., property damage only, injury, fatality) are not explicitly considered in this study. Considering that work zone crashes have a higher percentage of rear-end crashes, one could argue that work zone crashes are less severe. However, at the same time, work zones may include crashes between vehicles and workers and between vehicles and fixed objects, which can be quite severe. Thus it is thought that the overall crash costs will remain relatively stable and will not influence the final outcome of the risk analysis. Accident risk is first assessed by using safety performance functions (SPFs) calibrated for conditions without lane closure. Then, appropriate adjustments are made for an accident frequency increase in the work zone. Use of SPFs in road safety analysis was introduced by Hauer and Persaud (*13*). SPFs in essence are accident prediction models, which generally relate traffic exposure measured in annual average daily traffic (ADT) to safety measured in the number of accidents over a unit of time. A great deal of substantive and comprehensive work in the area of accident modeling was undertaken by Miaou and Lum (*14*), Hauer and Persaud (*13*), and Hauer (*15*). Details concerning data set preparation and model fitting for the development of the SPF are described by Kononov and Allery (*16*). The model parameters are estimated by the maximum-likelihood method in the generalized linear modeling (GLM) framework by using a data set containing 14 years of accident data. To estimate expected accident frequency during the peak period, the SPF calibrated specifically for urban freeways is used.

The case history presented in this paper to illustrate risk analysis methodology involves a highway improvement project on an existing urban six-lane freeway in the Denver metro area. By consulting the SPF calibrated by the Colorado DOT specifically for six-lane urban freeways, it was found that 37.4 accidents per mile per year might be expected for an ADT of 100,000 vehicles. The SPF used is shown in Figure 2. An ADT of 100,000 vehicles existing within project limits on this six-lane facility suggests some reserve capacity. This availability makes this segment a candidate for a lane closure consideration during the peak period. The question now explored in

