**Research Report**
Agreement T4118, Task 27
Incident Response

# INCIDENT RESPONSE EVALUATION PHASE 3

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Prepared for

The State of Washington
**Department of Transportation**
Paula J. Hammond, Secretary

February 2011

# TECHNICAL REPORT STANDARD TITLE PAGE

| 1. REPORT NO. | 2. GOVERNMENT ACCESSION NO. | 3. RECIPIENT'S CATALOG NO. |
|---|---|---|
| WA-RD 761.1 | | |

| 4. TITLE AND SUBTITLE | 5. REPORT DATE |
|---|---|
| Incident Response Evaluation Phase 3 | February 2011 |
| | 6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) | 8. PERFORMING ORGANIZATION REPORT NO. |
| Mark Hallenbeck, Chuong Pham, and Kari Watkins | |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS | 10. WORK UNIT NO. |
| Washington State Transportation Center (TRAC)<br>University of Washington, Box 354802<br>University District Building; 1107 NE 45th Street, Suite 535<br>Seattle, Washington 98105-4631 | 11. CONTRACT OR GRANT NO.<br>Agreement T4118, Task 27 |
| 12. SPONSORING AGENCY NAME AND ADDRESS | 13. TYPE OF REPORT AND PERIOD COVERED |
| Research Office<br>Washington State Department of Transportation<br>Transportation Building, MS 47372<br>Olympia, Washington 98504-7372<br>Project Manager: Doug Brodin, 360.705.7972 | Research Report<br>14. SPONSORING AGENCY CODE |

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT:

This project investigated the basic relationship of incidents to delay on Puget Sound area freeways. The intent was to determine the amount of delay caused by incidents and the benefits obtained from the incident response actions taken by the Washington State Department of Transportation (WSDOT). The analysis was based on data from 2006 and included all days in 2006. The study area included I-5 from SR 526 in the north to S. 320th in Federal Way in the south; all of I-90 west of milepost 19.5, which is east of Front Street in Issaquah; all of I-405; SR 167 from I-405 to SR 18; and all of SR 520.

The study showed that incidents, including crashes, do not, in and of themselves, cause measurable delay. They cause delay only when the disruption they create causes functional capacity to fall below actual demand. However, the researchers calculated that the average incident that does not involve a lane closure results in 576 vehicle-minutes of delay per minute the incident is present. If the incident closes a lane, the effect of that lane closure adds 814 vehicle-minutes of delay per minute of closure.

For the 2006 study year, a conservative estimate is that crashes and other traffic incidents (including disabled vehicles, debris, and other events requiring WSDOT intervention to remove hazards) cost travelers 5,300,000 vehicle-hours of delay, in addition to typical congestion delay, on the Puget Sound region's freeway system. That is roughly 30 percent of the total delay from all causes that occurred on these roadways. Approximately 11 percent of the total delay (1,950,000 veh-hrs) was the result of reported vehicle crashes.

The study also determined that crash rates increase substantially when delays caused in part by incidents occur. In fact, a simple summary of the available data indicated that crash rates essentially double in corridors slowed by unexpected incident-related queuing. Consequently, because reducing the duration of incidents results in faster clearance of incident-related queuing, it will also have a significant safety benefit, as measured in a reduced crash rate.

| 17. KEY WORDS | 18. DISTRIBUTION STATEMENT |
|---|---|
| Incident response, performance evaluation | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616 |

| 19. SECURITY CLASSIF. (of this report) | 20. SECURITY CLASSIF. (of this page) | 21. NO. OF PAGES | 22. PRICE |
|---|---|---|---|
| None | None | | |

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# EXECUTIVE SUMMARY

This project investigated the basic relationship of incidents to delay on Puget Sound area freeways. The intent was to determine the amount of delay caused by incidents, and the benefits being obtained from the incident response actions taken by the Washington State Department of Transportation (WSDOT). The analysis was based on several data sets from 2006. The following were the five major data sources:

- the FLOW roadway performance data summarized in 5-minute intervals (volume, lane occupancy data, converted to measures of travel time and volume)
- incident response data from the Washington Incident Response Team System (WITS)
- crash data obtained from state accident records
- weather data obtained from the National Weather Service station at SeaTac airport
- construction event information from the NW Region variable message sign (VMS) message logs.

Below is a summary of the project findings.

## THE SIGNIFICANCE OF CRASH- AND INCIDENT-INDUCED TRAFFIC DELAY

For the 2006 study year, a conservative estimate is that crashes and other traffic incidents (including disabled vehicles, debris, and other events requiring WSDOT intervention to remove hazards) caused travelers to experience 5,300,000 vehicle-hours of delay, in addition to typical congestion delay, on the Puget Sound region's freeway system.[1] That is roughly 30 percent of the total delay from all causes that occurred on these roadways. Approximately 11 percent of the total delay (1,950,000 veh-hrs) was the result of reported vehicle crashes.

[1] The study area included I-5 from SR 526 in the north to S. 320th in Federal Way in the south; all of I-90 west of milepost 19.5, which is east of Front Street in Issaquah; all of I-405; SR 167 from I-405 to SR 18; and all of SR 520.

These same disruptions also geographically transferred delay from one group of travelers to another. However, this study did not estimate the amount of delay transferred from one set of travelers to another. To illustrate this shift in delay from some travelers to others, see Figure E-1.

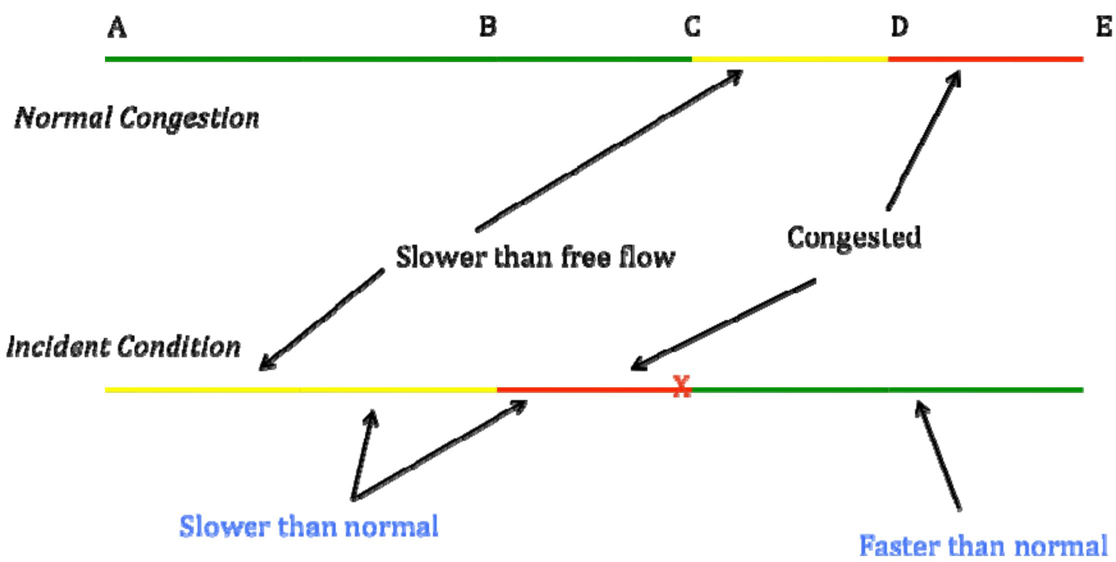


**Figure E-1: Shift of Delay from One Group of Travelers to Another under Incident Conditions**

This figure illustrates an example freeway under both routine (normal) conditions and incident conditions. Road segments colored green are free flowing. Those in yellow are slowing, and those in red are congested. The example incident occurs at the red "X." Travelers entering at point C or D on the example freeway section travel faster than normal under incident conditions, while travelers using the roadway section from A to C experience unusually long delay under those same incident conditions, and travelers going from A to E experience moderate time increases (the incident delay in segments AB and BC is somewhat balanced by faster travel downstream of the incident in segments CD and DE.) An example of a transfer is as follows: if a crash occurs in the morning commute period on I-5 southbound near Northgate, the bottleneck created at that location allows I-5 at the Ship

Canal, south of Northgate and which normally experiences a certain level of commute-related congestion, to flow better than it would have had the crash not occurred. Thus, travelers who enter the freeway south of Northgate get a faster than expected trip, while travelers north of Northgate are stuck in a worse than normal back up—both circumstances are "caused" by the crash—and delay is "transferred" from south of Northgate to north of Northgate. The calculations developed in this study estimate *the change in delay from A to E* and assign that change in delay to the incidents that caused it. They do not measure the delay only from A to C.

Traditional incident delay calculations compute location-specific delay, which includes delay that has been transferred from elsewhere, and do not consider the time "savings" elsewhere that are also related to the incident. In the example, they would measure the delay that occurred north of Northgate but not consider the decrease in delay that occurred south of the incident. They also assign all of that delay to the incident, rather than calculating how much is from traffic demand exceeding roadway capacity and how much is added by the incident. In contrast, the calculations developed in this project subtract the "benefit" that occurs in one location from the related delay occurring elsewhere to estimate the total, corridor-length *change* in delay caused by the incident. For example, they would subtract the time savings seen south of Northgate from the delay that occurred north of Northgate. This is a different delay measure than the incident delay statistics computed by most scholarly work to date, but the project team believes it is the appropriate measure for estimating the *regional* delay benefits that can be achieved through better incident response.

## THE EFFECTS OF INCIDENT DURATION ON CONGESTION AND DELAY

Incidents, including crashes, do not, in and of themselves, cause measureable delay. *They cause delay only when the disruption they create causes functional capacity to fall below actual demand*. Therefore, the impact of any given incident is not constant but is a function of where it occurs, when it occurs, and the traffic demand relative to functional roadway capacity at the time it occurs.

At low volumes, even modestly large incidents may create no measurable delay (except for the "rubbernecking slow down" as vehicles pass the scene). At moderate volumes (relative to roadway capacity), moderately large incidents lower functional roadway capacity to the point at which queues form, creating significant measurable congestion. As volumes begin to approach the functional capacity, even small incidents can create queuing and a dramatic increase in congestion. However, if volumes have grown to the point at which congestion has already formed, minor incidents create only a minor increase in the existing congestion. In this last case, the functional capacity of the roadway has already decreased because of the volume-based congestion. Therefore, the incident reduces that functional capacity only slightly more, resulting in only a small increase in congestion. However, crashes and other major incidents do cause significant increases in delay during these conditions because they generally reduce functional capacity substantially below simple over-saturated flow capacity.

Once a queue forms—regardless of why—the maximum functional capacity of the roadway is governed by the capacity of the roadway at that queue, which is lower than the capacity under free flow conditions. That queue—and the resulting congestion delay—will remain until the volume approaching the back of the queue drops low enough to allow the queue to dissipate.

As a result, a queue that forms because of an incident that occurs just before the start of a peak period will remain throughout the peak period. It will only dissipate when volumes drop at the end of the peak period, even if the original cause of the queue (the incident) has been cleared. Because of the incident, the queue that would normally have been present during the peak period forms earlier than normal, consequently contains more vehicles than normal, and therefore lasts longer than normal, adding to the delay experienced throughout the peak period.

When volumes are moderate (e.g., after the peak period has ended), the clearance of an incident results in very quick dissipation of the queue it has caused, because the volumes reaching the queue are much lower than the escape volume leaving the queue.

However, in both high and lower traffic volume cases, the longer the disruption (incident) lasts, the larger the queue that forms, and the longer the queue takes to dissipate, resulting in greater the total delay created by the incident.

Because of the complex interaction between incident size, duration, traffic volume, and roadway capacity, there is no simple relationship that defines the amount of delay caused by an incident of any specific length. However, for planning and programming purposes, such a value is important. This project determined that growth in delay is roughly linear to the duration of an incident[2] regardless of whether the incident occurs in low or high volume conditions. Therefore, by dividing the total delay incidents add by the total duration of those incidents, it is possible to determine the average vehicle-delay per minute of incident. These figures are as follows.

- The average incident that does not involve a lane closure results in 576 vehicle-minutes of delay per minute that the incident is present.

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[2] See the main body of the report for the defense of this finding.

- If the incident closes a lane, the effect of that lane closure results in 814 vehicle-minutes of delay per minute of closure.

Note that because these are average figures, they will significantly underestimate the delay created by an incident in heavy volume conditions and significantly overestimate the delay in low volume conditions.

It is also important to note that these statistics represent *the additional delay* that would not have occurred if an incident had not happened. They do not include delay from normal congestion levels. In addition, they do *not* represent the shift in delay from one portion of a corridor to another, a different measurement approach.

The project team believes that using these delay statistics to determine the value of incident response is very conservative. There are two reasons for this opinion. First, because our methodology measures the change in delay, the "normal" delay travelers experience (i.e., the delay on road segment AE in Figure E-1 above) is not attributed to incidents. In traditional measurement methods, all delay upstream of the incident is considered "incident" delay, even if some congestion would have already existed because of high demand or roadway geometrics. Traditional methods are not able to separate out the delay *that would have been present had the incident not taken place*. Although the selected method, as a result of making that distinction, does not include all of the delay present during an incident, it does more accurately compute the amount of delay that would be subtracted from the corridor should incidents be instantaneously cleared or prevented.

The second reason our method is conservative is that we assume that the value of time saved when traveling faster than normal (e.g., the "benefit" occurring in sections CD and DE under incident conditions in Figure E-1) is equal to the value of time lost to unexpected congestion (e.g., sections AB and BC under incident conditions in Figure E-1).

However, studies on the value of travel time reliability have shown that travelers value time lost as a result of unexpected delay at considerably higher rates than the time gained when delays are not as bad as expected. (That is, getting to the airport 10 minutes early is not as "good" as getting to the airport 10 minutes late is "bad.") Accordingly, the value of our computed "time lost" should be weighted more heavily than our "time gained." Because our process weights the vale of these times equally, it makes our estimates of the value of incident delay conservative.

## THE EFFECTS OF INCIDENTS ON THE DURATION OF PEAK PERIOD CONGESTION

While the congestion effects of incidents during both peak periods tend to be greater and last longer than those in the off-peak, the congestion effects of incidents are different in the morning and evening peaks. These differences are caused by how the underlying traffic volume patterns differ by time of day. Examples of time of day volume graphs are shown in figures E-2 and E-3.

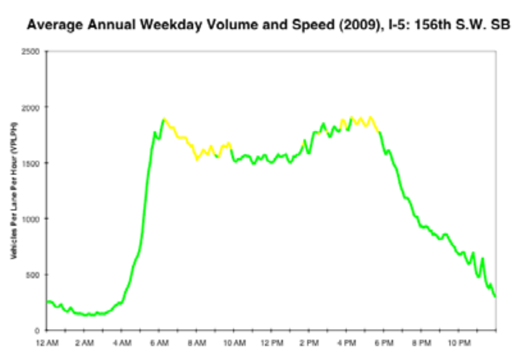


**Figure E-2: Example Traffic Volume Pattern with High Midday Volume**

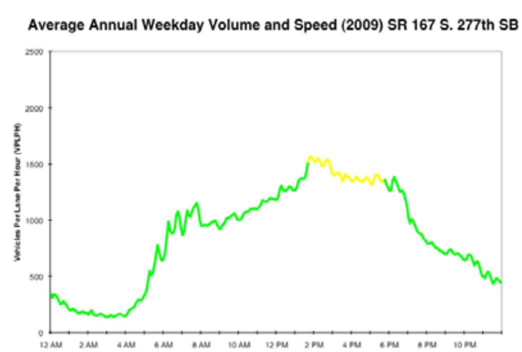


**Figure E-3: Example Traffic Volume Pattern with Modest Midday Volume**

In Figure E-2, peak direction traffic volumes increase very sharply at the beginning of the morning peak period. While they decline at the end of the morning commute, midday traffic volumes often remain fairly high. Conversely, the PM peak starts with fairly high midday volumes and ends with a fairly steep drop-off of volumes.

As a result of these volume patterns, in the morning most incidents do not cause congestion to occur until shortly before volumes peak. However, once congestion forms, it can last many hours, continuing well after the end of traditional morning commute hours. This is because traffic volumes are high relative to roadway capacity, and therefore, queues made larger by an incident do not dissipate quickly.

Conversely, volumes are already reasonably high during the mid-afternoon. As a result, incidents that occur even an hour or two before the "start" of the evening commute but that are not quickly cleared can create queues that remain as the commute volumes rise. The result is that the evening commute period is congested from start to finish. However, unlike in the AM peak, congestion rarely lasts long after the end of PM peak hours if incidents have been cleared, simply because fewer and fewer cars enter the freeway, allowing even large queues to clear fairly quickly.

In Figure E-3, morning traffic volumes are never near capacity. Therefore little incident congestion will occur unless a major crash happens, and once that crash is removed, queues will quickly dissipate. However, volumes at this site grow steadily throughout the afternoon, leading into the PM peak period. For this reason, a queue formed as a result of an incident near 2:00 PM, unless the incident is cleared very quickly, is likely to result in congestion lasting through the entire PM peak until just before 7:00 PM (when volume drops precipitously), as little spare capacity exists after 2:00 PM with which to clear that queue.

The detailed empirical analysis of this phenomenon showed that non-crash incidents increased the mean duration of congestion on only two of 23 corridors that routinely experienced peak PM peak period congestion. In the AM, 11 of 20 congested corridors showed an increase in duration, with an average increase across all 20 corridors of 1 hour and 18 minutes. Crashes had a larger impact on both the AM and PM peaks. In the PM, crashes lengthened the end time of congestion on 12 of the 23 corridors that experienced routine congestion, with an average extension of 12 minutes of congestion across all 23 corridors. In the morning, 17 of 20 corridors experienced an extended congestion period, with a mean extension of over 2 hours of congestion for all 20 corridors. Tables E-1 and E-2 list examples of how incidents affected the mean time during which congestion was found during the peak periods.

**Table E-1: Changes in How Long Congestion Lasts During the PM Peak Period as a Result of Incidents**

| Study Corridor | Mean PM Peak Travel Rate (Min / Mile) | Median PM Peak Travel Rate(Min / Mile) | Normal Time When Congestion Abates | Additional Congestion Time After a Non-Crash Incident[3] | Additional Congestion Time After a Crash[3] |
|---|---|---|---|---|---|
| I-405 Bellevue SB | 3.73 | 3.6 | 19:44 | 0:13 | 0:20 |
| I-405 Eastgate SB | 2.73 | 2.6 | 19:12 | 0:00 | 0:15 |
| SR 520 Sea WB | 2.72 | 2.6 | 20:00 | 0:00 | 0:12 |
| I-405 South NB | 2.58 | 2.6 | 20:41 | 0:00 | 0:17 |
| I-5 South SB | 1.76 | 1.6 | 18:08 | 0:00 | 0:19 |
| I-405 North NB | 1.61 | 1.6 | 19:18 | 0:00 | 0:14 |
| I-5 Everett NB | 1.87 | 1.4 | 17:08 | 0:28 | 0:58 |
| I-5 SeattleN NB | 1.74 | 1.4 | 18:34 | 0:00 | 0:00 |
| SR 167 Renton SB | 1.63 | 1.4 | 18:47 | 0:00 | 0:16 |

[3] Only those times found to be statistically significant at the 90$^{th}$ percentile level of confidence are shown as non-zero numbers.

**Table E-2: Changes in How Long Congestion Lasts During the AM Peak Period as a Result of Incidents**

| Study Corridor | Mean AM Peak Travel Rate (Min / Mile) | Median AM Peak Travel Rate | Normal Time When Congestion Abates | Additional Congestion Time After a Non-Crash Incident[3] | Additional Congestion Time After a Crash[3] | Adjusted End of Congestion Travel Time Value[4] |
|---|---|---|---|---|---|---|
| I-405 Kennydale NB | 3.66 | 3.4 | 11:47 | 0:00 | 1:33 | 10% |
| I-405 North SB | 2.82 | 2.4 | 9:56 | 1:27 | 2:09 | |
| I-5 Nking SB | 2.07 | 1.8 | 11:06 | 0:48 | 1:29 | 10% |
| I-405 Kirkland SB | 1.76 | 1.8 | 10:16 | 0:56 | 1:14 | |
| SR 167 Auburn NB | 1.68 | 1.6 | 11:40 | 0:00 | 0:00 | 20% |
| I-405 Eastgate NB | 1.66 | 1.6 | 11:38 | 0:00 | 1:04 | 10% |
| I-5 SeattleN SB | 2.15 | 1.4 | 9:38 | 1:10 | 4:58 | |
| I-405 Kennydale SB | 1.54 | 1.4 | 9:08 | 1:19 | 1:23 | 20% |
| SR 167 Renton NB | 1.62 | 1.2 | 9:13 | 1:47 | 1:22 | 20% |
| SR 520 Sea WB | 1.51 | 1.2 | 9:51 | 0:47 | 2:54 | 10% |

## THE VALUE OF DELAY CAUSED BY INCIDENTS

### Time Savings

On the basis of the congestion caused by various incidents and crashes, this study computed the following cost per minute of incidents for three types of traffic disruptions:

Incident[5] = $244 / minute of incident
Closure = $345 / minute of lane closure
Crash = $286 / minute of crash duration[6]

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[4] On some study corridors, for the "end of congestion" to occur before noon after the AM peak period on days with incidents or crashes, it was necessary to change the definition of "congestion" from 20 consecutive minutes of average travel times being faster than 1.05 times the travel time at the speed limit to either 1.10 time the travel times at the speed limit (indicated by the value of 10 percent) or 1.20 times for travel time at the speed limit (indicated by 20 percent).

[5] This includes all incidents reported in the WITS database. "Closure" incidents are a subset of those incidents that involve the closure of one or more lanes.

[6] The time it takes to clear crashes is not recorded in the state crash reporting system, and WSDOT's Incident Response team does not respond to many crashes in the Puget Sound region, especially many of those occurring in off-peak periods. Therefore, the duration of the "incident event" is not known for many crashes. To compute a per minute of duration value, it was necessary to assume a duration for each crash event. This value was selected to be 20 minutes for this computation. This was the only computation for which this specific assumption was required.

Dollar values per vehicle minute of delay were based on values of time previously developed by WSDOT[7], which are $21.90 per hour for passenger cars and $57.40 for trucks (comprising a mix of heavy and medium duty vehicles). In addition, it is assumed that trucks make up 10 percent of the traffic stream.

Note that, like the delay per minute of incident statistics upon which these values were based, these figures are simple averages. For times and locations where delays are longer than average, these values will underestimate the value of incident clearance. For times and locations where lower volumes result in lower delays per minute of incident, these values will overestimate incident response benefits. Similarly, truck percentage and make-up also vary by time of day and from corridor to corridor. In terms of dollar savings, corridors with higher truck volumes benefit more per minute of incident response savings than corridors that serve almost exclusively passenger vehicles.

## Safety Benefits

Although this study did not attempt to quantify the safety benefits of incident response, they are important to mention.

Even if incidents are cleared at times when and in places where congestion has not formed, the service is still valuable because removal of the distraction provides a major safety benefit. For example, when an Incident Response Team member stops on the side of the freeway in the off-peak travel direction to remove a piece of debris or help a stranded motorist, that recorded incident does not directly "reduce delay" because the "incident" recorded in WITS occurs at a time when and in a direction where it causes no delay.

[7] Assessing Cost of Travel Annual Update, by the Urban Planning Office and Freight Office, WSDOT, April 2009, internal WSDOT document

However, that debris removal and/or motorist assistance removes hazards that would have likely caused more significant problems later.

There is one other significant safety benefit of incident response. This study determined that *the probability of a crash occurring roughly doubles when an incident has influenced travel conditions.* While additional statistical analysis should be performed, a review of peak period crash rates indicated that in the AM peak period, if travel times were affected by an incident of any kind, crash rates increased across all 42 test corridors by an average factor of 2.97. In the PM peak, crash rates increased by a factor of 2.66. Of the 42 corridor sections, 31 showed a probability of a crash occurring that was at least 1.5 times greater than the rate when incidents had not occurred . Eight of the 11 corridors that did not show this increase had no routine AM peak congestion, meaning that most "incident influenced" congestion was very small and occurred under light traffic conditions. In the PM peak, 27 of the 42 test corridors showed an increase in the probability of a crash occurring that was at least 1.5 times greater than the rate when incidents had not occurred.

The project team speculates that this increase in crash rates is the result of incidents causing queues in places where drivers do not expect them. This remains true even for small, peak period incidents that do not significantly change corridor travel times. Even small incidents can shift queue locations within a peak period, increasing the chance that motorists unexpectedly encounter slowing vehicles thus increasing the potential for crashes to occur.

## WHEN AND WHERE INCIDENT RESPONSE MAKES SENSE

In addition to the dollar benefit from incident response, two other factors must be known in order to estimate the cost effectiveness of any new incident response deployment: the cost of that deployment and the number of incidents for which response will be needed.

Statistics available from WSDOT indicate that, on average, WSDOT incident response costs around $50 per hour. This value includes the cost of labor and equipment. These costs vary somewhat, depending on the type of equipment deployed as well as a variety of other factors. Larger, more capable response trucks (heavier tow trucks) cost more but can also more quickly clear a greater percentage of incidents without having to call (and wait) for additional incident response resources.

To obtain a positive benefit to cost ratio at this basic rate and at the "savings rate" discussed in the previous section requires one incident response action for each five hours of incident response activity <u>if only travel time savings are included.</u> Safety benefits could be added on top of this value, but this study did not attempt to compute the dollar value of those benefits.

Note also that the dollar value from incident response will vary considerably depending on the nature of the incident being cleared, the speed of that clearance, and the roadway conditions (volume relative to functional capacity, and the mix of traffic contained in that volume) at the time of the incident.

The next section provides some basic guidance about when roadway volumes are high enough for fast incident response to either help prevent congestion from forming or significantly limit the scope of that congestion.

## The Roadway Conditions Present When Incidents Create Congestion

Congestion is caused by a combination of factors involving traffic volume (demand), driver behavior, and roadway characteristics (as measured in terms of operational roadway capacity). Recent research has shown that driver behavior, especially in combination with roadway configuration changes (e.g., uphill grades, sharp curves), can produce congestion under volume conditions lower than conventional traffic flow theory would suggest. The presence of various driver distractions is thought to be a major cause of these slowdowns. Incidents—both those that close lanes and those that simply create visual interest—are a key source of distractions. Larger, lane blocking incidents are also the direct cause of lost roadway capacity.

Analysis of Puget Sound freeway data that compared volume to capacity (V/C) ratios with the presence of slow vehicle speeds[8] showed that on six-lane freeway (three lanes in each direction), congestion is unlikely (< 20 percent) to form at V/C ratios of below 0.8 if no disruption event occurs. On smaller freeways (two lanes in each direction) congestion forms more than 20 percent of the time at V/C ratios as low as 0.5 or 0.6. But if a lane is closed by an incident, speeds fall below 45 mph 75 percent of the time if the V/C ratio is equal to or greater than 0.3. Crashes have effects similar to those caused by lane closures.

These findings agree with theoretical expectations. Table E-3 shows how previous research[9] described the effects of incidents on functional roadway capacity. These values suggest that for any given V/C ratio, roadways with larger capacity simply have more "absolute capacity to spare" and therefore experience a lower proportional loss of capacity than smaller roadways, even if the absolute loss of capacity due to incidents is higher.

[8] Defined as spot speeds in the corridor falling below 45 mph.
[9] Blummentritt, C.W., Pinnel, C., and McCasland, W.R., "Guidelines for Selection of Ramp Control Systems," *NCHRP Report 232*, Transportation Research Board, Washington, DC, May 1981.

**Table E-3: Percentage of Capacity Reduction by Type of Incident and Size of Roadway**

| Nature of Incident | 2-Lane Roadway (One Direction) | 3-Lane Roadway | 4-Lane Roadway |
|---|---|---|---|
| Shoulder | 25 % | 16% | 11% |
| Blocking One Lane | 68% | 47% | 44% |
| Blocking Two Lanes | 100% | 78% | 66% |

The combination of real performance data and previously published findings indicate that even minor traffic incidents can create congestion whenever the V/C ratio reaches about 0.7 for a two-lane (one-direction) freeway or 0.8 on a three-lane or larger freeway. Slightly larger incidents cause congestion at even lower volumes.

Because the goal is to clear incidents before congestion occurs (the largest travel time and safety benefits accrue when incidents can be cleared before congestion occurs), incident response actions—even for minor incidents—are likely to be cost-beneficial whenever V/C ratios exceed about 0.6 for two-lane roads and 0.7 for larger roads, especially when those V/C conditions occur at the beginning of a rise in traffic volume (e.g., at the beginning of a peak period).

Unless they are in response to large traffic disruptions, which tend to occur infrequently, incident response actions taken in V/C conditions lower than these rates are unlikely to result in travel time savings of sufficient value to outweigh the cost of the incident response.

## Estimating the Frequency of Incidents

The more volume that is present, the more likely that various types of incidents will occur. However, in this study, an examination of the relationship between volume or vehicle-miles-of-travel and the number of incidents recorded by WITS did not reveal any statistical consistency. A stronger correlation was found between the annual number of vehicle crashes and the number of incident responses (see Figure E-4). This means that given data on the annual number of vehicle crashes along a particular roadway segment, we can predict the future annual frequency of incidents (of which crashes are only a subset) and thus the overall required level of incident response.

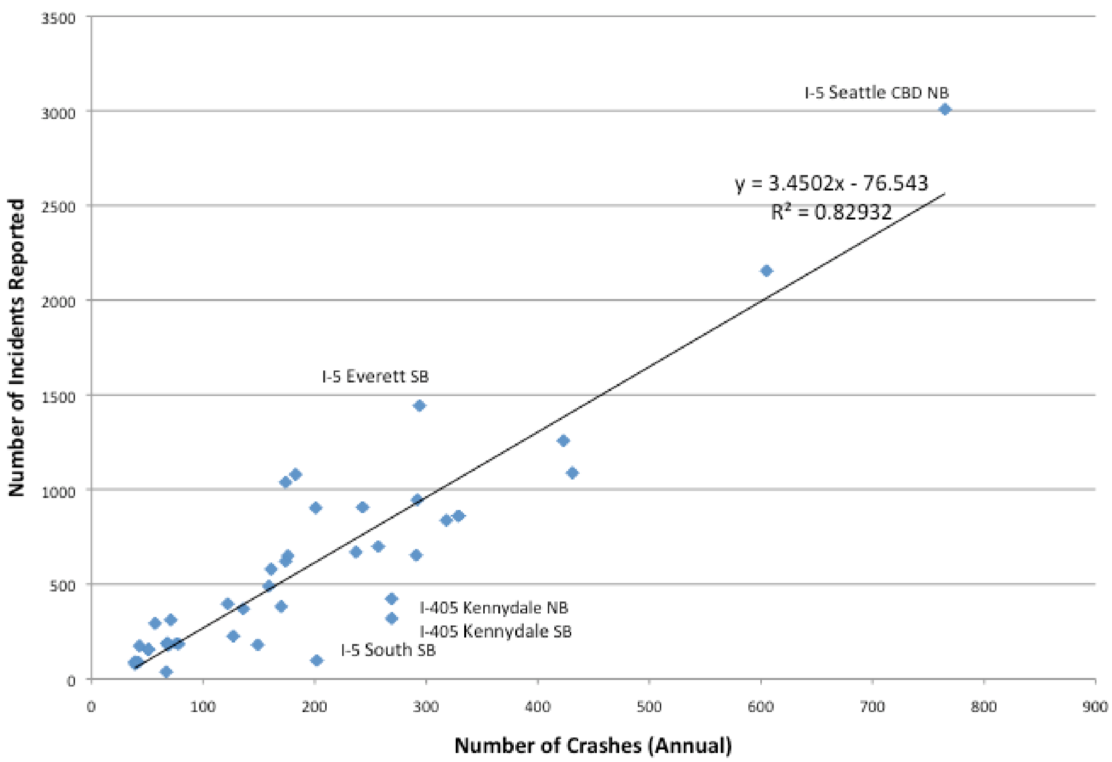


**Figure E-4: Relationship of Annual Number of Crashes to Annual Reported Number of Incidents**

Note that the incidents reported by WITS—and included in Figure E-4—primarily occurred during weekdays in the peak periods, with a smaller number occurring mid-day. These are the primary periods when WITS resources are deployed. (This is likely one of the major reasons why fewer incident response actions are shown for nights or weekends than would be expected if incidents were simply a function of traffic volume.) Crash data, on the other hand, were obtained from state accident records collected 24 hours per day, 365 days of the year. Therefore, the time periods of the two statistics shown in Figure E-4 (total annual crashes and total incident response actions reported from WITS) are not actually the same. Nevertheless, this relationship was more statistically robust (in terms of R-squared) than that produced by similar analyses that compared only peak period peak direction crashes and reported incidents or that compared incident rates with volume or VMT.

The project team believes that several factors explain why the annual number of (primarily peak period) incidents correlates better to the annual number of crashes than to either annual VMT, peak period VMT, or peak period crashes. We believe the following:

- The annual number of (primarily peak period) incidents correlates well to the annual number of crashes because incidents and crashes are in fact related. The factors that cause crashes also influence the number of incidents that warrant a WITS response, but there is more to this relationship than the simple explanation of "more crashes in the peak period equals more incidents in the peak period."
- Volumes correlate less well to the annual number of incidents because geometric conditions (presence versus lack of shoulders, frequency of interchanges, the frequency and nature of traffic merge/diverge movements) play a major role—on top of, but overshadowing volume—in determining whether crashes and incidents occur. Note that many of the outliers shown in Figure E-4 can be directly traced to unusual, temporary conditions (e.g., I-405 in the south end has narrowed lanes and very limited shoulders because of ongoing construction, increasing the number of crashes relative to the number of incidents).
- Peak period crashes correlate less well to peak period incidents than do annual number of crashes to annual number of incidents because, once deployed, WITS staff respond to incidents on both sides of a freeway. That is, they see and respond to debris and disabled vehicles in the off-peak direction of travel as they return to the start of their roving area in order to detect and respond to incidents occurring in the peak direction. (Many of these incidents likely occur during other periods but are not noted until an incident response vehicle is on duty to see them.) This artificially increases the number of incidents that occur in "off-peak" directions for which there is no corresponding increase in the number of crashes.

  Note that these "additional incident responses" are quite valuable, as they remove potential incident- and crash-causing hazards, even though those hazards are unlikely to cause congestion *at that time* in the off-peak direction. Removing hazards during the off-peak has significant incident delay reduction benefits for the *next* peak period movement, because the potential cause of delay has been removed before it can cause a more serious incident or crash.

Finally, the project team believes that these basic relationships are valid statewide. (That is, roadway segments subject to higher numbers of crashes are more likely to benefit from incident response.)

The difficulty with the regression equation illustrated in Figure E-4 is not that it is "Seattle centric" but that, given a particular number of crashes, site-specific conditions will cause roadways to be either more or less likely to experience incidents. For example, roadways with wide shoulders, easy access to exit ramps, and no routine congestion are likely to have fewer significant incidents per crash than predicted by the equation. Roadways with limited shoulders, a lack of access to services (places to get fuel, fix a flat tire), or where other conditions tend to cause incidents are likely to have a higher number incidents per crash.

## SUMMARY OF RECOMMENDATIONS

By combining the equation illustrated in Figure E-4 with the $50 per hour cost of incident response and assuming that the application of incident response resources results in a 2.5-minute savings in incident duration per non-crash incident and a 5-minute reduction in the duration of crash-involved incidents, it is possible to estimate the following:

- Roadway segments that produce roughly 45 crashes per year in one direction of travel will exhibit enough savings in travel time from incident response to warrant the deployment of incident response on the basis of travel time savings alone.

Two additional constraints need to be applied to that basic statement.

- The 45 crashes need to occur within a limited geographic area (roughly a 5- to 7-mile stretch of freeway).

- Roving incident response activities are only financially warranted during times when volumes exceed a V/C ratio of 0.6 on two-lane (in one direction) roadways or 0.7 on three-lane or larger roads.

The first of these constraints helps identify locations where sufficient, concentrated crash and incident activity takes place to warrant routine incident response deployment. The second constraint ensures that sufficient volume is present to produce delay savings. This second constraint may mean that active (roving) incident response patrols are warranted during only relatively limited hours of the day in some locations.

In some locations across the state, short duration commute peaks (less than two hours) may create labor utilization issues in deploying incident response teams. In other locations, incident response deployment may be best associated with recreational traffic movements. For example, incident response deployed during peak weekend travel movements on I-5 through Centralia/Chehalis during many Thursday and Friday evenings and on Sundays during major three-day holiday weekends would probably show a significant benefit/cost ratio.

In rural areas subject to heavy recreational traffic volumes, incident response teams may have significant benefit/cost ratios in terms of travel savings if they can be deployed cost effectively during those the periods when traffic volumes meet the V/C criteria identified above.

Additional analysis is required to determine whether it is possible to cost effectively deploy incident response team resources in more remote recreational areas, given the distances involved, as well as the unique timing of the peaking of those recreational traffic volumes. For example, the average $50 per hour cost of IR response used to estimate when IR is cost beneficial, may not be applicable to rural areas, due to the greater distances involved, and the need for incident response vehicles to travel those distances simply to correctly position them at locations that meet the V/C and crash frequency conditions which indicate places where IR will provide significant savings. Costs for IR in these areas might also be adjusted by using different approaches to labor utilization than applied in congested urban areas. Currently permissible and/or potential labor utilization strategies (location, training, and equipment needs) that might be used in these areas were not examined as part of this study.

# INTRODUCTION

Congestion on freeways is often caused by collisions, disabled vehicles, or spills that interfere with the normal flow of traffic. With highways in the State of Washington regularly operating at capacity, a blocking incident can result in long backups and extensive delays. Incidents also have the potential for creating secondary incidents as a result of braking and lane changing in the congestion. The Incident Response (IR) program in Washington state is responsible for clearing roadways as quickly and as safely as possible to restore the normal flow of traffic. The analysis performed in this study can be used to develop a needs-based system to guide the Washington State Department of Transportation (WSDOT) in deploying IR program elements.