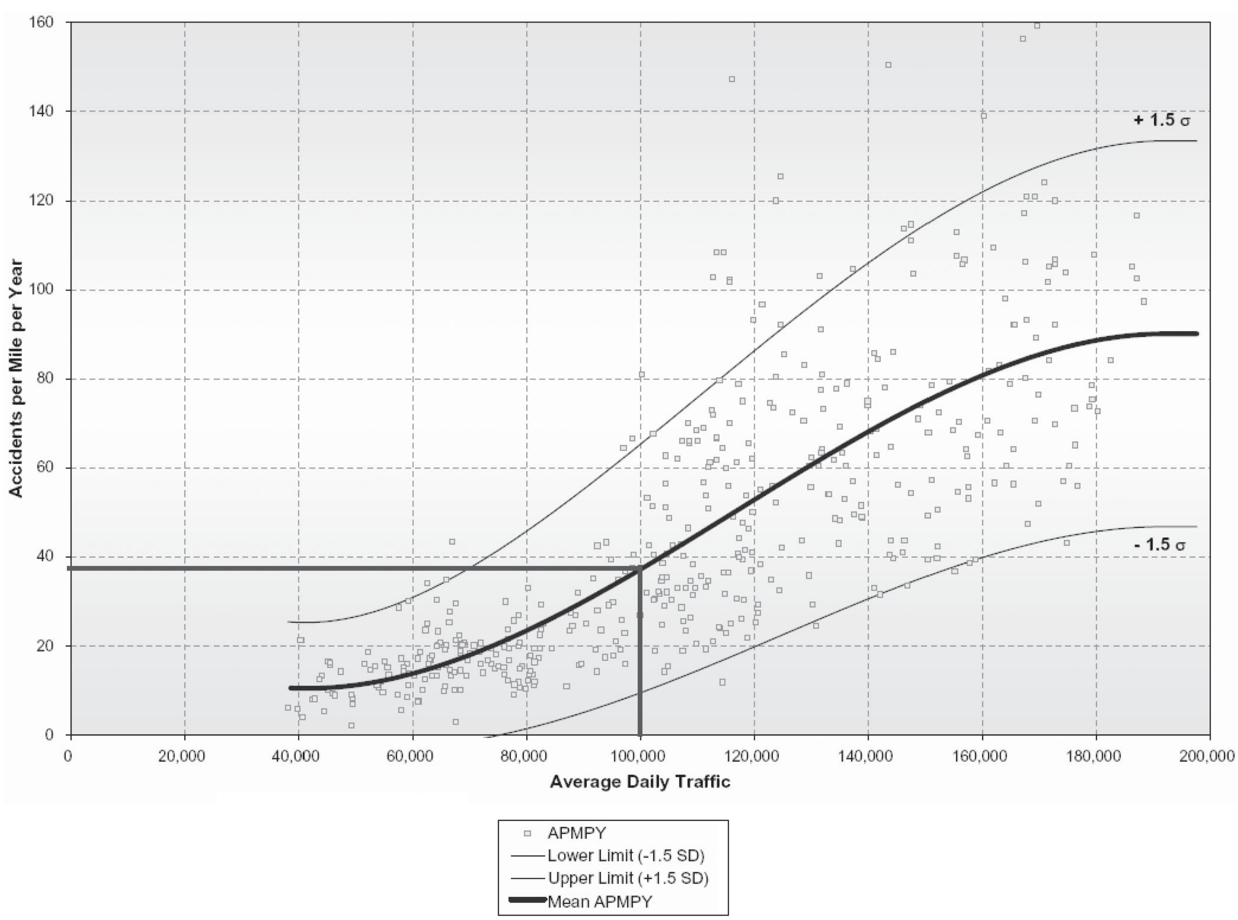

FIGURE 2 Six-lane urban SPF, 1989–2001.

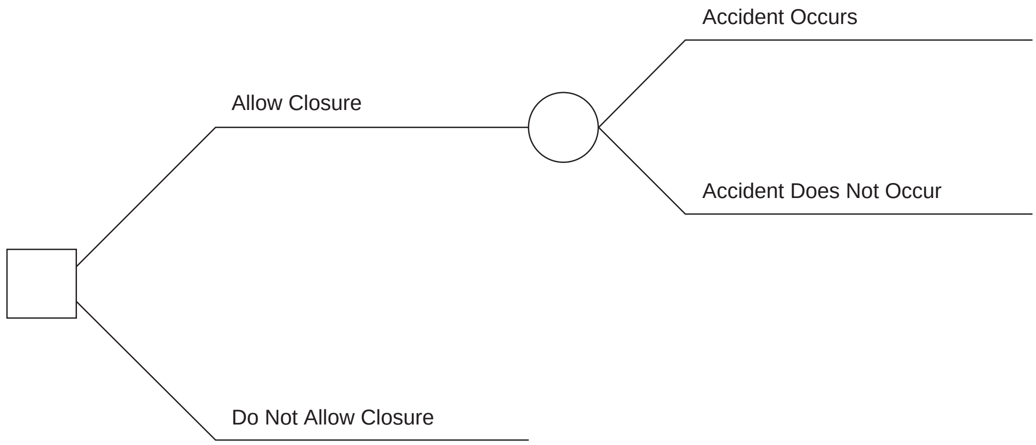

FIGURE 3 Conceptual framework of decision tree.

detail is whether the cost savings and expediency of construction outweigh delays related to an accident in the work zone during peak period traffic.

The decision-making process, and the consequences of each possibility, of whether to allow lane closures for construction during the peak period can be illustrated by using the framework of a decision tree, as shown in Figure 3.

The challenge then becomes to populate each branch of the decision tree with realistic values. From the scope of work of the highway project in the case history, it was ascertained that a job time frame includes 60 days of lane closure and a closure length of 1.0 mi. Given ADT of 100,000 expected frequency of 37.4 accidents per mile per year attained from the urban six-lane freeway SPF graph translates into accident expectancy of 6.1 through completion of the 60-day job.

Since this analysis is concerned primarily with accident occurrences during the peak period, a 10-year query of the Colorado DOT accident database shows the distribution of the 69,310 accidents presented in Figure 4 for Denver metro freeways on weekdays.