## BACKGROUND

An Incident Response Team (IRT) was initiated in the greater Seattle area in 1990 in connection with the Goodwill Games. The IR program has steadily expanded to all six regions. The IR program now consists of a partnership among the WSDOT IRT, Washington State Patrol (WSP), contracted registered tow truck operators (RTTOs), and contracted private media assistance vans (MAV). Expansion of the program also included the addition of "roving" units during peak traffic with the goal of reducing response and clearance times.

In 1997, the Washington State Transportation Center (TRAC) conducted a comprehensive evaluation of the effectiveness of the IR program throughout Washington state. The research approach consisted of a national review of similar programs, a comprehensive review of WSDOT's IR program organization and operation in the Northwest, Olympic, Southwest, and Eastern regions and their respective Maintenance

Areas, modeling exercises to quantify IR program benefits, and general public and other response personnel surveys to determine the perceived benefits of the IR program. The evaluation provided recommendations to improve the effectiveness of WSDOT's IRT, including improving call-out procedures, developing minimum guidelines for on-site services and equipment, standardizing documentation methods, and increasing awareness of the IR program within and outside of WSDOT. The evaluation identified a need for the development of a needs-based deployment strategy to improve the efficiency of the program. Since the evaluation in 1997, the program has expanded and changed, and a process for improving efficiency still does not exist.

## PROJECT OBJECTIVES

This project was intended to improve the WSDOT's understanding of the benefits from Incident Response actions, with specific emphasis on how to use that understanding to more effectively guide the deployment of available incident response resources. Toward that end, this report covers the following key objectives of this project:

- provide a national review of the state of the practice for IR evaluations and deployment practices
- analyze the impacts of incident response service measures, such as response time and clearance times, on traffic conditions
- develop a methodology to help WSDOT best deploy the IR program elements on the basis of desired costs and service levels.

# RESEARCH APPROACH

This chapter discusses the basic research approach taken to develop an better understanding of the relationship between the incident response process and delays experienced by travelers on the state roadway system. The approach was carried out in close cooperation with the Strategic Highway Research Program (SHRP) project, SHRP2 L03: *Analytical Procedures for Determining the Impacts of Reliability Improvement Strategies*. Like the SHRP2 L03 project, this project used travel time rather than delay as the basis of its analytical tests.

The chapter is divided into the following sections:

- an introduction to the analytical approach taken to determine the effects on travel time delay of different incident response outcomes
- a description of the data base used for those analyses
- a description of the analytical tests performed.

The next chapter of this report presents the findings from the analytical tests.

## INTRODUCTION TO THE RESEARCH APPROACH

The research project consisted of a brief literature review, followed by statistical analysis of actual Puget Sound roadway performance information for 2006, given a wide variety of external factors, including incident response performance. This approach allowed the research team to determine the conditions under which incident response actions had the most significant congestion relief benefit and allowed the development of more definitive mathematical relationships between incident duration and background traffic condition. These relationships were then used to provide guidance on the deployment of incident response equipment and resources.

## BACKGROUND: WHY TRAVEL TIME IS THE BASIS OF STUDY ANALYSES

The vast majority of previous research into the benefits of incident management has examined the size of back-ups created by incidents, the delays associated with those back-ups, and the value of those delays in terms of time, fuel, and pollutants. These calculations have generally been based on queuing analysis performed at the point at which the incident occurred. This approach does an excellent job of estimating delay at the incident scene but does a poor job of understanding how those delays affect travel times in the rest of the corridor, as delays at one location can shift delays to other locations. When delays throughout a corridor are not examined, the benefits to corridor-wide performance of incident response are not fully understood. This phenomenon is explained below.

When an incident occurs in a portion of a corridor that is experiencing routine congestion, the incident can create a traffic blockage that causes delays at the scene. Those delays may decrease downstream traffic volumes to the extent that the recurring congestion which would otherwise have occurred downstream of the incident scene does not occur. When this happens, and delays are examined throughout the corridor, the change in delay (when measured as a total for the corridor) created by the incident is not as large as that computed if delay is measured only at the incident scene. Rather, the incident shifts where the delay occurs. This is illustrated in Figure 1:

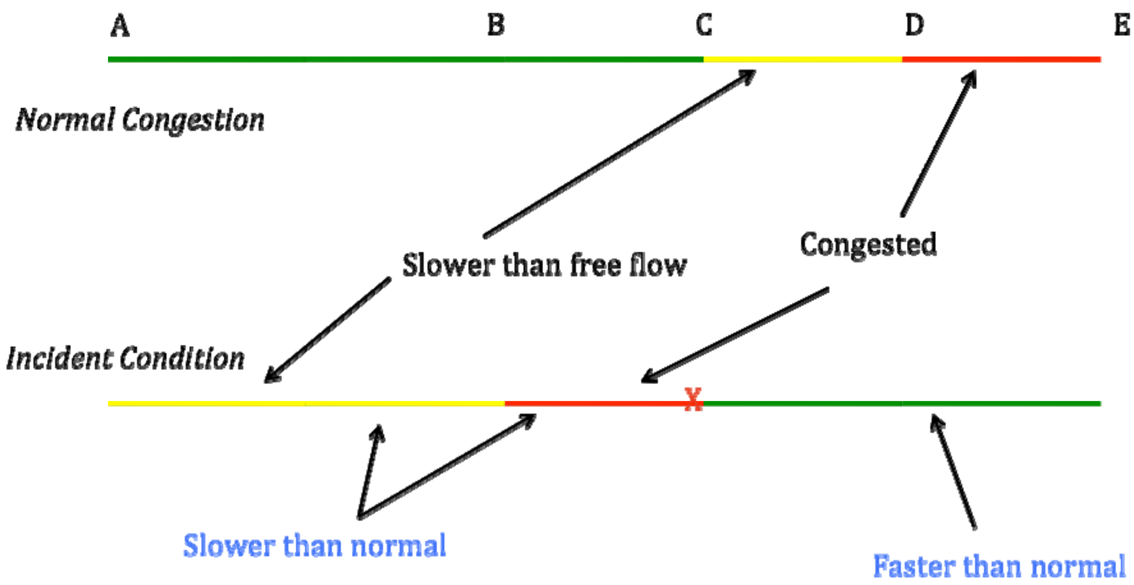


**Figure 1: Shift of Delay from One Group of Travelers to Another under Incident Conditions**

This figure illustrates an example freeway under both routine (normal) conditions and incident conditions. Road segments colored green are free flowing. Those in yellow are slowing, and those in red are congested. The example incident occurs at the red "X." Travelers entering at point C or D on the example freeway section travel faster than normal under incident conditions, while travelers using the roadway section from A to C experience unusually long delay under those same incident conditions, and travelers going from A to E experience moderate time increases (the incident delay in segments AB and BC is somewhat balanced by faster travel downstream of the incident in segments CD and DE). Along the Puget Sound freeways, this effect can be seen when a crash southbound on I-5 at Northgate allows traffic at the Ship Canal Bridge to flow more smoothly than normal during the morning commute. Most traditional incident delay calculations only measure the change in delay in sections AB and BC. The calculations used in this study to measure the delay caused by congestion estimate *the change in delay* *from A to E* and assign that change in delay to the incidents that caused it. They do not measure the delay only from A to C. The study also developed measures of total delay (A to E) and assigned it to the combination of delay causes which occur (for example, when multiple causes such as rain, a crash, and traffic volume all contribute to delay.)

This change in total corridor delay can be calculated by using simulation modeling. With simulation modeling it is possible to directly examine the effects of incidents by running otherwise identical simulation efforts with and without reductions in roadway capacity caused by specific incidents. The problem with the use of simulation models is that 1) they are difficult to calibrate, and 2) it is too expensive to model all of the different conditions under which incidents occur, since incidents occur at different times of the day, in different locations, and under different volume conditions.

Therefore, to understand how incidents of different kinds and durations affect travel in a corridor, this project (with support from the SHRP2 L03 project) developed a database containing travel time statistics for every 5-minute time period for an entire year, along with data describing the use (volume) of the facility during each of those 5-minute time periods and the external events (incident occurrences, weather, construction activity, etc.) that contribute to the performance of the roadway system. A variety of statistical analyses were then performed to determine the combined effects that these various independent factors had on the performance (travel time) of the roadway system.

## THE ANALYTICAL DATABASE

The primary analytical database consisted of a combination of data from several data sources. All data were from 2006 because this was the latest year available for all data sources at the start of the Strategic Highway Research Program's L03 project, which paid for the construction of the multi-source analysis database. The data covered all days in 2006 and were obtained for the Puget Sound freeway system:

- I-5 (from Federal Way in the south to Everett in the North)
- I-405 (the entire roadway)
- I-90 (from Issaquah in the East to downtown Seattle)
- SR 520 (the entire roadway)
- SR 167 (from SR 18 in Auburn in the south to the I-405 interchange in the north).

The data were stored by roadway segment (described in the next subsection of this chapter), by 5-minute intervals. That is, a single record was maintained for each 5-minute time interval in 2006 for each study segment. That record contained data on roadway performance, incidents, weather, and construction activities. (Earlier work for WSDOT examined special events, but Special Event data were not included in the analysis performed for this study.) Data were stored by direction for each study corridor. So for each direction for each study corridor, there were 105,120 records of data.

Additional variables were then computed to allow more detailed analysis of roadway performance under various conditions. The base data obtained for this study are described late in the chapter, followed by a description of the computation of the additional variables.

A complete description of the variables contained in the analysis data set is provided in Appendix A.

## Roadway Segmentation

While use of travel time as the dependent variable allows the more widespread effects of incidents to be examined, use of travel time requires the selection of specific sections along which to measure that travel time. If the section length is too long, the effects of small incident delays will be lost in the "noise" of other factors that affect travel times. If the section lengths are too short, the full effects of incident delays will not be observed.

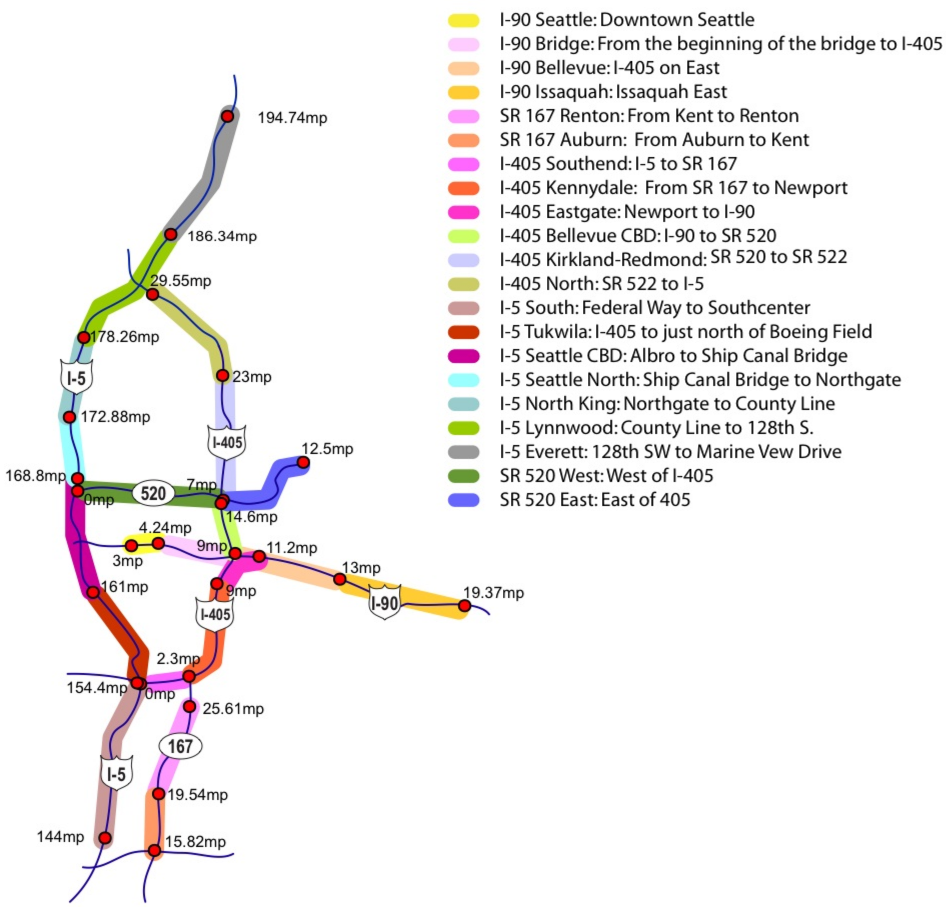


**Figure 2: Seattle Study Sections**

To surmount these problems, the researchers divided the Puget Sound freeway system into a series of different corridor segments. The segments were defined by intersections of major freeways, with some additional breakpoints associated with recurring congestion bottlenecks. Figure 2 illustrates the 21 study sections selected. The segmentation of each roadway is described briefly below.

**I-5**

I-5 was divided into six segments, named from south to north as follows: South, Tukwila, Seattle CBD, Seattle North, North King, Lynnwood, and Everett. Their basic attributes are discussed below.

South is the longest segment. It is primarily four lanes wide, with an HOV lane on the left side, and travels from the southern edge of WSDOT's instrumented roadway system to the southern I-5/I-405/SR 518 interchange. Its traffic is heavily directional (relative to its capacity). It contains a very large hill at the northern end of the segment. The hill can affect congestion southbound in the evening peak period because of buses and trucks slowing to climb the grade, especially those entering I-5 from I-405 and SR 518. Both directions of traffic can be affected by downstream congestion.

Tukwila, the next segment to the north, stretches from the southern I-5/I-405 interchange to just north of Boeing Field and is also mostly four general purpose lanes wide, with one inside HOV lane. The northern end of Boeing Field is the approximate end of the back-up from much of the recurring congestion that occurs both in the AM and many PM peak periods. Much of that congestion stems from bottlenecks occurring in the next roadway section to the south. In the southbound direction of travel this segment tends to be relatively congestion free (the congestion tends to be bottlenecked north of it, in the downtown sections). It does occasionally suffer from back-ups in the downstream segment, when very severe congestion getting onto I-45 northbound, combined with queuing on the Southcenter Hill, can interfere with traffic flow. Otherwise, most congestion is commonly caused by disruptions of some kind.

The Seattle CBD section is the next section to the north. This section contains a significant number of bottlenecks in closely spaced succession. Unfortunately, they are so closely spaced that it was not practical to divide them into separate roadway sections. At its southern end, this is a four-lane GP, one-lane HOV roadway. One of the GP lanes is dropped at the West Seattle freeway interchange. This is followed by the interchange with I-90, which includes a collector/distributor lane that also serves as a mechanism for separating downtown ramps from some of the mainline traffic flows. Immediately north of the I-90 interchange is the southern terminus of the I-5 Express Lanes, a reversible roadway that primarily operates southbound in the AM and northbound in the PM. During this stretch of highway, the left hand HOV lane becomes a general purpose lane and then becomes an exit only lane to the northbound Express Lanes. When the Express Lanes are operating southbound, these lanes become part of a left hand exit to downtown. Another of the through-lanes also becomes an exit only ramp to downtown, leaving only two general purpose through-lanes. (One additional lane exists as part of the collector distributor to I-90 and other downtown ramps.) This is another bottleneck location. This area is followed by a series of on- and off-ramps (including the on-ramp from the collector-distributor that provides the on-ramps from I-90) to downtown. This section of the freeway also moves underneath the state's Convention Center, as part of a short tunnel segment with modest visibility and sight distances. The collector/distributor becomes the third lane when it rejoins the main roadway underneath the Convention Center, and then a fourth lane begins partway through downtown as an add-lane from one of the downtown ramps. No HOV lane exists on this stretch of freeway. Finally, as the roadway exits the downtown Seattle area, it reaches the end of this roadway segment, the SR 520 interchange. The right two lanes become exit only lanes to SR 520. These lanes are often stop-and-go during both peak periods because of congestion on SR 520. In addition, the last ramp from downtown (Mercer) is a left hand on-ramp, which sets up a C-class weave, as many vehicles entering at Mercer wish to be in the right hand lanes in order to exit to SR 520.

In the southbound direction, all of these features also exist. The only difference is that the Express Lanes terminus is an add-lane, located just south of the downtown core. Consequently, it has less impact on the overall freeway performance than the northbound terminus does. However, the C-class weave from SR 520 to Mercer (again a left hand on-ramp followed by a right hand exit lane) is a bottleneck, as are the effects of the downtown exit- and on-ramps.

The <u>North Seattle</u> roadway section is the next section to the north. This section starts at the I-5/SR 520 interchange, goes across the Ship Canal bridge, and continues to the northern terminus of the Express lanes. This section of roadway has only modest routine northbound congestion. However, southbound, it is affected by a C-class weave from the NE 45$^{th}$ St and NE 50$^{th}$ St on-ramps to the SR 520 interchange. In addition, the Ship Canal Bridge is exposed to wind, adding to the factors that affect throughput on this roadway. This roadway comprises four general purpose lanes in the southern section and becomes three lanes wide with an add/drop to Lake City Way (about halfway through the study segment). No HOV lane exists in this section of the roadway. (Note that this study did NOT include the Express Lanes themselves, which serve as the HOV facility—and as additional GP capacity—during the peak directional movements.)

The North King County section of the roadway starts with the northern entrance of the Express Lanes and then continues to the King/Snohomish County line. It is four lanes wide, with an HOV lane on the left. The HOV lane starts/ends at the Express Lanes terminus. This roadway experiences routine congestion associated with that terminus in both directions. When the Express Lanes are operating northbound, considerable weaving takes place into/out of the left hand HOV lane. In addition, northbound, modest volumes of vehicles move from the left hand entrance to the general purpose exits on the right side of the freeway. Southbound, this section of roadway has minor merge-related slowdowns both as vehicles decide to enter the Express Lanes and when the Express Lanes are closed, as I-5 loses two lanes of capacity at that time (one GP lane and the HOV lane).

Lynnwood is the next section of I-5 to the north. This section of roadway goes from the King/Snohomish County line to SE 128$^{th}$ St and includes the northern I-5/I-405 interchange. This section of roadway has four general purpose lanes and one HOV lane. Additional lanes exist at the I-405 interchange to smooth flow between the freeways.

Everett is the final I-5 section. It is primarily three lanes wide with an HOV lane on the left side. Of greatest significance for this study is the fact that in 2006, a major construction project was under way north of the instrumented roadway. This included the extension of the HOV lanes and significant redesign of the ramps in Everett. These construction activities did create some back-ups that extended into the Everett study section, mostly late at night but occasionally on weekends.

**I-405**

The I-405 freeway was divided into six sections. From south to north they were as follows:

- South
- Kennydale
- Eastlake
- Bellevue CBD
- Kirkland-Redmond
- North.

The South section contains two general purpose lanes and one left-hand HOV lane. It extends from the I-405/I-5 interchange to the SR 167 interchange. Bottlenecks occur at both of these interchanges, with the most significant of those being the northbound movement. The southern end of this study segment is also significantly impacted by on- and off-ramps that lead to/from the Southcenter Mall. (Short ramp lengths and the narrow freeway cause difficulties merging, leading to a commensurate increase in traffic disruption from these ramps.)

The Kennydale section is among the most routinely congested sections in the region. It stretches from the SR 167 interchange to two miles south of the I-90 interchange. This stretch of road includes the merge (northbound) from SR 167 to I-405 and diverge (southbound) from I-405 to SR 167. Both of these movements cause major bottlenecks because they are routinely over capacity. North of the SR 167 interchange on I-405 are a series of ramps to/from the City of Renton that also create considerable ramp disruptions. The freeway then goes up and over a major hill (the Kennydale Hill), which can slow heavy trucks, and there is significant heavy truck traffic on this route as it is the primary route for travel from the region's major distribution centers to I-90 and all points east. Because the roadway is only two GP lanes and one HOV lane through most of this section (there are some add/drop lanes), any slow moving vehicle is likely to create minor congestion. The roadway is also severely over capacity, especially northbound in the morning and southbound in the evening.

The Eastlake section of the freeway is a short, two-mile segment designed to examine the effects of I-90 interchange congestion. In the peak directions, this is a very congested segment. In the off-peak directions it flows well.

The Bellevue CBD section stretches from the I-90 interchange just south of the Bellevue CBD to the SR 520 interchange just north of the Bellevue CBD. Bellevue is the second largest city in the region and a significant urban center. While considerable traffic uses I-405 to reach Bellevue, I-405 also serves a considerable pass-through movement. For traffic coming from the north (including SR 520, which serves the Microsoft headquarters complex), I-405 is the primary connection to I-90 and the other bridge across Lake Washington. As a result of the combination of through-movements, considerable Bellevue-based ramp movements, and the congestion that occurs at the I-90 and SR 520 interchanges, this section of roadway is also routinely congested during peak periods.

The Kirkland-Redmond roadway section has a southern boundary at the SR 520 interchange and travels north to the SR 522 interchange. Unlike I-405 south of Bellevue—which while directional has a strong reverse direction movement—the Kirkland-Redmond section is very directional: southbound in the morning and northbound in the evening. The roadway changes width from four GP lanes and one HOV lane between SR 520 and Kirkland to three GP lanes and one HOV lane north of the NE 80$^{th}$ St interchange. In addition to severe demand-related congestion at most of the major on-ramps, the roadway study segment also has a very steep hill (uphill southbound) just south of the SR 522 interchange.

The North study segment is the last of the I-405 roadway segments. It is a two-GP, one-HOV lane section that extends from SR 522 to the northern I-5/I-405 interchange. This section has no significant bottleneck points but does have some simple capacity issues, primarily southbound in the morning.

**I-90**

The I-90 roadway was divided into four segments from Issaquah heading west to downtown Seattle. These were defined as (moving from east to west) Issaquah, Bellevue, Bridge, and Seattle.

The Issaquah segment is a three-GP-lane, one-HOV-lane roadway section that travels six miles from the city of Issaquah toward Bellevue. While there are no significant geometric bottlenecks on this study segment, it does contain three very high volume ramps. The result is routine AM congestion westbound. In the evening, some off-ramp queuing can cause delays in the right-hand lanes of the roadway eastbound.

The Bellevue study segment covers the remaining distance between Issaquah and the I-405 interchange. Two additional on-ramps add traffic, although an additional lane is added in this section before becoming a drop lane at the I-90 interchange. As with the Issaquah eastbound PM movement, this roadway section can be affected by significant off-ramp queuing to I-405---in this case in the westbound AM peak period. On very bad days, queues on I-90 from the downstream section of I-90 can also reach the western portions of this segment during the AM peak period.

The Bridge study section contains both I-90's Lacey V. Murrow Memorial (floating) Bridge and the stretch of I-90 that crosses Mercer Island, which also contains a short tunnel. A reversible express lane also sits in the middle of this study section. (The express lane section was not included in this analysis.) The eastern end of the express lane is located just to the west of I-405. The eastbound exit from the express lanes cause little disruption because of direct ramps from that facility to the I-405 interchange and an add-lane to the I-90 mainline. Westbound it causes congestion only when the express lane is eastbound, in which case the HOV lane must merge into the three GP lanes, causing a merge bottleneck. In addition to the ramps from Mercer Island to I-90, several other locations on this section of roadway can become bottlenecks under specific conditions. The most significant are the exit from the tunnel section—which leads to the bridge and creates some visibility issues when the sun is at some angles—and the bridge itself, which can suffer from considerable visual distraction.

The Seattle section is the last section on I-90. It covers the western end of the floating bridge through tunnels underneath Capitol Hill to I-5, where I-90 ends. Westbound travelers can exit to downtown Seattle or turn north or south on I-5. All three of these ramps can experience queues that extend back onto I-90, depending on the time of day, the types of events occurring in downtown Seattle, and the congestion found on I-5. Eastbound, this roadway section has only one entrance ramp other than the ramps from I-5 or downtown. Merge congestion is therefore modest. However, back-ups from the Bridge section of I-90 can easily extend back into this section, creating congestion.

**SR 167**

This roadway is east of I-5 and travels in a north/south direction through the region's primary warehouse and distribution centers. It also serves a number of manufacturing areas, as well as a growing residential population, especially to the far south. This roadway was divided into two study sections for this project, Auburn and Renton. The entire roadway contains two GP lanes and one HOV lane. (That HOV lane is now a HOT lane, but in 2006 it was still a traditional HOV lane.)

The Auburn section extends from the SR 18 interchange (the southern end of the surveillance equipment, although not the end of the SR 167 freeway) north to the City of Kent. This stretch of roadway has no major geometric bottlenecks northbound but does suffer from on-ramp merge congestion due to high traffic volumes northbound in the AM. Southbound in the PM, it has a bottleneck at the southern terminus to the study section, where the HOV lane ends (becoming a GP lane), and one of the GP lanes becomes an Exit Only lane to SR 18. In addition, because of the restricted number of lanes, traffic south of this bottleneck can move very slowly in the PM peak, further worsening the queues observed southbound on the study section.

The Renton study section stretches from Kent north to the I-405 interchange. The I-405 interchange is a significant bottleneck. The ramp queues from northbound SR 167 to I-405 frequently back up onto SR 167 in both peak periods (although the AM peak is the primary movement), as I-405 simply does not have the capacity to accept the SR 167 traffic volumes. Southbound the SR 167 section also congests simply because of very high traffic volumes. There are no significant geometric causes for those delays.

**SR 520**

The final roadway in the study was SR 520. This roadway also as divided into only two sections, called Seattle and Redmond.

The Seattle section goes from I-5 east across the Evergreen Point Floating Bridge to I-405. This section has two general purpose lanes. There is an HOV lane in the westbound direction only, and that HOV lane ends in a lane drop at the approach to the bridge itself. The bridge has no shoulders. The lack of shoulders means that any incident occurring on the bridge or its approaches blocks a lane. On the western end of the study section are two ramps, one of which leads to the University of Washington. This roadway operates near capacity in both directions over 13 hours each weekday. Because both directions are capacity constrained, the directional volumes are roughly equal throughout the day. The primary difference in the measured performance of the two directions for this roadway is the location of the bridge relative to the entire study section. Eastbound, the study section only travels a little over one mile from I-5 to the bridge itself, and all of this distance is a two-lane roadway. This means that the measured queue eastbound is never larger than roughly one mile. Once the queue grows larger than one mile, it extends onto I-5, where its affects are felt in the southbound Seattle North study section or the northbound Seattle CBD study section. Conversely, in the westbound direction, the study section allows for the measured queue from the bridge deck to extend east for more than three miles. In the heart of the PM peak period, this entire roadway section is routinely stop-and-go congestion.

The Redmond study section includes SR 520 from I-405 east to the end of the freeway, a signalized intersection with SR 202 and other local roads. (The freeway branches into two parts as it ends, each of which ends at a signal.) The freeway passes by the Microsoft headquarters campus. Consequently, significant traffic volumes move toward the center of this study section in the AM peak period and away from the center of the study section in the PM peak period. In addition, the eastern end of the roadway serves a large residential population that travels to both Bellevue and Seattle. Therefore, the AM peak also contains a large westbound home to work movement that extends the length of the study section, while the PM peak contains a large eastbound work to home movement. From a bottleneck perspective, there is one major bottleneck, the signalized intersections at the eastern end of the facility. The result of the signals is that significant congestion extends back from the eastern end of the facility during the PM peak period. In the morning, the lights simply serve to meter traffic entering the roadway, allowing the roadway to operate fairly well. The only other bottlenecks that occur are minor ramp delays leading to Microsoft (these can add considerable delay to travelers headed to Microsoft, but they don't significantly affect the main freeway lanes), and queues that originate on the Seattle section of SR 520 but that extend east into the Redmond section. This happens, on average, at least once a week, usually as a result of crashes or other major traffic incidents on the Seattle section of the roadway.

**Base Data Collected for Each Roadway Segment**

This subsection discusses the base data obtained for use in the project analysis. It also describes the variables formed by simple Highway Capacity Manual-based transformations of those base data into other commonly accepted descriptions of highway use and performance. The transformations included in this section involve only commonly accepted mathematical transformations of highway statistics (e.g., the conversion of volume data into VMT estimates, and the conversion of point based speed statistics to travel time estimates). The next subsection describes the variables computed for use in this study that are not routinely performed throughout the country or that required specific analytical assumptions.

The primary data sources used in this project were as follows:

- the WSDOT's Northwest Region FLOW 5-minute freeway performance data archive
- the WSDOT's Washington Incident Tracking System (WITS)
- the state's crash records
- National Weather Service for Seattle-Tacoma airport
- construction event postings from WSDOT's Variable Message system logs.

**FLOW Data**

The FLOW data archive provided vehicle volume and lane occupancy data at 5-minute intervals by location. Data were available roughly every half mile throughout the study area. These data were then transformed to average facility speed estimates by location for each 5-minute time interval. Speed estimates were then converted into travel time estimates by using a "stair-step" algorithm for roadway segments. The travel time reported was for a trip entering each study segment at the beginning time period represented by the time stamp for that record. (That is, the travel time statistic stored in the 8:00 record for March 5$^{th}$ indicated the time it took to traverse the study roadway segment if a vehicle entered that segment at 8:00 on March 5$^{th}$.)

Because speeds and volumes differ over the geographic extent of a given corridor, the project database also recorded the minimum and maximum observed vehicle volumes, speeds, and lane occupancies recorded within the segment during each 5-minute time period. These statistics could occur at different locations within the corridor segment. That is, the maximum speed for a given 5-minute period might be located at a different location than the minimum lane occupancy, which might be located at a different location than the minimum or maximum volume statistic.

Reporting these statistics allowed a determination of whether spot locations were experiencing congestion during any 5-minute period, in addition to whether congestion at that or other locations was limiting throughput along the corridor. (That is, by examining differences in volume and speed along a corridor segment it was possible to determine whether congestion was causing vehicle throughput to drop below vehicle demand, indicating the formation of queues.)

Finally, summary corridor statistics of vehicle miles of travel (VMT) and vehicle hours of travel (VHT) were also produced for all roadway segments and 5-minute periods.

**WITS Data**

The WITS data provided records that described each incident to which WITS staff responded within the study area. The key WITS variables used in this analysis were the time and location of each incident, the duration of the incident, and whether the incident did or did not close one or more lanes or travel.

For placement in the analysis database, incidents were assigned to the specific 5-minute periods when the incident/accident/event occurred, and to the specific roadway segment in which they were located. Because incidents have durations (e.g., WITS records an incident as lasting 20 minutes), each incident was placed within all 5-minute records during which that incident was active. For example, if an incident occurred from

11:03 to 11:23, an "active incident" would be noted in the records for the roadway section that contained that milepost for five 5-minute periods: 11:00-11:05, 11:05-11:10, 11:10-11:15, 11:15-11:20, and 11:20-11:25. While an incident was "active," a "rubberneck incident" was also created for the opposite direction of that roadway segment (indicating that a visual distraction existed on that roadway segment but no active incident was occurring.)

**State Accident Records**

Because in 2006 WITS recorded incidents only when WITS staff were present at an incident scene, to provide a more complete estimate of incidents, specifically larger incidents, the project team also obtained state accident records for the study area for 2006. This provided a comprehensive data source for all crashes that occurred in the study area. The data obtained from the crash records included the time, location, and severity of the crash (property only, injury, or fatality).

Like incidents, crashes were assigned to the 5-minute period in which they were reported and to the roadway section (and direction of travel) in which the crash occurred. Because no "duration" variable is included in the state accident record, unlike incidents, a crash was indicated as "active" only in the single 5-minute time in which it was reported. For analytical purposes, an assumed "crash duration" was computed as part of this project. This value is discussed below in "Computed Variables".

There was some overlap between the accident records and WITS data in the analytical database. Unfortunately, it was not possible to either remove or fully quantify this overlap. All crashes that occurred on the study roadways in 2006 should have been present in the state accident records. Most of the crashes that occurred during the peak commute periods (when WITS is most active) were also included in the WITS database. However, not all peak period crashes are included in WITS, as WITS staff can be busy responding to other incidents and thus not be available to assist at some crash scenes. Outside of the peak periods, most crashes are reported only in the state accident records.

Given the data available in 2006, it was not possible to consistently identify specific matches between WITS incident reports and vehicle crashes reported in the state accident records. This is because no direct link (data key) exists between the two databases, and the time and location information in these two sources is often not consistent. Many accident records are filled out well after the occurrence of the crash, and thus "time of occurrence" is often rounded to a "reasonable" or "roughly equivalent" time by the individual filling out the form. As a result, the WITS record for that event might indicate that a crash occurred at 8:13 AM, but the accident record might record the crash as occurring at 8:00 AM. Similarly, the milepost locations from the two databases can be different. As a result, automated matching of these records was problematic. Furthermore, the large size of the database placed manual matching of these records beyond the scope of this project. As a result of these differences, both records were kept in the database, and the duplication of "events" had to be handled directly by the analytical process.

**Weather Data**

The weather data used for these analyses were obtained from publically available records collected from the National Oceanic and Atmospheric Administration (NOAA) weather station at Sea-Tac International Airport. The analytical database created for this study tracked the major statistics reported by NOAA on an approximately hourly basis, including the following:

- visibility (up to 10 miles)
- temperature (dry bulb)
- wind speed (average speed and highest gust speed per hour
- precipitation: inches
- weather type (rain, mist, thunderstorm, drizzle, haze, snow, freezing, small hail, hail, ice pellets, squall, fog).

These data were too detailed for the basic analyses intended for this study. Consequently, the project team performed a considerable amount of analysis to determine the types of summary weather statistics that would effectively indicate whether weather conditions contributed to congestion. The end result was a series of binary variables indicating that rain, heavy rain, wind, snow, or fog conditions had occurred in the last hour.

While weather data are generally reported for one-hour periods, if significant changes in weather occur, additional records are generated by the weather service indicating those changes. These records are in addition to the hourly records.

For placement of these data in the 5-minute data records of the study database, the weather variables reported were assumed to apply equally across the time period (usually one hour) represented by that record. (That is, it was assumed that rain fell equally over the geographic area at a constant rate.) Weather was also assumed to occur uniformly across all study sections.

The study team acknowledges that these were not “accurate” assumptions but were reasonable given other limitations in the data set and were necessary given the difficulty in obtaining and applying weather data that accounted for differences in rainfall by time and geographic area, as well as differences in pavement drying conditions by time of day, season, and location.[10]

**Construction Event Data**

A variety of construction activities took place within the study area during 2006. Some, but not all, of that activity was tracked within the analysis database.

By obtaining the variable message sign (VMS) logs from the Northwest Region traffic operations center, it was possible to determine when overnight construction or maintenance activity took place and the approximate periods when those lanes were closed. (Actual lane closures are subject to some variation from the times recorded on the VMS, as actual lane closure activity can vary on the basis of the speed of any given night's construction activity.) From the VMS logs it was possible to determine on which days temporary lane closures took place and the time periods (starting/ending time for the message postings) during which motorists were told to be aware of those construction activities. By using the location and directional orientation of the variable message signs containing the posted warning messages, along with the time periods noted on those messages, it was possible to place flags in the analytical database for specific roadway segments (by direction) and time periods (for specific days) indicating the presence of construction activity that closed travel lanes.

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[10] Considerable effort went into looking at how best to create a usable summary weather variable or set of variables. No approach examined was entirely satisfactory, given the complex ways in which weather can affect roadway performance. In Seattle, rarely are very heavy thundershowers present; thus "rain" can be indistinguishable from "road spray" in most common driving conditions. This means that from the perspective of degrading a driver's ability to see the road and other vehicles, "wet roadways" are roughly equivalent to "rain." For this reason, it was determined that any "rain" measured in an hour could be applied to the database such that all 5-minute periods within that hour were "rain affected."

The study did not track when long-term construction activity narrowed travel lanes, nor when lane lines were changed to reflect changes in the construction staging for a specific project. Neither could the study team obtain detailed information on the exact times when specific lanes were closed to traffic. (This was considered a minor loss, since all lane closures occur at night, when traffic volumes are low, thus decreasing the importance of the exact closure times for this study.)

Construction events were assigned to all roadway segments that were affected by a given construction event, as determined by the location of the VMS carrying the construction warning message.

## Computed Variables in the Database

To perform the analyses described in the next section, it was necessary to compute a variety of variables that were used to describe the performance of the roadway system relative to ongoing traffic conditions. For example, it is well known that, even on a divided highway such as an urban freeway, vehicle crashes can create a visual distraction for motorists traveling in the opposite direction of travel from that crash scene. This phenomenon is commonly called “rubbernecking.”

To account for this type of “incident,” it was necessary to create a “rubbernecking variable” from the incident and crash records. The rubbernecking variable was used to indicate that a visual distraction existed on the other side of a roadway. Separate rubbernecking variables were created for crashes and incidents. In both cases, the rubbernecking variable was a binary variable set to “1” if a crash or incident was actively occurring and left blank if no incident or crash was actively occurring. Since the duration of crashes was not known, the rubbernecking variable for crashes was set equal to only one 5-minute time period—the 5-minute period in which the crash was reported. For incidents, the rubbernecking variable was set to "1" for the entire reported duration of the incident.

A variety of computed variables was developed for use in this project. The types of computed variables are listed below. Specific descriptions of those variables and how they were computed are presented below the list.

- computed delay (in vehicle-seconds)
- holidays
- regime (a variable describing roadway performance using a combination of volume and speed)
- regime change (indicates whether a roadway segment has changed from one regime to another in a given amount of time)
- influence variables (indicate whether an event or disruption has "influenced" travel times—that is, is actively creating at least a visual distraction or has apparently created a reduction in capacity that has in turn created a queue or increase in queuing that is worse than existed prior to the event and that increased travel time in the corridor)
- duration of queuing associated with given types of disruptions (expressed as the number of 5-minute increments for which queuing can be associated)
- secondary incident indicators (indicate that a crash has occurred during a time period "influenced" by a previous incident or crash)
- causation variables (a variety of variables used to indicate the "cause" of the "influence" variables. For example, these variables would indicate that both an incident and a crash had occurred previously on a given corridor, and that the queues associated with those two events had not yet cleared. This variable was also used to indicate when congestion on a ramp or downstream off-roadway segment had grown to the point that queues from those off-segment locations had backed up enough to create on-segment slowdowns.)

- congestion ending indicators (record when congestion "ends" on a corridor at the end of both the AM and PM peak periods).