By using these numbers, one can then calculate the number of expected accidents in the 60-day job site during the peak period to be about 2.1. This calculation is

$$E = \mu \frac{J}{365}\left(\frac{W_p}{W_p + W_o}\right)$$

where

μ = average accident frequency per mile per year from applicable SPF for a work zone that has a specific ADT and length,
J = length of job in days,
W_p = average number of weekday peak period accidents,
W_o = average number of weekday off-peak accidents, and
E = expected accidents in the work zone during the peak period.

Since it has been shown that accident patterns closely fit a Poisson process, one can then determine the chances of at least one (one or more) accident occurring in the work zone area during the peak period.

Since experiencing at least one accident is complementary to experiencing zero accidents, the expression is

$$P(X \geq 1) = 1 - P_r[\text{no accidents}] = 1 - P_r(X = 0)$$

or, in terms of the example,

$$P_r(X = 0) = p(0,2.1) = \frac{2.1^0 e^{-2.1}}{0!} = 0.122$$

and then 1 − 0.122 = 87.6%.

Thus the odds of observing one or more accidents during the peak hour in the project area without construction are 87.6%. However,

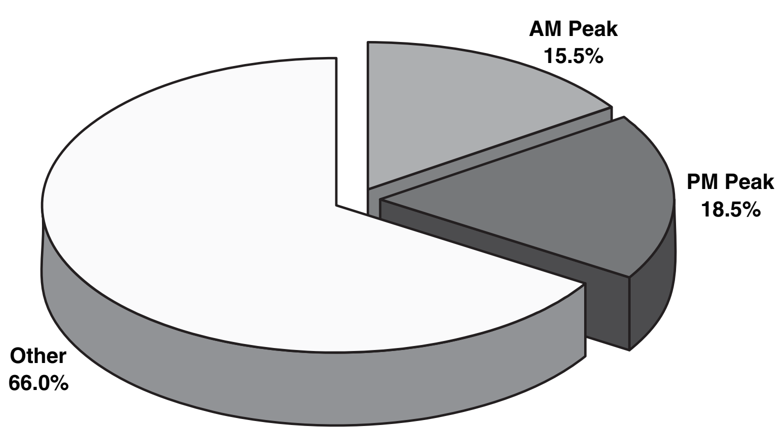

FIGURE 4 Accident distribution by peak, off-peak periods on Denver metro freeways (morning peak: 7 to 9; evening peak: 4 to 6).

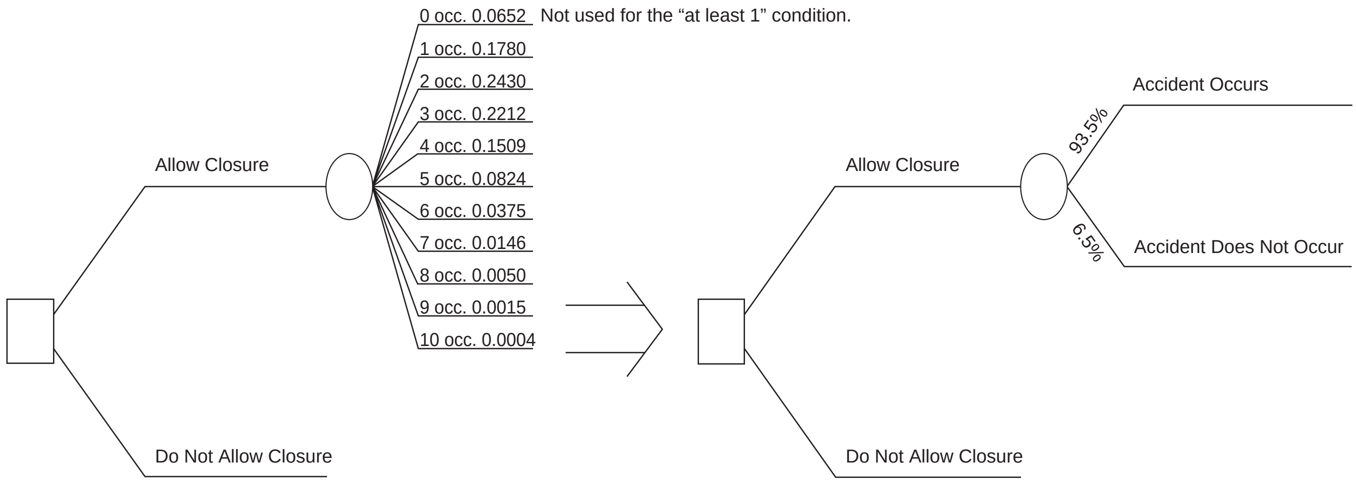

FIGURE 5 Decision tree with estimated chance nodes.