In addition, to the above variables, the database contained a number of logical variables that were simply used to define whether various events or the queues associated with those events were present. For example, a variable called "Effected Inc vs Crash vs Nothing AM" indicated whether—at that time in the day—an incident or crash had occurred. The variable was initially set to zero at midnight of each day. If an incident occurred, the variable was set to "1" and remained set to one for the rest of the day unless a crash occurred. If a crash occurred, the variable was set to "2." Once set to "2" the variable remained set to "2" until midnight. (For this variable, a crash overrode an incident.) A complete list of variables in the project database is presented in Appendix A.

**Computed Delay**

This variable was used to estimate total vehicle delay in a corridor during a 5-minute period. It was computed by subtracting free flow travel time from actual travel time and multiplying the result by the maximum observed traffic volume in the roadway section. Maximum volume estimated the number of vehicles traveling on the corridor rather than average volume because in periods of heavy congestion, measured volume under-represents the number of vehicles actually sitting on the roadway, moving slowly. "Maximum volume" was assumed to be a better estimator of actual demand on the roadway than average volume.

**Holidays**

It is well known that traffic on holidays differs from normal day-of-week traffic. To account for these differences, the following holidays were noted within the database: January 2 (New Years), February 20 (President's Day), May 29 (Memorial Day), July 3 and July 4 ($4^{th}$ of July), September 4 (Labor Day), November 10 (Veteran's Day), November 23 and November 24 (Thanksgiving), December 25 and December 26 (Christmas).

**Regime**

The "Regime" variable was developed to describe the "worst" condition found in the test segment during each 5-minute interval. "Regime," illustrated in Figure 3, was a categorical variable for which 1 = free flow traffic, low volumes, 2 = free flow traffic, less than one lane of capacity remains, 3 = constrained flow, very high volumes, 4 = congestion exists, 5 = recovery. Regime was used to define the basic operating condition of the roadway study section.

The speed used to determine the "regime" for a given 5-minute period was the slowest observed anywhere in that segment. The volume used was the highest volume per lane observed during that same time period. The speed and volume statistics did not have to come from the same location.

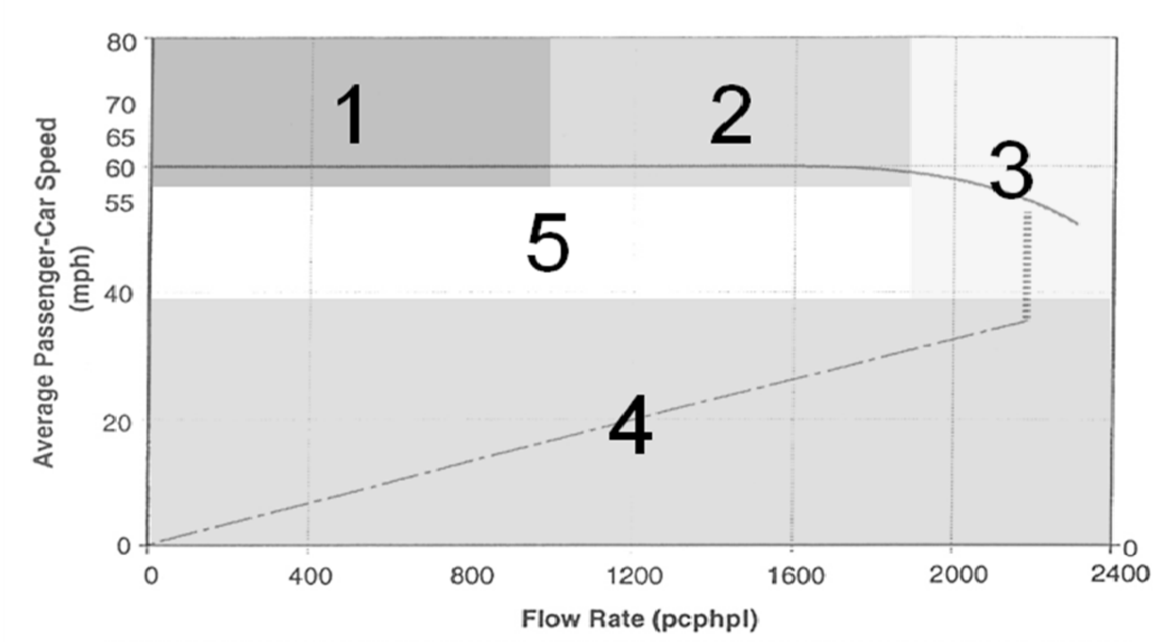


**Figure 3: Regime Variable Categories as Determined by Using Speed and Flow Rate**

## Regime Change

This binary variable—1 = true, 0 = false—indicated whether a change in regime occurred within a given time frame. The intent was to provide a simple indicator that a significant change in roadway operating condition was occurring or about to occur. These variables were then used in combination with the occurrence of an event (incident/crash) to examine whether that event changed the probability of a change in operating condition occurring.

Six regime change variables were computed. Three variables indicated whether Regime changed from a “2” (free flow speeds, less than one lane of traffic capacity exists) to a “4” (congestion exists): one variable for “within the next 5 minutes, ” one variable for “within the next 10 minutes” and one variable for “within the next 15 minutes.” The other three Regime Change variables were used to look for changes from

Regime 3 (high volumes, constrained speeds) to Regime 4 using the same three periods in which that change could occur.

**Influence Variables**

The "Influence" variables, particularly the "Queue Extending Influence" variable, were key to the analyses. They indicated whether an event or disruption had "influenced" travel times. (Note: this means that some portion of delay—but quite possibly not all of that delay—in a corridor could be attributed to a given disruption.) This concept and the three variables computed to associate delay with any given event are described below.

As a human by-stander, it is fairly easy to watch traffic flow around the location of an incident and define the delay associated with that incident. Intellectually, the delay associated with that incident is the queue that forms at the location of that incident. As long as that queue remains in place, even if it moves up- or down-stream as a result of shock waves and other physical phenomenon, all that delay can be associated with the incident. Even if that section of roadway might "normally" have a queue for a portion of the time the "incident queue" exists, all delay can be considered "incident delay." In a perfect research world, this delay could then be compared to the delay that would have been present without the incident. The difference between those two conditions would be considered to have been "caused" by the incident.[11]

However, when examined at a broader corridor level, the queues that form as a result of incidents can create a number of side effects that change the travel time

[11] Of course, we can't actually measure "the delay that would have been present," which is one difficulty in determining the benefit from incident response. It is not correct to directly compare a given incident delay to "normal" or "average" (non-incident) delay conditions without also accounting for the effect differences that input volumes have on delay formation during peak periods.

motorists experience in the corridor. For example, in some cases, the incident queue reduces downstream traffic volumes, allowing traffic to flow more smoothly. In other cases, the release of a queue that has formed behind a major crash scene can create a traffic volume "wave" when that accident scene is cleared, and that wave can create one or more secondary queues downstream of the accident location. This condition is illustrated in Figure 4, which shows (in red) the downstream movement of congestion caused when a "pulse" of vehicles flows downstream after having been released from a major accident scene. These secondary queues are also "incident caused," even though they are located at points removed from the location of the actual incident.

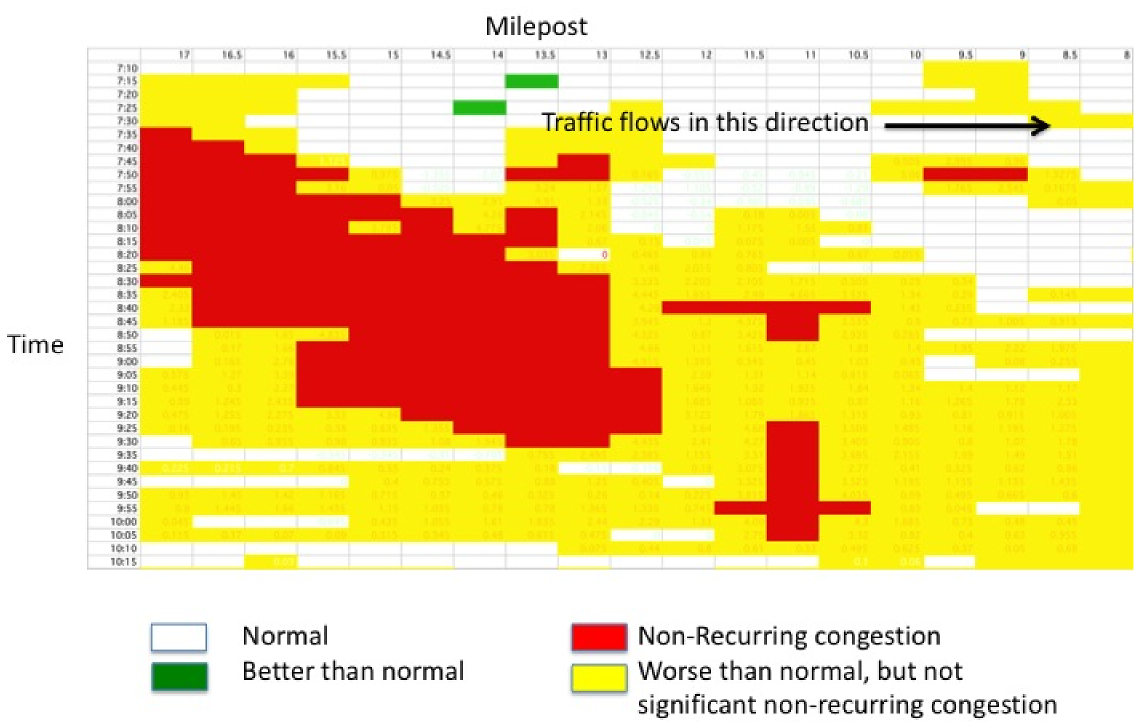


**Figure 4: Extra Congestion Caused by Release of Traffic Delayed Behind a Major Accident Scene on Westbound I-90**

Visually, these effects can be identified on a case by case basis as long as sufficient data are present. Mathematically, for very large datasets, and when only summary statistics (like corridor travel time, VMT, or VHT) are available, this task becomes much more difficult. Part of the mathematical challenge is that incident-caused delay can last considerably longer than the incident itself and, as noted above, can extend to geographic regions far removed from the incident location itself. (In Figure 4, the actual incident lasted from 5:30 AM to 7:00 AM and occurred at a location just east of where traffic surveillance starts in the corridor, essentially to the left and above the "red" congestion "blob" in Figure 4.) Part of the problem is that the geographic and temporal extent of the incident-caused delay is a function of the background traffic conditions under which the incident occurs. The problem is also a function of how travel times, which occur over extended times and spaces, differ from incidents, which occur in narrow temporal and geographic spaces.

This challenge, of associating an incident with a trip travel time, is best explained with an example. For this example, assume that the corridor being studied is 10 miles long (extending from milepost zero to milepost 10), and the free flow speed is 60 miles an hour. Thus it takes a car 10 minutes to travel the length of the corridor. An accident takes place at milepost 6 at 8:00 AM. It lasts three minutes, until 8:03. A trip traveling the length of the corridor starting at milepost zero at 8:00 will be affected by this incident, even though the incident has been cleared before the car arrives at the scene, because the car starting its trip at 8:00 AM must travel through the queue formed by the accident. But importantly, a car starting on that same trip at 7:55 (five minutes <u>before</u> the accident occurs) will also be affected by the incident, because even at free flow speeds, that car is only at milepost 5 at 8:00 AM when the accident occurs. However, if that same accident occurs at milepost 1 instead of milepost 6 (both inside the study corridor), the 7:55 trip will not be affected, whereas the 8;00 AM trip will be.

The other difficulty with associating incidents and specific trips is understanding the duration of the congestion that forms as a result of the incident. In the above example, the queue formed by (or disruption caused by) the 8:00 AM accident may last anywhere from zero additional minutes to several hours. If the 8;00 AM accident in the above example occurs in the middle of the AM commute period, the queue associated with that accident may last a full hour before traffic volumes reduce enough to allow the queue to dissipate. On the other hand, if traffic volumes are light, the queue may dissipate immediately. Thus a trip starting at 8:30 AM on this same corridor may or may not be influenced by the 8:00 AM accident, depending on the corridor's background traffic conditions and the nature of the accident itself.

Therefore, without a VERY detailed and complex data set and analysis algorithm for identifying time- and day-specific speeds, along with that same level of detail for when and where incidents occur within a corridor, it is impossible to directly associate any given trip with a given incident. This level of detail was not available to this study team for this analysis.

Consequently, no simple algorithm was developed that could identify which travel time (or VMT or VHT) measures for a given corridor were "directly influenced" by a given incident. As a substitute, this project developed three different methods for defining "the extent to which delay or trip travel time is 'influenced' by any given incident." Each method has strengths and weaknesses. Taken together they offer reasonable explanations for how incidents affect travel time and travel time reliability. The selected measures were defined as follows:

Active Influence: Assumes that any trip that starts into the corridor during a time period that contains an active incident is affected by that incident. Since travel time data were available on a 5-minute basis, this method of association works as follows: if an incident occurred from 8:04 AM to 8:08 AM, trips with start times of 8:00 and 8:05 AM would be associated with this incident. No other trips would be considered to be influenced by this incident.

This measure is the most restrictive of the methods used to associate incidents with travel times. All trips assumed to be "influenced" by an incident in this method are known to be influenced by incident-caused queues (if any have formed), but the method will miss some of the "earliest" trips influenced by the incident, and it will miss later trips that are influenced by the residual queue left after the incident has been cleared.

Time Extended Influence: Assumes that all incidents happen in the center of the study segment and extends the "influence" period earlier in time equal to the time needed to drive half the corridor at free flow speed. In addition, this measure assumes that "influence" extends an additional 15 minutes after any given incident ends. (Using the 8:04 to 8:08 AM accident from the Active Influence example above, this method would assume that the incident's "influence" would extend from trips starting at 7:59 AM to those ending at 8:23, meaning that the 7:55 AM trip would be the first affected, and the 8:20 AM trip would be the last affected—an extension of three 5-minute periods after the last period in which the incident was actually "active.")

This methodology captures the majority of the trips that are influenced by the formation of the incident caused queue. (It misses a few incident-influenced trips when incidents occur at the far upstream portion of the study corridor segment.) It also captures a significant portion of trips that are affected by residual queues. Where those queues are non-existent or short lived, it over-estimates the influence of a given incident. However, since the intent of this analysis was to capture the effects of incidents on trip reliability, over-estimating the number of "fast trips" that are incident-influenced was less important than making sure that all very slow trips were associated with their causes. Therefore, this bias was assumed to be acceptable.

Queuing Extended Influence: Assumes that once an incident has occurred, any travel time increase on the corridor is associated, at least in part, with the (potential) queue that forms as a result of that incident. This measure assumes that any increase in travel time that occurs while an incident is "active" is associated with that incident.

This approach selects the fastest corridor travel time experienced before and during the incident. All subsequent travel times are assumed to be "influenced" by that incident until corridor travel times return to that fastest time. Once a measured travel time faster than the reference travel time is observed after the Time Extension has ended, the "influence" of that disruption is considered to have ended.

The Time Extended definition above was used to define the time periods from which the reference (fastest) travel time was selected. (Note that this approach was originally tested using the 5+15 minute version of the Time Extension approach.) It was then recomputed—with new variables—including a more simple Time Extension definition of one time period before the disruption occurs and one time period after the disruption has been cleared. These Queue Extension variables include the term "5+5" in their variable definition to reflect the 5 minutes prior to—and after—the recorded incident time.

For off-peak conditions (low volume/capacity conditions), this approach is an excellent measure of incident effects. If the incident occurs at the beginning of peak period conditions, it is likely to associate all of the peak period congestion with the incident. This may or may not overstate the extent of any given incident's congestion-causing influence. (It can be easily argued that the incident makes the queue experienced in the peak period larger, meaning that trips in the middle of the peak—even after the incident has been cleared—are longer than they would have been,. And since the queue is larger than otherwise, congestion is extended longer at the end of the peak, so that trips made at that point are also "influenced" by the earlier incident.) This example also points out how difficult it is to separate out the "lasting influence" of the incident on bottleneck formation, as well as to separate "incident-caused" congestion from "volume-caused" congestion in the peak periods, even when very detailed statistics are available. This is why the term "influenced" is used rather than "caused" for this variable. This finding was also key in the selection of how delay was attributed to different causes in this project.

The "Queuing Extended Influence" variable was thus assumed to be a good "liberal" measure of the effects of incidents on the travel times experienced by motorists.

None of these measures is perfect. Taken together, however, they are quite descriptive of the degree to which congestion and delay are related to incident occurrences.

By tracking all travel times influenced by a disruption, it is possible to identify the wide range of impacts a single disruption causes. That is, the "extra delay" a trip experiences as a result of any given disruption changes depending on the time—relative to the formation of the queue—that a given trip arrives at the queue caused by the disruption. That queue grows from nothing to its largest extent, and then shrinks back to nothing. If the trip being monitored arrives at the beginning or end of the queue formation, the added delay is modest. If it arrives at the height of the queue, its delay is the maximum experienced.

The methodologies described above associate each 5-minute average travel time with an incident or non-incident condition, and some of these measured travel times "experience" the shoulders of the incident queues, while some "experience" the maximum queue. The result was an ability to monitor the entire spectrum of delays associated with each incident. It was therefore possible to explore the different travel times associated with any given incident and, if desired, select the maximum travel time associated with that incident. The trip with the largest travel time was assumed to be the trip made "most unreliable" as a result of that particular incident.

In general, the findings presented in the main body of this report concentrate on using the "Queue Extended (5+5)" measure of influence. The project team considered the queue extended measure to be the "best" measure of incident influence (it was also the measure of maximum influence).

**Duration of Queuing**

A "duration of queue" variable was computed by using the Queue Extended Influence" variable for both incidents and crashes. The duration is the number of 5-minute increments associated with a specific incident. For crashes, this value was stored in the same row (record) of the database as the crash indication. For incidents, the duration variable was stored in the first row in which a given incident was recorded. (Note that incidents were reported in each 5-minute time period during which they were active.  The "duration of the queue" was reported only once, <u>not</u> during each of those 5-minute periods.)

The variable is computed by simply counting the number of consecutive 5-minute time periods in which an "influence" variable is set.  When more than one incident/disruption occurs, the two incidents/events "end" at the same time.

**<u>Secondary Incident Indicators</u>**

Two kinds of secondary incident indicators were used. One indicates whether a given incident/crash is occurring at a time when the effects of a previous incident/crash are still active.  The second counts the number of "secondary" incidents that occur during the duration of any given incident/crash.

Both of these variables were based on the "Queue Extending Influence" variable. That variable indicates that a queue is "larger than it would have been without an incident."  Since that queue exists, any new incident occurring is attributed to those "changed" conditions.  (This is a reasonable but not entirely accurate assumption. The available information in the analysis database could not determine whether the second incident actually occurred in that queue. Therefore, this indicator likely overstates, by a modest amount, whether these were truly "secondary incidents"—that is, directly caused by the previous incident.)

Separate variables use the same technique but look only at crashes.  In this case, both the initial "influencing" event and all secondary events must be crashes.  (That is, a crash cannot be a "secondary crash" if the "influencing congestion" is caused by a disabled vehicle.)