to account for historical increases of accident probability due to the presence of a work zone, the chances of an accident occurring are increased. Although there is some uncertainty related to this question, an estimate developed by Huebschman et al. (*4*) of 30%, considered conservative, is used. Thus the expression becomes

$$P_r(X=0)=p(0,2.1\times 1.3)=\frac{(2.1\times 1.3)^0\,e^{-2.1\times 1.3}}{0!}=0.065$$

and then $1-0.065=93.5\%$.

The odds of observing one or more accidents in the work zone during construction in the weekday morning and evening peak periods are 93.5%, which means that not observing an accident is highly unlikely. The decision tree for the example can then be updated (Figure 5) to reflect the chances of accidents occurring under Poisson assumption.

What remains is determination of the consequences of the decision to allow lane closure on a 60-day project. Research shows that average delay costs range from about $10 to about $20 per vehicle hour in 2004 dollars; for this example analysis, a delay cost of $15 per vehicle hour is used for all delayed vehicles.

The next variable to consider is the number of vehicles that may be affected by an accident during the peak period in the work zone. The map in Figure 6 shows the approximate location of the accident referred to earlier that occurred on I-76 during the evening peak in Denver. This accident effectively closed I-76 and thus can be used as an illustration of what would happen if an accident occurred in a work zone during the peak period. The outlined area on the map approximates the extent of backups on other freeways and highways affected by the closure of I-76. The area shown is a combination of known backups that occurred during the incident in some areas and estimations of backups in other areas.

From the scaled map presented in Figure 6, it was determined that about 23 mi of backups occurred during this incident. With three lanes of travel affected, and an assumed 25 ft of length per vehicle, this equates to about 15,000 delayed vehicles. This figure does not account for delay on minor streets, but it may overestimate delayed vehicles on the highway since it counts delayed vehicles in both directions. Given the uncertainty in estimating the overall number of vehicles delayed, sensitivity analysis for a range of delayed traffic from 5,000 to 25,000 vehicles will be conducted.

By using the range now established, the results of the two-way sensitivity analysis were tabulated and are given in Table 2. The analysis relates costs associated with a series of delays with the number of vehicles affected.

Each value was calculated by using the formula

$$(\text{number affected})\times(\text{cost of delay})\times(\text{length of delay})$$

or, for the first cell in the example (rounded down to the nearest 1,000 to be conservative),

$$(5{,}000\text{ vehicles})\times(\$15/\text{h})\times(10/60\text{ h})=\$12{,}000$$

The example will use $112,000 as an average estimate of the delay cost associated with one accident.

The mean number of accidents that will occur during the peak period during the example job is estimated to be 2.1 accidents, and it was shown that the increased probability of an accident occurring in the work zone is about 30% versus when a work zone is not present.

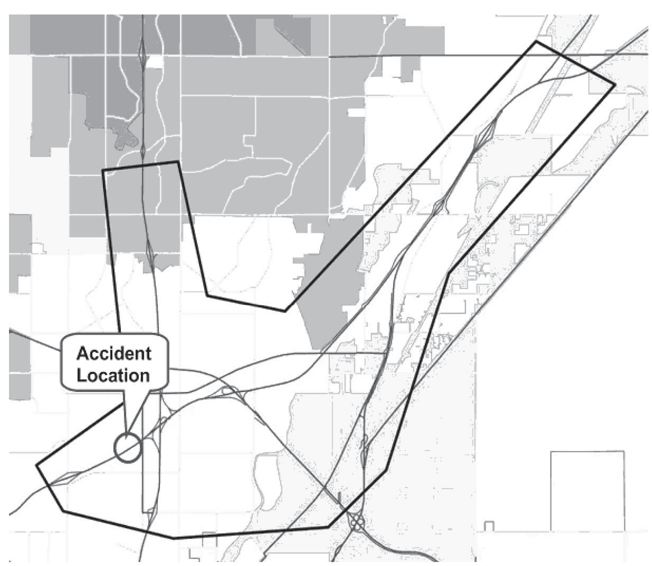

FIGURE 6 Scaled map of incident-related backups.