## Causation Variables

The "causation variables" are categorical variables that indicate that specific events have influenced delay. (These categorical variables cannot be used to indicate the amount of delay associated with any one cause. They only indicate that a "cause" was active and could have influenced the amount of congestion measured.)

To create these this, influence variables were initially computed independently for incidents and crashes. Other "causes" were assumed to be active if 1) measurable rain had fallen in the last two hours, 2) a VMS sign indicating construction activity was operating on the roadway segment in question, or 3) an off-ramp leading to a major freeway or at the end of the freeway segment was congested (e.g., the ramp leading to SR 202 at the end of eastbound SR 520).

A new variable was then created to describe whether any of these conditions occurred. Where congestion on downstream freeway segments caused queues from those segments to back up onto the study segment, the "cause" for those back-ups was also captured to be included in the roadway segment being analyzed. A "causation" variable was assigned for each record in the analysis database. The values for that variable are defined below:

0 - No cause of congested noted in available variables
1 - ONLY Incident Queue Extended is present
2 - ONLY Accident (crash) Queue Extended is present
3 - ONLY Preciphour is present (it has rained in the past two-hours)
4 - BOTH Acc Queue Extended and Inc Queue Extended are present
5 - BOTH Inc Queue Extended and Preciphour are present
6 - BOTH Acc Queue Extended and Preciphour are present
7 - An Accident Queue Extended, an Incident Queue Extended, and rain all are present

8 - Ramp Congestion exists, but no cause for ramp congestion is known
9 - Construction activity is going on
10 - Construction activity plus Ramp Congestion
11 - Construction activity plus an Incident Queue Extended
12 - Construction activity plus an Accident Queue Extended
13 - Construction activity plus Rain
14 - Construction activity plus an Accident and an Incident Queue Extended
15 - Construction activity plus an Incident Queue Extended and Rain
16 - Construction activity plus an Accident Queue extended and rain
17 - Construction activity plus an Accident and an Incident Queue Extended and Rain

While several different "causation" variables were assigned in the database, they differed only in the number of "categories" they incorporated. (For example, the initial causal variable did not include an examination of construction activity. The second causal variable did not consider "spill back" of downstream congestion.) Only the final variable (the categories described above) was used in the final analyses.

**Congestion Ending Indicators**

One of the analyses performed in this project was to examine whether incidents and crashes extend the congestion that normally occurs during the AM and PM peak periods. (That is, if a crash occurs, does peak period congestion last longer than normal, or does the free flow condition return at the same time regardless?) To perform this analysis, it was necessary to define "when congestion ends." Consequently, "End of Congestion" was defined as the point when travel times for 20 consecutive minutes (four 5-minute periods) have been less than the travel time at the speed limit plus 5 percent.

One problem with the use of this definition was that for 11 test sections in the AM peak period, the mean time of day when congestion ended did not occur before noon. A review of the travel times routinely experienced on these routes showed that a variety of traffic flow conditions (e.g., excessive merging at bottlenecks near the end of the corridor, heavy traffic flows influenced by large truck volumes) frequently kept these road segments operating slightly below the speed limit during late morning and midday time periods. These routes all operated at or above the speed limit during late night hours and during many midday hours, but they routinely operated at speeds lower than the speed limit for reasons other than traffic disruptions during the middle of the day.

The result was that on many days that did not experience incidents, the "AM peak period" frequently did not end until late in the day—and these very late ending times dragged the mean value of the AM peak period into the afternoon. This "starting condition" limited the benefit of the intended analysis. As a result, "end of congestion" was redefined as being sustained speeds within either 10 or 20 percent of the speed limit.

These "lowered expectations" were tested on other corridors but frequently caused the "end of congestion" flag to be set during obviously congested conditions. This was particularly true in the afternoon peak period, when all routes reached travel times within 5 percent of that achieved at the speed limit by a "reasonable" time of day. Consequently, the "slower speed" needed for the "definition of congestion" was used only for the 11 sections and only for the AM peak period. Of those eleven, six used 10 percent of free flow speed, and five used 20 percent of free flow speed as the end of congestion marker.

## ANALYTICAL TESTS PERFORMED

A variety of tests were performed to gain a better understanding of how incidents and incident characteristics affect roadway performance. This section describes the tests that resulted in specific knowledge that could be used to better understand how and when incident response provides benefits to travelers and to the WSDOT. It also discusses specific analytical concerns that had to be addressed as these analyses were performed.

The following analyses were performed:

- The Significance of Crash- and Incident-Induced Traffic Delay
- The Effects of Incident Duration on Congestion and Delay
- The Effects of Incidents on the End of Peak Period Congestion
- The Effects of Weather on Congestion Formation Travel Time
- Roadway Conditions Present When Incidents Create Congestion
- The Effects of Incidents and Crashes on (Secondary) Crash Rates
- The Effects of Rain on Crash Rates
- Estimating the Frequency of Incidents in Areas with Limited Incident Response
- The Value (Cost) of Delay.

The analytical approach to answering these basic research questions is briefly presented below.

### The Significance of Crash- and Incident-Induced Traffic Delay

This set of analyses examined the amount and percentage of delay caused by crashes and incidents in general. The intent was to develop a better understanding of the size of the problem and scope of potential benefits that could be obtained from incident response in the Puget Sound region.

Two different approaches were used to examine the significance of crashes and other incidents on roadway delays. Both techniques made use of the Queue Extended Influence variable, which indicates which 5-minute periods have been influenced by crashes and/or incidents. (Note that the term "incident" includes all incidents responded to by WSDOT's incident response program, including crashes; however, it does not include the effects of many crashes that occurred during off-peak time periods and to which only WSP officers responded.)

The first of these two techniques used the "Causation[12]" and "Delay" variables to aggregate delay by the cause of that delay. Traffic volume, whether it was "routine" volume or an unusual surge in volume associated with something like a special event, was not explicitly tracked in this analysis. "Unexplained congestion" was assumed to be caused exclusively by the presence of too much traffic volume.

The second analysis compared the mean travel time performance for each roadway study segment for those periods that were affected by incidents and crashes and those that were not affected by any disruptions (crashes, incidents, rain, or roadway construction). The difference in the mean travel times was assumed to be caused by incidents and/or crashes. The difference between free flow travel times and the mean travel time under non-disruption conditions was assumed to be caused by too much volume.

The computation of mean travel time was performed by hour for all non-holiday weekdays and then again (separately) for weekends and for holidays. The mean value was calculated by treating all 5-minute records as independent measures of hourly

[12] See page 45 "Causation Variables"

roadway travel times and using the causation variable to determine with which category any given 5-minute travel time was associated.

Mean travel times were converted to delay estimates by multiplying the difference between the mean travel time and free flow travel time by the average volume per hour. This delay value was then annualized by multiplying by the number of 5-minute periods that were crash- and/or incident-affected and dividing by 12. Total delay caused by incidents was then compared with the total delay measured for the roadway test segment to determine the percentage of delay caused by incidents and crashes.

This analytical approach made several key assumptions. 1) It assumed that all 5-minute travel times within an hour period were randomly distributed with respect to being influenced by crashes and incidents. 2) It assumed that the proportion of days with incidents and crashes was equivalent on low volume and high volume days. 3) It ignored the "extra" congestion effect of adding rain to crash and incident days. (That is, days when rain affected travel but no incidents occurred were removed from the "no disruption" side of the calculation. They were included in a third category of the analysis, "other disruptions," that was not used in the computation of the effects of incidents and crashes on travel time and delay.)

None of these assumptions is perfectly true. For example, in the peak period, because "incident influence" tends to continue for most of the peak period once an incident has occurred, a higher proportion of 5-minute periods toward the end of an hour are "incident influenced" than toward the beginning of the hour. (That is, a travel time at 7:55 AM is more likely to be incident influenced than one at 7:05 AM.) Early in the peak periods, this will produce a minor bias in the "non-incident" travel time, making it slightly "fast." However, this difference appears to be quite minor. In addition, there appears to be little bias associated with the end of the peak period.

Because increased VMT is associated with increased crash and incident rates (more traffic means more vehicles to potentially have a problem), the second assumption is also likely false. However, again, the effects of this bias are very limited. In fact, an earlier analysis for WSDOT showed that the worst congestion days, which usually involve crashes, are not among the highest volume days. This is because high levels of congestion cause motorists to seek other routes or delay their trip until congestion eases. Thus, actual driver behavior creates a counter-bias that limits—to at least a certain degree—the effect of the expected bias. A review of actual traffic volume data showed that days that experience crashes tend to have statistically higher traffic volumes during the 5:00 AM and 6:00 AM hours, but statistically lower traffic volumes after 8:00 PM. During the majority of the day, traffic volumes are not different by a statistically significant amount on most test sections.

## The Effects of Incident Duration on Congestion and Delay

It is not possible, given current technology, to eliminate the occurrence of crashes and other incidents. Consequently, incident response is designed to reduce the impact of the incidents and crashes that do occur. It does this by reducing the duration of those events, with the expected result that reducing the time an incident exists on the roadway will reduce the delays associated with that incident. This analysis developed relationships that describe the benefits (in minutes of delay saved) that can be obtained by reducing the duration of incidents.

A simple review of roadway performance that compares roadway performance with and without incidents of any kind shows that incidents, including crashes, do not, in and of themselves, cause measureable delay. They cause delay only when the disruption they create causes functional capacity to fall below actual demand. Therefore, the impact of the duration of any given incident is not constant but is a function of where it occurs, when it occurs, and the traffic demand relative to functional roadway capacity at the time it occurs.

Consequently, to develop a good understanding of the benefits that could be gained by shortening incident duration, the research team conducted a three stage analysis. The first stage examined empirical roadway performance data under both incident and non-incident conditions. This confirmed the theoretical expectations that most incidents have negligible effect on roadway performance when traffic volumes are moderate to low, but cause or measurably increase congestion when traffic volumes are moderate.

The second stage of the analysis used queuing theory to explore the effects on queue size and durations given different incident sizes and durations (where an "incident" was defined as a given decrease in capacity) on the amount of delay experienced.

This same analysis was then performed but with traffic volumes being varied to simulate time of day travel patterns actually occurring on the roadway, with traffic volumes increasing at the beginning of the peak period and decreasing at the end of that period. Not only was traffic volume varied, but the timing and duration of the "incident" was also varied. This allowed the analysis to examine how total delay increased, given a defined incident occurring at the beginning of the peak period, the middle of the peak, or the end of the peak.

The results were then summarized to illustrate how changing the duration of an incident affects delays, given the fact that incidents occur throughout the day and under a variety of traffic conditions.

**The Effects of Incidents on the End of Peak Period Congestion**

One of the outcomes of the analytical tests described above was the finding that the key variable in the speed at which a roadway recovers from incident-related congestion is the difference between the amount of traffic demand entering the back of the incident queue and capacity of the roadway. (Essentially, the smaller the input volume to the back of the queue, the faster that queue dissipates.)

This finding, confirmed by empirical data, showed that roadways tend to recover very quickly from incidents during times of day when traffic volumes are declining. This finding has significant implications on the benefits to be obtained from incident response, so an additional analysis was performed to examine whether empirical data supported the idea that incident congestion dissipates much more quickly at the end of the PM peak, as traffic volumes decline, than it does at the end of the AM peak, when traffic volumes tend to remain moderate.

To accomplish this analysis, the research team first defined the “end of congestion” (see previous). The end of congestion was determined for all non-holiday Tuesdays, Wednesdays, and Thursdays. Two sets of statistical comparisons were then made to determine whether the time when congestion normally ended changed if an incident or crash occurred during the peak period. (That is, if an incident occurred at any time during the AM peak, could a traveler expect a statistically increased probability of the presence of congestion?)

One of the two tests was conducted under the assumption of a normal distribution. The other was conducted by using the Anderson-Darling K-sample test,[13] a non-parametric test that allows comparison of two populations with skewed distributions.

Tests were done separately for the AM and PM peak periods. Tests were also performed separately for "any incident" or "a reported vehicle crash." For the AM peak, the incident or crash had to occur after 4:00 AM and before the end of congestion for a peak period to be associated with that incident/crash. For the PM peak, the incident/crash had to occur after 3:00 PM and before the end of congestion.

## The Effects of Weather on Congestion

Another aspect of incident response for which additional information was needed was how weather affects roadway performance. While the entire scope of this topic was too large for this project, it was possible to address parts of it. To do so, this set of analyses explored both how to define "bad weather" and exactly how, when, and where bad weather affects roadway performance.

A large number of studies have looked at the effects of various weather phenomena on roadway performance. None of these has answered the basic question, what quantifiable effect does bad weather have on roadway performance?

In examining this question, the research team discovered a number of key problems. Part of the problem is that the effects of bad weather, such as rain or snow, are not restricted to the time when precipitation is falling. For example, the effects of snow

[13] Scholz, F.W. and M. A. Stevens. K-Sample Anderson-Darling Tests. Journal of the American Statistical Association, Vol 82, No. 399, 1987, pp. 918-924.

last long after the snow has fallen—IF the snow sticks to the pavement. However, snow may have a very limited effect if the ground is warm enough to melt the snow as it lands.

This highlights a second problem we faced: the weather at the weather station can be very different than the weather at a specific location geographically removed even a short distance from that station. This is particularly true for weather conditions that can be localized, such as fog, or conditions such as snow that stick in some locations but not others because of minor differences in temperature and shading.

Finally, despite its reputation for rain, Seattle does not typically experience several of the "bad weather" conditions that have particularly noticeable effects on roadway performance. Seattle rain tends to be light, not heavy like a Midwest thundershower. As a result, Seattle drivers rarely, if ever, experience rain that is so heavy that it reduces their visibility enough to force them to slow dramatically. On the other hand, water spray from rain that fell an hour previously is quite common in Seattle. Similarly, while Seattle gets occasional snow storms, snow is uncommon. Lastly, while Seattle does get fog, fog is a very localized condition and one that could not be well accounted for given the weather data sources available to the research team.

As a result of these limitations, a variety of analyses were performed with the available weather variables. The results are very informative, but the statistics that relate delay to weather can be applied only to freeways in the region. While the basic conditions apply anywhere, the summary statistics that describe those relationships are not applicable to other geographic locations even within the state, such as Spokane, which experience very different weather conditions.

### Rain versus Roadway Performance

One of the researchers' first analyses was to examine empirical roadway performance (travel times) given a variety of summary weather statistics to determine which summary weather statistics showed the best correlation with increases in changes in roadway performance. The two primary dependent variables used for this analysis were travel time in the roadway segment, and the probability that the roadway segment was operating in Regime 4 (congestion exists somewhere on the roadway segment).

Sensitivity tests were performed to determine what independent variables best described changes in roadway performance. These tests determined that the rain variable that most effectively predicted changes in roadway performance was whether measurable rain had fallen within the last hour. For example, assume that rain (as measured at Sea-Tac Airport) falls between 3:00 and 4:00 PM. The time periods between 3:00 and 5:00 PM are assumed to be "rain affected" (within one hour of when measurable rain has fallen). Travel times occurring at 4:55 that day are considered to be "rain affected," whereas travel times at 5:05 are considered "dry" trips. The biggest limitation with this analysis was that the rain may have created a queue that affected the 5:05 dry trip. For the analysis results discussed later, that possibility was ignored, thus slightly underestimating the potential impacts of rain on travel time.

### Snow versus Roadway Performance

When the effects of snow were examined, the research team discovered that because of 1) the limited number of snow events and 2) the overwhelming impact of non-weather variables on roadway performance during those limited time periods (i.e., Were motorists able to avoid driving on freeways during the snow event? What level of snow accumulation occurred? Did geographic features such as hills or sharp corners create difficult driving conditions?), the definition used for "rain" did not work. Therefore, the analysis of snow impact was performed as a case study, rather than as a statistical analysis.

**Wind versus Roadway Performance**

The effects of wind on roadway performance were also analyzed differently than the effects of rain. This is partly because—other than the lasting effects of any queues formed—wind does not have a lasting effect similar to that of rain. (Once wind stops, its direct effects stop, unlike the spray from wet roadways caused by rain.) The lack of this effect also limited our confidence in the use of the available NOAA wind data for specific roadway sections.

As a consequence, the "wind gust" variable produced by NOAA was not used. The project team had little confidence that this variable was effectively applicable to geographically removed locations. Similarly, the "wind speed" variable that was used was assumed to be only a reasonable surrogate for "windy conditions," rather than a definitive statistic indicating the precise wind speed at which travel might be affected.

To test the effects of wind on travel times, the data set was divided into "wind affected" and "not wind affected" groups on the basis of the wind speed variable present in each 5-minute time slice. The travel times for these two groups were then compared within specific time intervals with both traditional T-tests, which assumed normally distributed travel times within those periods, and non-parametric tests of the sample means. Tests were performed only for non-holiday Tuesdays, Wednesdays, and Thursdays (combined).

Sensitivity tests were performed with different values of the wind speed variable to determine the sensitivity of the analysis results to the break point selected for identifying "windy" versus "not windy" conditions. The performance of different roadway corridors was found to be sensitive to different wind speeds. The researchers believe that this is due in part to differences between actual wind speeds within the study corridor and those measured at the airport, and in part to the way that site-specific roadway geometry affects how drivers respond to wind. (That is, travel times over the SR 520 floating bridge, which has narrow lanes, no shoulders, and physically moves when struck by wind-blown waves, are affected at much lower wind speeds than travel times on I-5 in the northern reaches of the metropolitan region, where lanes are wider, full-width shoulders exist, and wind does not cause the roadway to move.) In the end, sustained wind speeds of 16 mph were used as the primary split between "windy" and "not windy" conditions. Adopting a different definition would marginally change the travel times associated with windy and not windy conditions for some corridors but would not change the ultimate conclusions of the study.

**<u>Roadway Conditions Present When Incidents Create Congestion</u>**

A key aspect of determining when and where to deploy incident response resources is an understanding of what baseline conditions are required before a significant number of incidents actually create congestion. This analysis started with findings from the SHRP2 L03 project, in which Dowling Associates showed that "routine" congestion formed on Bay Area freeways frequently formed at volume/capacity ratios of around 0.5.

Because the intent of the study was to gain insight into the baseline volume conditions at which incident response becomes valuable, the project team undertook an analysis of the available Seattle freeway data to determine at what volume to capacity ratios congestion formed in this area, and whether those values changed by size of roadway.

The basic analysis approach was simply to determine the frequency with which congestion formed for given volume/capacity ratios for the different freeway test segments and to summarize those results.

## The Effects of Incidents and Crashes on Crash Rates

While the major focus of this project was on the delays caused by incidents, a secondary interest was whether those increases in congestion cause crash (accident) rates to increase. If this is in fact the case, then faster removal of incidents from the roadway and the expected faster dissipation of associated queues will also decrease the crash rate for that facility.

There is considerable belief that crash rates increase substantially in the queues that occur at incident scenes. This analysis effort explored whether the probability of a "secondary crash" occurring was higher than that of a crash occurring otherwise.

To perform this analysis, the project team tested the probability of a crash occurring by time of day for all weekdays during the year under different conditions. The project team used the "Queue Extended Influence" variable to split the data set into two samples, one in which no "incident event" had occurred and one in which the corridor was operating "under the influence" of a queue caused in part by an incident. The probability of a crash occurring under these two different regimes was then tested statistically by using both parametric and non-parametric tests. The same analysis was then performed with only "crash-influenced" time periods versus "non-crash-influenced" time periods.