TABLE 2 Two-Way Sensitivity Analysis Outcomes per Accident

Average Blockage (minutes)	Delay Dollars/Accident	Number Affected 5,000	10,000	15,000	20,000	25,000
	10	12,000	25,000	37,000	50,000	62,000
	20	25,000	50,000	75,000	100,000	125,000
	30	37,000	75,000	112,000	150,000	187,000
	40	50,000	100,000	150,000	200,000	250,000
	50	62,000	125,000	187,000	250,000	312,000

TABLE 3 Two-Way Sensitivity Analysis Outcomes with Lane Closure per Project

Average Blockage (minutes)	Adjusted Delay Dollars/Project	Number Affected 5,000	10,000	15,000	20,000	25,000
	10	32,000	68,000	101,000	136,000	169,000
	20	68,000	136,000	204,000	273,000	341,000
	30	101,000	204,000	305,000	409,000	510,000
	40	136,000	273,000	409,000	546,000	682,000
	50	169,000	341,000	510,000	682,000	851,000

Carrying this to the next step, each cell can then be multiplied by 2.1 and by 1.3 accidents per project to determine the expected number of accidents, on average, for the lane closure scenario. Table 3 reflects a range of delay costs that can be incurred throughout 60 days of project duration (rounded down to the nearest 1,000 to be conservative).

This says that on average, a delay cost of \$305,000 should be assumed for the example job. This cost must be considered when the decision to allow a peak period lane closure is made.

This can then be compared to the total cost of allowing lane closure only off-peak. A survey of area contractors and estimators shows that on average, a job can be expected to last about 15% longer when peak period work is not allowed. Additionally, a premium of about 15% in job cost will also be required for off-peak-only work. For a \$1,000,000 project, this translates into a premium payment of \$150,000. Considering an average cost of \$112,000 in delay per accident, in concert with Poisson assumptions, the final decision tree is then reduced to Figure 7.

In this example, 30% increase in accident frequency due to construction is used. It is interesting to note that even if safety performance during construction does not change, which is highly improbable, the outcome of the risk analysis does not change. Figure 8 shows a

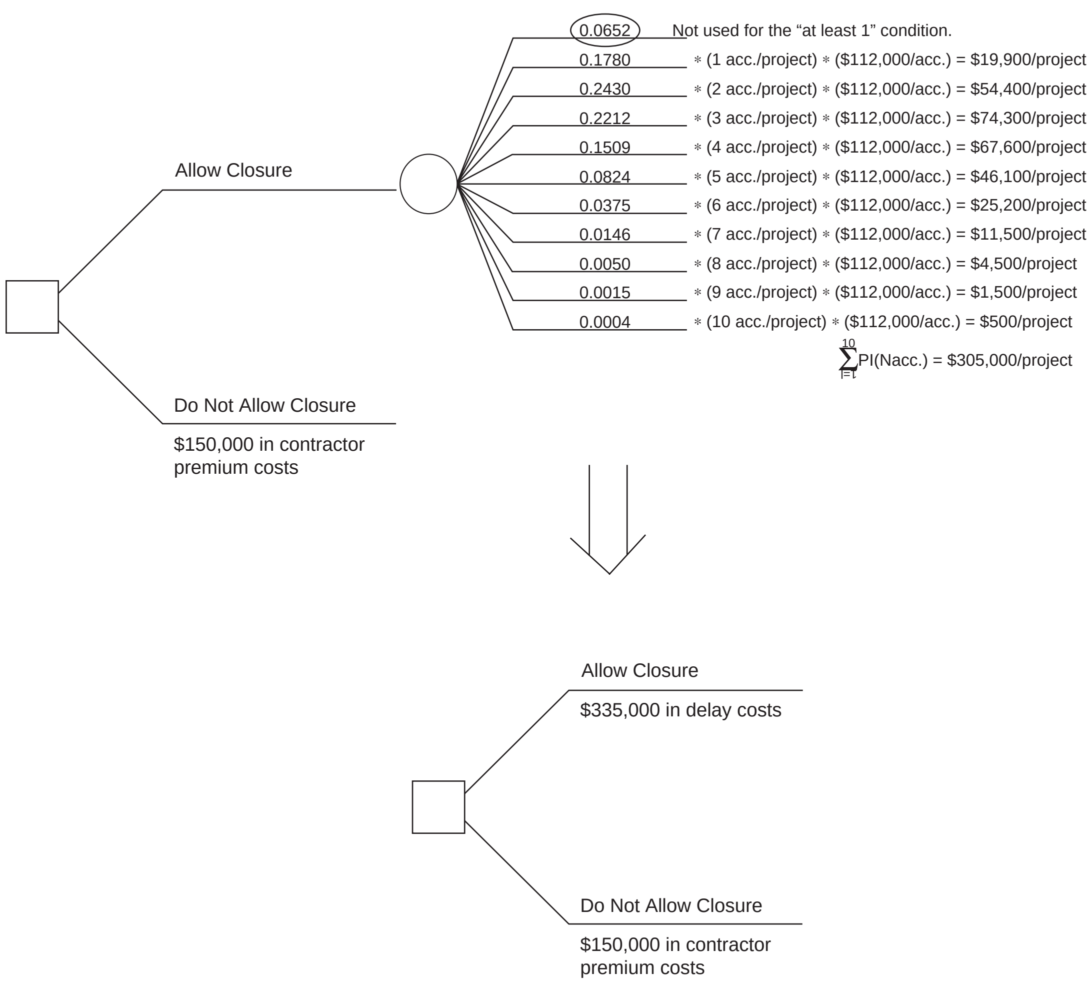

FIGURE 7 Final decision tree.

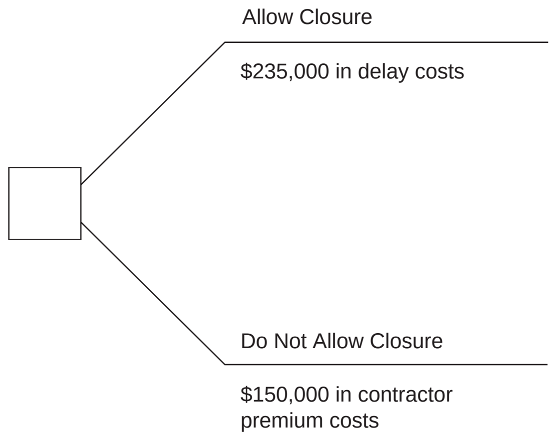

FIGURE 8 Final decision tree with no reduction in work zone safety.

reduced decision tree that reflects accident probability, which assumes that safety performance in the work zone is the same as without it.

CONCLUSIONS

This analysis showed that it is critical to consider the delay resulting from potential accidents when making decisions about lane closures during peak periods on an urban freeway. Establishing criteria that is based solely on available capacity is not sufficient.

It can also be seen from this analysis that the odds of an accident in the work zone occurring in the Denver metro area during a peak period closure are quite high. Thus the probability of massive backups and delays occurring at least once during a typical project requiring a lane closure is nearly certain (93.5%).

The best estimate of the expected number of accidents in the work zone on the segment of road is probably its safety performance absent construction. It is generally accepted that safety performance during construction will be characterized by an increased number of accidents; the magnitude of the increase, however, is uncertain. Despite this uncertainty, it is possible to assess the risk of potential accidents by using sensitivity analysis. The case history on this busy urban freeway illustrates that even if safety performance during construction remains the same as without it, lane closure during the peak period on an urban freeway is best avoided.

In the case example, the expected cost of delay for allowing a peak period lane closure is $305,000. In contrast, a premium of $150,000 is incurred by the state DOT for allowing work only off-peak. This equates to net overall societal disbenefits in the amount of $155,000 when work during the peak period is allowed. From the standpoint of making policy, and considering the secondary adverse impact, including driver frustration and negative public relations, it appears that closure during the peak period on the urban freeway should be avoided whenever possible.

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The Safety Data, Analysis, and Evaluation Committee sponsored publication of this paper.