All of these tests were performed by corridor.

## The Effects of Rain on Crash Rates

Similar to the analysis of secondary crashes, the project team performed an analysis of the statistical probability of a crash occurring on SR 520 under rainy conditions versus "dry" conditions. As with other analyses performed for this project, conditions were considered "rainy" if the Sea-Tac Airport had experienced measurable rainfall within the last two hours.

Because rain is not a "time sensitive" value in Seattle (i.e., it is as likely to rain in the peak period as it is at night), crash probabilities were tested for both daily and peak period conditions. The statistical approach used to test for differences in the probability of a crash occurring was as follows:

Because accidents are rare events, it is reasonable to treat their occurrence from time interval to time interval as independent events, with probability p1 when there is no rain and with probability p2 when there is rain. The number X1 of accidents observed over the no rain intervals, n1, can be treated as having a binomial distribution with parameters n1 and p1. This distribution in turn is very well approximated by a Poisson distribution with a mean ($\lambda 1$) equal to n1 * p1. We express this distributional relation as

$$X1 < \text{Pois}(\lambda 1 = n1\ p1).$$

Similarly, we write

$$X2 < \text{Pois}(\lambda 2 = n2\ p2),$$

where X2 is the accident count over the n2 intervals with rain.

Estimates of $p_1$ and $p_2$ are easily obtained as $\hat{p}_i = X_i / n_i$ for $i$ =1, 2, respectively, with the resulting estimate $\hat{p}_1 / \hat{p}_2$ for $p_1/ p_2$. 100γ percent confidence intervals for $p_1/ p_2$ were obtained by the exact method (Clopper-Pearson) as explained in Scholz[14]. Computationally, the confidence intervals xL, xU are obtained in the statistical software package “R” via the commands.

xL =(1/qbeta((1 + gam)/2, X2 + 1, X1) − 1) □ n2/ n1

and

xU =(1/qbeta((1 – gam)/2, X2 + 1, X1) − 1) □ n2/ n1

where gam = γ = .95, X1 = $X_1$, X2 = $X_2$, n1 = $n_1$, and n2 = $n_2$. qbeta denotes the beta distribution quantile function that is intrinsic to R.

The resulting estimates and 95th percentile confidence bounds for $p_1/ p_2$ can then be used to test for any statistically valid differences in the two probabilities.

**Estimating the Frequency of Incidents in Areas with Limited Incident Response**

The next problem this project faced was that before WITS begins operating along a stretch of roadway, WSDOT has no information on the number of non-crash incidents that take place along that stretch of roadway. While it is logical that the higher the traffic volume on any given stretch of roadway, the larger the number of incidents that will occur, no work has been done to develop a relationship that could estimate the number of incidents that can be expected along a roadway.

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[14] Scholz, F.W. (2007), “Confidence Bounds & Intervals for Parameters Relating to the Binomial, Negative Binomial, Poisson and Hypergeometric Distributions With Applications to Rare Events,” notes for Stat 498B, Industrial Statistics, University of Washington, Seattle, Washington.

Consequently, this project tested the statistical relationships of volume, vehicle miles of travel, and crash rates with the number of incidents recorded by WITS within the Puget Sound study area. A strong linear correlation was found between the annual number of vehicle crashes and the number of incident responses (see Figure 5). This means that given data on the annual number of vehicle crashes along a particular roadway segment, we can predict the future annual frequency of incidents (of which crashes are only a subset), and thus the overall required level of incident response can be estimated.

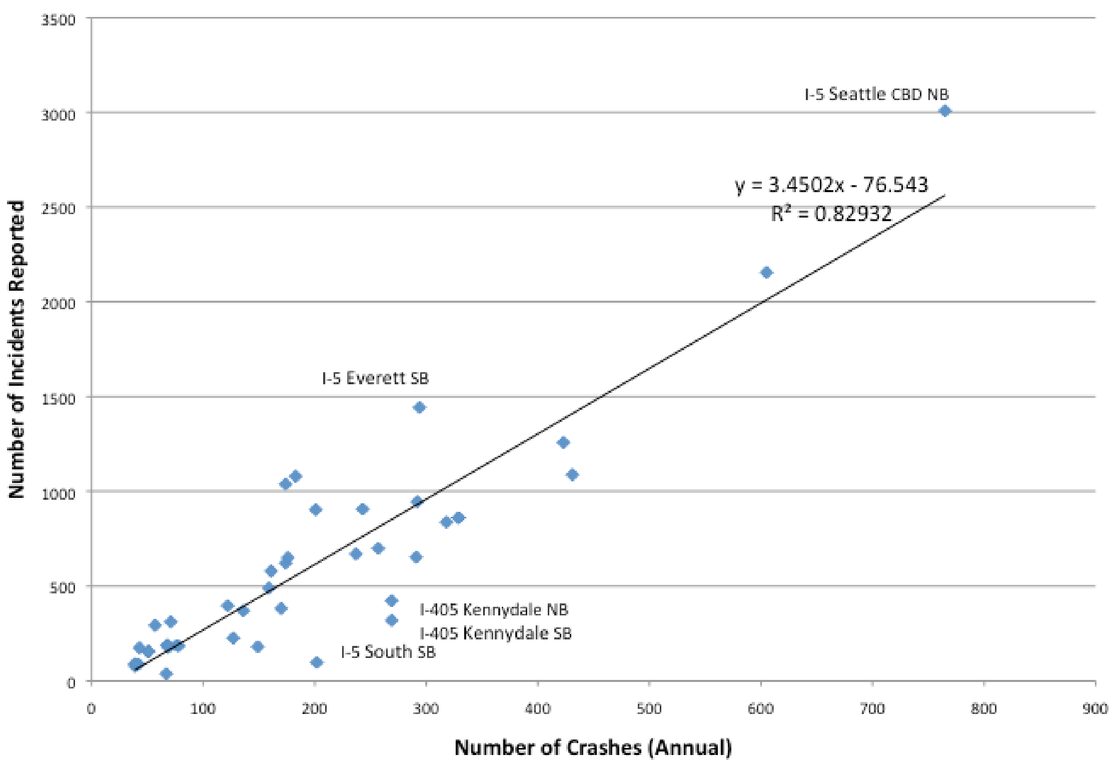


**Figure 5: Relationship of Annual Number of Crashes to Annual Reported Number of Incidents**

**The Value (Cost) of Delay**

To compare the value of delay savings achieved through the incident response process with the cost of providing those incident response services, it was necessary to convert time savings to dollar values. Dollar values per vehicle minute of delay were based on values of time previously developed by WSDOT[15], which are $21.90 per hour for passenger cars and $57.40 for trucks (comprising a mix of heavy and medium duty vehicles). In addition, it was assumed that trucks make up 10 percent of the traffic stream. This value was obtained by selecting a representative value from the truck percentages for Puget Sound freeways listed in WSDOT's Annual Traffic Report.

[15] Assessing Cost of Travel Annual Update, by the Urban Planning Office and Freight Office, WSDOT, April 2009, internal WSDOT document

# FINDINGS

This chapter presents the results of the analytical tests described in the previous chapter.

## THE CAUSES OF CONGESTION

This set of analyses examined the amount and percentage of delay caused by crashes, incidents, and other traffic disruptions. The intent was to develop a better understanding of the size of the problem and the scope of potential benefits that could be obtained from incident response in the Puget Sound region.

Congestion occurs where there is too much volume and too little roadway capacity. This can occur because

- traffic demand is too great for the designed roadway capacity, or
- some disruption reduces functional roadway capacity (supply) to levels below demand that would otherwise flow unimpeded on that roadway segment.

Demand varies both as a result of travel patterns that tend to repeat themselves (e.g., time of day, day of week, seasonal patterns) and as a result of unusual activity patterns that cause larger than normal numbers of travelers to use a roadway at a given time. These changes in activity patterns can be caused by planned events such, as a major sports game, or unplanned events, such as vehicles diverting to one roadway in order to avoid congestion on another roadway.

Functional roadway capacity (supply) can vary as a result of a variety of factors, including weather, the effects of traffic management strategies (work zones, the application of different traffic control plans), and a variety of traffic incidents that disrupt the normal operations of a roadway.

This combination of supply and demand effects are generally categorized into seven categories, known as "the seven sources of congestion":

- traffic incidents
- weather
- work zones
- fluctuations in demand
- special events
- traffic control devices
- bottlenecks/inadequate base capacity.

These factors interact in the formation of congestion, and the relative importance of any one of these factors varies from location to location.

In many rural areas, demand is routinely low relative to roadway capacity. Consequently, delay happens only when major disruptions to the roadway occur, usually as a result of bad weather (e.g., snow), a major traffic incident, or reductions in roadway capacity due to road construction and maintenance activities.

In other rural areas, especially those that experience recreational traffic flows, large and somewhat predictable traffic surges create traffic congestion during times of peak demand. Similarly, in suburban and urban areas, traffic flows associated with work and other common activities often reach levels that routinely push traffic demand beyond available roadway capacity, creating routine congestion. In both of these cases, a base level of congestion exists, however, a large percentage increase in congestion can occur on top of that base congestion as a result of a disruption in roadway operations, especially when that disruption occurs during times of high traffic volumes.

Lastly, in larger urban areas, traffic can routinely exceed roadway capacity for many hours each work day. In these areas, many roads operate near capacity for many additional hours of the day. Roadway disruptions on these roads can add large amounts of delay, but that added delay may be only a modest percentage increase in total annual delay. (In simple terms, routine congestion may have already slowed down traffic, so that a fender-bender in the existing queue slows vehicles only a little more because they were already moving slowly.)

Table 1 summarizes the amount of delay influenced by each type of disruption tracked in this study. "Percentage of delay" was computed by totaling all vehicle hours of delay in the region associated with each of the types of disruptions and then dividing by the sum of all measured delays. This computation automatically weighted the delays experienced by each roadway on the basis of the relative amount of VHT occurring within that roadway section. (In Table 1, delays that occurred when more than one type of disruption influenced the size and scope of the delay are counted in each of the categories of disruption; therefore, the percentages total to more than 100.)

**Table 1: Percentage of Delay by Type of Disruption Influencing Congestion**[16]

| Causes of Congestion<br>Ongoing Disruptions That Influence Congestion Duration and Severity | Percentage of Delay |
|---|---|
| Incidents | 38.5% |
| Crashes | 19.5% |
| Bad Weather (Rain) | 17.7% |
| Construction[17] | 1.2% |
| No Cause Indicated (mostly volume) | 42.2% |

Taken at face value, this simple summary table supports the commonly heard statement that "incidents and crashes cause between 40 and 60 percent of all delay." In

[16] Delays that occurred when more than one type of disruption influenced the size and scope of the delay are counted in each of the categories of disruption, and therefore, the percentages total to more than 100

[17] "Construction delays" do not include any delays caused where general roadway capacity was reduced by temporarily narrowed or reconfigured lanes. They include only when construction activity took place along the roadway.

reality, a considerable portion of the delay associated with the incidents and crashes included in Table 1 was also at least partially “caused” by large traffic volumes. At the same time, as will be discussed below, limitations in our data and analytical processes suggest that a number of “incidents” are not effectively recorded or identified, and therefore, a percentage of the “no cause” congestion in Table 1 was also caused by incidents of various kinds.

Also of interest in Table 1 is the fact that rain had almost as much influence over congestion as vehicle crashes. Not surprisingly, construction (defined as lane closures during active construction or maintenance activity) had the least influence on congestion formation. The number associated with construction is small in large part because construction closures are allowed to occur on urban area freeways only during the late night hours, when volumes are low. Therefore, even when congestion (measured in terms of either the queue length or the amount of time an individual spends in that queue) is significant as a result of construction lane closures, total vehicle delay (vehicle-hours) is small relative to the amount of delay experienced in the peak periods, when volumes are high.

One type of construction delay not included in Table 1 was delay caused by the temporary geometric changes (narrowed lane widths, lane shifts) that are commonly required during many urban freeway construction activities. These geometric restrictions likely cause congestion to form earlier and last longer than it would with the roadway’s normal geometry. However, the project team did not attempt to establish when these semi-permanent geometric conditions were implemented, nor did we attempt to associate delays with these changes during non-closure hours (e.g., AM and PM peak periods).

The "no cause" category in Table 1 means that no cause of congestion was reported other than high traffic volume levels. The project team examined a number of these conditions as case studies. It was clear from that review that a variety of disruptions affect traffic flow, but they are not recorded within conventional traffic operations databases. Many of these disruptions are visual distractions (e.g., boats on the lake, sunshine slowdowns) that cause measurable delays only when traffic volumes are relatively high. In some of the case study investigations, traffic volumes on the study corridor were abnormally high because of disruptions on parallel roadways. This analysis did not attempt to track route diversion onto parallel roadways and therefore, was not able to associate congestion on one roadway with disruptions occurring on a second roadway.

Table 2 shows a more disaggregated version of Table 1 in that it tracks multiple disruptions occurring at the same time. Table 2 also illustrates the wide variation among the 42 study sections in the percentage of delay influenced by any given cause (e.g., incident-influenced queues may have been much more prevalent at one study site than at another) by presenting the maximum and minimum values observed for each combination of delay causes.

Table 3 shows the total amount of vehicle-hours of delay measured[18] in the test database for each of the 42 corridors examined and the percentage of that delay not associated with an identified traffic disruption (crash, reported incident, bad weather, or construction). In general, the roadway corridors with the highest percentage of delay

[18] Note that the northbound I-405 data sets were missing about 1.5 months of data (mostly from November and December), while other corridors periodically missed days or weeks of data as a result of a variety of data quality/availability issues. This means that the total measured delay was not the true annual delay for the region's freeways. However, the missing data should have only a marginal effect on the percentages of delay associated with different types of disruptions.

attributed to "unknown causes" tended to be those with the least absolute vehicle delay. That is, nine of the ten sections with the highest percentage of delay not caused, at least in part, by a known traffic disruption were among the 13 sections with the lowest total vehicle delay for the year.

**Table 2: Percentage of Delay by Type of Disruption Influencing That Congestion**

| Causes of Congestion<br>Ongoing Disruptions That Influence Congestion Duration and Severity | Percentage of Delay | Maximum Percent Within a Corridor | Minimum Percent Within a Corridor |
|---|---|---|---|
| No cause indicated | 37.1% | 74.2% | 14.3% |
| Incident-influenced queues are present | 23.9% | 48.2% | 1.0% |
| Crash-influenced queues are present | 6.0% | 25.3% | 1.7% |
| Rain is present | 8.4% | 25.8% | 2.0% |
| Both a crash and an incident have influenced queues that are present | 9.2% | 23.9% | 0.5% |
| Both rain and an incident have influenced queues that are present | 5.0% | 8.9% | 0.0% |
| Both rain and a crash have influenced queues that are present | 1.6% | 8.7% | 0.2% |
| Rain, a crash, and an incident have influenced queues that are present | 2.4% | 13.6% | 0.0% |
| Queues from a ramp—cause unknown—have influenced mainline queues | 5.1% | 37.3% | 0.0% |
| Construction activity has influenced queues | 0.6% | 16.2% | 0.0% |
| Construction and queues from a ramp—cause unknown—have influenced mainline queues | 0.0% | 0.2% | 0.0% |
| Construction and an incident have influenced queues present | 0.2% | 2.6% | 0.0% |
| Construction and a crash have influenced queues present | 0.1% | 1.4% | 0.0% |
| Construction and rain have influenced queues | 0.1% | 4.6% | 0.0% |
| A crash, an incident, and construction have influenced queues that are present | 0.1% | 1.2% | 0.0% |
| Construction, rain, and an incident have influenced queues that are present | 0.0% | 0.5% | 0.0% |
| Construction, rain, and a crash have influenced queues that are present | 0.0% | 0.7% | 0.0% |

**Table 3: Hours of Delay versus Percentage of Delay without a Known Type of Disruption**

| Corridor | Vehicle-Hours of Delay | Percentage of Delay Not Associated with a Disruption |
|---|---|---|
| I-5 Seattle CBD Northbound | 28,689,099 | 14.3% |
| I-5 Seattle North Southbound | 19,828,935 | 23.1% |
| I-5 South Southbound | 14,063,546 | 27.7% |
| I-5 Seattle CBD Southbound | 12,997,924 | 21.5% |
| SR 520 Seattle-Bridge Westbound | 12,901,102 | 43.3% |
| I-405 Kennydale Northbound | 11,531,897 | 55.3% |
| I-405 Bellevue Southbound | 11,345,712 | 20.8% |
| I-405 Kennydale Southbound | 11,077,760 | 56.9% |
| I-5 North King County Southbound | 10,782,330 | 45.2% |
| I-5 South Northbound | 10,441,430 | 41.6% |
| I-405 Kirkland Southbound | 9,655,929 | 34.0% |
| I-405 Kirkland Northbound | 9,651,791 | 24.4% |
| I-405 North Southbound | 9,116,178 | 44.2% |
| I-5 Lynnwood Southbound | 8,517,553 | 39.8% |
| I-5 Lynnwood Northbound | 7,733,702 | 53.5% |
| SR 520 Seattle-Bridge Eastbound | 6,445,475 | 29.6% |
| I-5 North King Northbound | 6,020,659 | 22.6% |
| I-5 Tukwila Northbound | 5,997,528 | 42.5% |
| I-90 Bridge Westbound | 5,310,825 | 57.3% |
| SR 167 Renton Northbound | 4,980,431 | 28.0% |
| SR 167 Renton Southbound | 4,582,608 | 58.3% |
| I-5 Seattle North Northbound | 4,399,711 | 35.9% |
| I-405 North Northbound | 4,327,382 | 56.4% |
| I-405 South Northbound | 4,091,618 | 61.8% |
| I-5 Tukwila Southbound | 3,863,679 | 45.1% |
| I-5 Everett Northbound | 3,838,909 | 33.0% |
| I-405 Bellevue Northbound | 3,773,393 | 52.0% |
| I-90 Bridge Eastbound | 3,744,002 | 17.2% |
| SR 520 Redmond Eastbound | 3,307,029 | 36.2% |
| SR 167 Auburn Southbound | 3,305,901 | 59.9% |
| I-90 Issaquah Westbound | 3,229,088 | 73.4% |
| I-405 Eastgate Southbound | 2,861,851 | 64.8% |
| I-405 South Southbound | 2,740,581 | 74.2% |
| SR 167 Auburn Northbound | 2,167,614 | 73.0% |
| I-90 Seattle Eastbound | 1,738,429 | 65.6% |
| I-405 Eastgate Northbound | 1,715,306 | 64.4% |
| I-90 Bellevue Westbound | 1,705,939 | 30.6% |
| SR 520 Redmond Westbound | 1,399,767 | 19.7% |
| I-5 Everett Southbound | 915,200 | 41.2% |
| I-90 Bellevue Eastbound | 519,902 | 66.1% |
| I-90 Seattle Westbound | 454,026 | 40.8% |
| I-90 Issaquah Eastbound | 256,341 | 63.5% |

The converse of this statement was not true. While the two test sections with the most vehicle-hours of delay did have fairly low percentages of delay not associated with known disruptions, only half of the ten test sections with the highest vehicle delay were among the ten sections with the lowest percentage of congestion influenced by an unspecified disruption. The sections with both very large amounts of total vehicle delay and large amounts of delay caused by unknown disruptions were all where frequent, significant peak period delays occurred. For example, the roadway sections that contained the SR 520 floating bridge and Kennydale Hill on I-405 (both directions for both corridors) operated near or above capacity for 10 to 14 hours per day. Two I-5 sections that had these characteristics (the South section northbound and North King County section southbound) both experienced routine AM peak congestion. Consequently, it is reasonable to assume that large amounts of the delay in these corridors were simply caused by too much peak period volume.

The percentage of delay occurring with no reported disruption was also compared with the AM and PM peak period travel rates[19] for each corridor. No correlation between these values was apparent.

This lack of correlation between different measures of congestion and the amount of delay without a known disruption was not expected at the outset of this analysis. It had been assumed that most of the delay without an observable cause was primarily due to too much traffic volume. The expectation was that highly congested locations, especially those with well known geographic bottlenecks, would have the most delay with unspecified causes because the congestion would be caused by a combination of

[19] AM and PM peak period travel rates are defined as the mean travel time for the peak period converted to units of minutes per mile

volume and roadway geometry-based capacity limitations. Test sections with lower levels of routine delay were expected to have higher percentages of delays with identified disruptions, as delay would exist on those road segments primarily when unusual events occurred.

In addition to simple volume/capacity issues, further analysis of the study corridors identified at least three major reasons for delay occurring without disruptions being present:

1) Operating agencies simply do not record many of the disruptions that occur, especially on less congested corridors and during less congested periods (weekends, at night).
2) In several cases the research team's analytical approaches did not adequately track all of the disruptions that occurred, given the data available to indicate when and where those disruptions actually happened. (Some of these limitations are explained below.)
3) Even on Seattle's less congested urban freeway segments that do not have major geometric bottlenecks, volume is frequently sufficient to cause at least modest amounts of delay.

In addition, because total delay values are small, these types of "no cause" delays can represent a fairly high percentage of total annual delay.

These conclusions were supported by several case study examinations of the various study corridors.

One such case study was performed on the I-90 Issaquah eastbound roadway section. This roadway segment had the lowest measured annual delay of all 42 segments studied for this project. Only 256,000 vehicle-hours of delay were measured in 2006, and 63.5 percent of that delay was not associated with an identified disruption.

The roadway segment experienced two major delay-causing events in November 2006 that were not identified by the analysis methods described earlier in this report. One of those events was a snow storm. The second was a major truck accident. A special analysis of the snow event determined that roughly 5.9 percent of all delay measured for the year—for this section of roadway—occurred during that event. Yet because the snow stopped falling (at least at the weather station from which data were obtained) several hours before congestion started on this freeway segment, the congestion delays recorded were not associated with that weather phenomenon. (A review of newspaper stories published the next morning confirmed that massive problems occurred that night on that roadway section and that they were snow related. Additional discussion of the difficulty in analyzing snow-related delays is presented later in this report.)

On a second day in November, an accident involving a truck killed the driver of a passenger car on I-90. That accident was not listed in either the state accident database or the WSDOT WITS database.[20] It is not clear why. (Again, information on the accident was obtained from newspaper reports.) It is clear from the database that travel times were significantly affected, as would be expected with both an accident involving a truck and with the time and lane closures required to investigate a fatal accident. While some delays on that day were associated with rain, the majority of delay was not associated with any disruption. Thus, another 5.1 percent of all annual delay (8.1 percent of delay

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[20] The newspaper indicated that the crash occurred in the westbound lanes of I-90 at 10:38 in the morning west of Front Street. That is on the eastern end (but within the boundaries) of the I-90 Issaquah test section. While the crash occurred in the direction opposite of the I-90 Issaquah eastbound roadway section examined in the case study, the eastbound section reported far larger delays than the westbound section after 10:30 in the morning. This may have been due to the location of the crash, which likely caused much of the westbound queue to form east of the monitored portion of the roadway. In addition, the eastbound delays were likely primarily "rubbernecking" delays, although some response equipment may have been parked on the eastbound section of the roadway.

not associated with a disruption) was erroneously attributed to no cause other than volume.

Consequently, for this roadway section, of the 63.5 percent of delay "not associated with a disruption," 11.0 percent was actually associated with just two events, leaving at most 53 percent caused only by too much traffic volume.

Similar case study analyses of significant but unexplained delays were undertaken on more congested road segments. One of the most congested segments in the region is the westbound section of SR 520 as it crosses Lake Washington from Bellevue to Seattle. This segment experiences over 50 times the annual delay experienced on the I-90 Issaquah section discussed above. The SR 520 bridge operates near or over capacity for 13 to 14 hours every weekday. It is parallel to another cross-lake bridge (the I-90 bridge, located to the south of SR 520), which is close enough so that motorists can easily divert between the two when one of them experiences heavy congestion.

Each August, a major hydroplane race takes place on Lake Washington, south of the I-90 bridge. During the weekend when the race happens, the U.S. Navy's Blue Angels flying team also performs an air show in between hydroplane race heats. The Blue Angels practice their routine, during the day, on the Thursday and Friday preceding the air show. During the times when the Blue Angels practice or perform their show, the I-90 bridge is closed to traffic.

Not surprisingly, considerable delay occurs that week across the two bridges. Much of that delay is caused by the visual distraction of pleasure boats on the lake going to and from the race course, and by airplanes flying low overhead. In addition, because the I-90 bridge is closed to traffic during the Blue Angel flights, considerable traffic diverts to the SR 520 bridge. This results in the "perfect storm" for creating congestion on SR 520, much of which is not related to a specific disruption on SR 520. The "disruption" (as noted in variable message sign records) is on I-90.

In 2006, on the Thursday prior to the hydroplane races, westbound SR 520 did not experience any major disruptions (i.e., recorded construction, lane closures, crashes, or rain). However, it did experience 117,000 vehicle-hours of delay (roughly half the total annual delay of the I-90 Issaquah Eastbound test section). About half of that delay was not associated with a disruption in the analysis database, and that value was over 2.5 times the usual "uninfluenced" Thursday delay. It was obvious from a manual review of the data that these delays were caused by excessive demand due to the 2-hour closure of the I-90 bridge combined with a high level of visual distraction for motorists crossing the lake. However, because the delays routinely experienced on this section of roadway are so high, this "very bad day" for travel on this section of roadway contributed only 0.9 percent of the total annual delay for this test section, and therefore, the large "not influenced" delay for that day was less than 0.5 percent of the annual total.

Taken together, these case studies illustrated that a large percentage of the congestion in the analysis data set without a "cause" could be traced back to some type of unusual occurrence. However, because of limitations in both the analysis data set and the methodology used to associate delays to specific events, this analysis was not able to reliably identify all of those congestion sources. Consequently, three conclusions are drawn from the above examples:

1) The statistics presented in this report should be assumed to be a very conservative estimate of the amount of delay caused by the various types of disruptions.

2) The percentage of delay caused by any given factor can be a misleading statistic about the importance of that factor, since it is highly correlated to the total amount of delay on a given roadway.
3) In the presence of moderately heavy volumes, a large number of factors that are not tracked by operating agencies may be the cause of congestion.

## THE INFLUENCE OF VOLUME ON TRAVEL TIME IMPACTS CAUSED BY DISRUPTIONS

One factor that quickly became clear in the analysis of congestion was that in most cases, traffic volume is a major contributing factor to congestion. In some cases incidents cause congestion where moderate volumes exist but congestion would otherwise not occur. In other cases, incidents take place during peak periods, exacerbating congestion that already exists due to too much volume for a given roadway segment. Figure 6 illustrates the interplay of the effects of incidents, bad weather, and traffic volume on travel times on I-5 northbound heading toward downtown Seattle. This graph shows that congestion forms only as traffic volumes peak. It also shows that the resulting congestion lowers observed throughput while increasing travel times. Finally, it illustrates how all types of disruptions to normal roadway performance (rain, crashes, non-crash incidents) cause congestion to start earlier and last longer during the peak period, increasing travel times during the normally congested times periods.

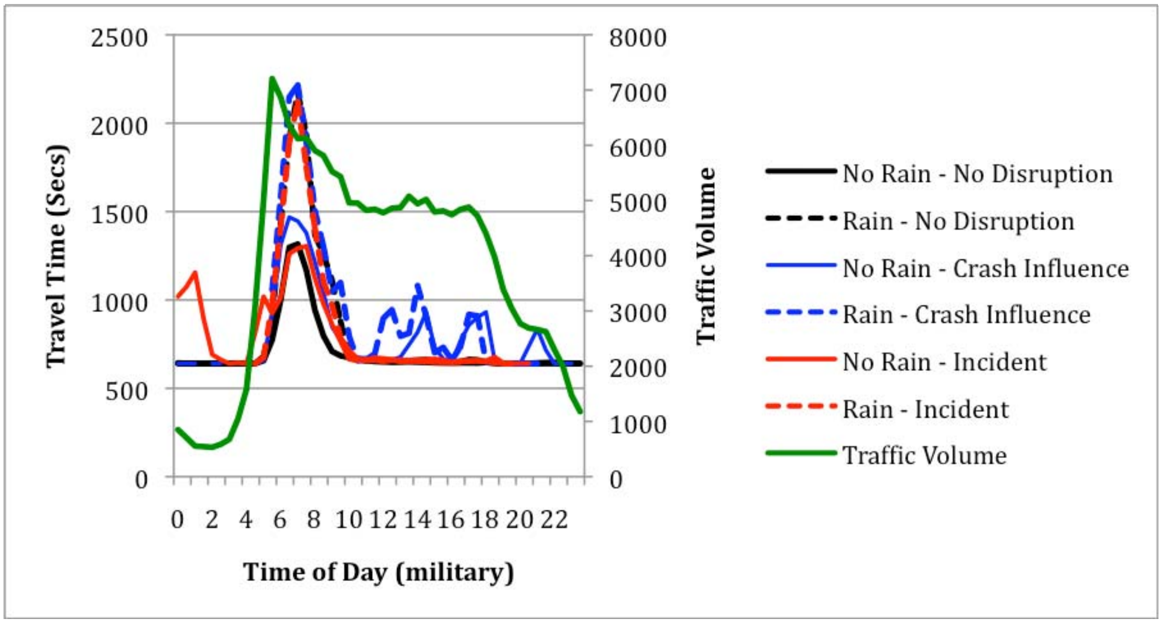


**Figure 6: Average Travel Times on I-5 Given Disruptions and Traffic Volume Northbound South Section**

Incidents and other disruptions can also cause congestion to form during times of the day that are normally free from congestion. However, congestion only forms when the disruption lowers functional capacity below traffic demand. Therefore, as seen in Figure 6 on this section of I-5, minor disruptions such as rain or non-crash incidents generally did not cause congestion in the mid-day or the evening peak period (the off-peak direction) on this section of roadway. For this four-lane freeway section, sufficient unused capacity existed during those periods that modest disruptions to roadway capacity did not cause congestion. However, some crashes caused sufficient disruption to create congestion during those off-peak periods. Late at night, because construction activity was taking place along this roadway segment, even smaller incidents—combined with those construction lane closures—caused congestion to form.

Thus volume—relative to roadway capacity—is a key component of congestion formation, and in urban areas it is likely the primary source of congestion. Disruptions then significantly increase the delay that the basic volume condition creates.

The fact that traffic volume is the basis of congestion also informs how various traffic disruptions affect travel patterns. Not only does the background traffic volume affect whether a specific incident causes congestion, but it affects how long that congestion lasts once the primary incident has been cleared. The Seattle data showed that in the morning peak, traffic disruptions that occur (and are cleared) before the peak generally have only a modest effect on congestion, whereas disruptions during the peak often have a noticeable effect that significantly extends how long peak period congestion lasts. Conversely, in the afternoon peak, disruptions that occur prior to the start of the peak can cause significant travel time changes well before the start of the traditional peak period. But as long as the disruption has been cleared, most congestion ends at a time that is very close to when congestion would normally dissipate.

Figures 6 (above) and 7 (below) illustrate these trends by showing the mean travel times that occur under different disruption conditions. In both of these graphs, it is also possible to observe that crashes can cause enough of a reduction in roadway capacity that congestion forms even off-peak.

The volume lines in figures 6 and 7 explain why incidents affect congestion differently in the AM and PM peak periods. Very early in the AM peak period, insufficient volume exists to cause congestion to form. Once volumes grow, disruptions (incidents/rain) either cause congestion to form or make existing congestion worse.

Then, because midday volumes are still fairly high, residual queues from the AM peak can take a long time to clear.

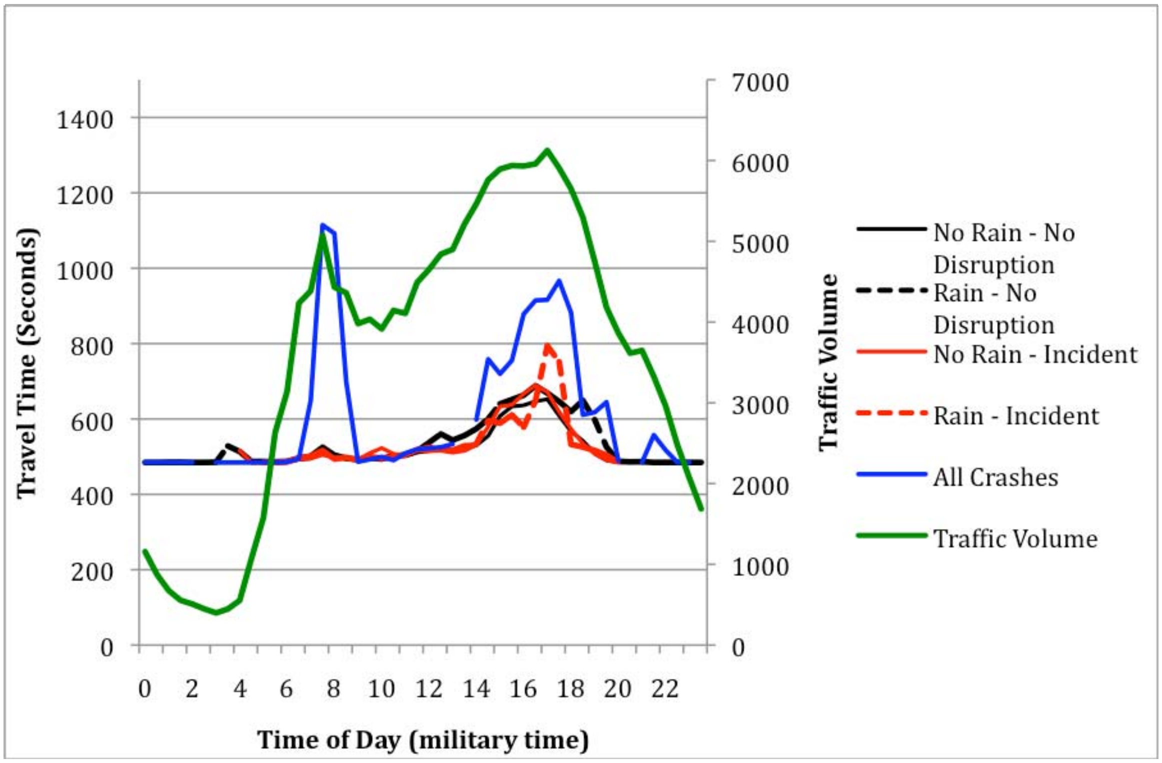


**Figure 7: Travel Times on I-5 Given Disruptions and Traffic Volume Northbound Lynnwood Section**

In the PM, those same fairly high midday volumes (especially for corridors experiencing peak direction movements) mean that even small disruptions are likely to cause congestion before the normal start of the PM peak period. But even though queues grow larger than usual during those peak periods, the sharp decline in traffic volumes at the end of the PM peak means that those queues tend to dissipate quickly at the end of the peak period—as long as the disruption has been cleared.

While results varied dramatically among study sections, if the results of all 42 study sections are simply averaged, in the morning, a crash occurring during the AM peak period would add an average of 2 hours and 17 minutes to the duration of the morning's peak period congestion. In the PM, peak, the fact that a crash occurred on a study section would add only adds 33 minutes to the time when congestion could be expected to clear. Similarly, a non-crash incident would add 1 hour and 14 minutes to the morning peak, whereas in the PM only 10 minutes would be added to the time that congestion could be expected to last.

As seen in Figure 6, travel times also generally increased within the peak period when disruptions occurred to normal freeway flow. On average, AM peak (6:30 to 9:30 AM) travel times increased in test corridors that experienced even modest AM peak period congestion by 17 percent when non-crash incidents occurred. Non-crash incidents increased PM peak (3:00 to 7:00 PM) travel times an average of 21 percent on those corridors experiencing any routine PM peak congestion. In both the AM and PM peaks, crashes added roughly 40 percent to the expected travel times.

These effects varied significantly from corridor to corridor, depending on the nature of the traffic volumes and routine congestion patterns. They also changed dramatically within any given corridor depending on the size, duration, and timing of the disruption. Interestingly, $80^{th}$ and $95^{th}$ percentile travel times were less affected by non-crash incidents, whereas crashes generally had significant impacts on both of these performance measures. This is not surprising because non-crash incidents tend to be smaller disruptions and, consequently, have less of an impact on those very bad days when congestion is at its worse, whereas crashes are often one of the contributing factors to very bad commute days.

## THE SIGNIFICANCE OF CRASH- AND INCIDENT-INDUCED TRAFFIC DELAY

This set of analyses examined the amount and percentage of delay caused by crashes and incidents in general. The intent was to develop a better understanding of the size of the problem and scope of potential benefits that could be obtained from incident response in the Puget Sound region. These analyses differed from those presented above in that they were designed to specifically remove recurring congestion (i.e., congestion caused by routinely occurring traffic volumes) from the delay statistics associated with incidents and crashes.

**For the 2006 study year, a conservative estimate is that crashes and other traffic incidents (including disabled vehicles, debris, and other events requiring WSDOT intervention to remove hazards) caused travelers to experience 5,300,000 vehicle-hours of delay, in addition to typical congestion delay, on the Puget Sound region's freeway system**.[21] That is roughly 30 percent of the total delay from all causes that occurred on these roadways. Of those incidents, 1,385,000 vehicle-hours of delay were caused by incidents that closed at least one lane. Approximately 11 percent of the total delay (1,950,000 veh-hrs) was the result of reported vehicle crashes.

These same disruptions also geographically transferred delay from one group of travelers to another. However, this study did not estimate the amount of delay transferred from one set of travelers to another. An example of such a transfer is as follows: if a crash occurs in the morning commute period on I-5 southbound near Northgate, the bottleneck created at that location allows I-5 at the Ship Canal, south of Northgate and

[21] The study area included I-5 from SR 526 in the north to S. 320th in Federal Way in the south; all of I-90 west of milepost 19.5, which is east of Front Street in Issaquah; all of I-405; SR 167 from I-405 to SR 18; and all of SR 520.

which normally experiences a certain level of commute-related congestion, to flow better than it would have had the crash not occurred. Thus, travelers who enter the freeway south of Northgate get a faster than expected trip, while travelers north of Northgate are stuck in a worse than normal back-up—both circumstances "caused" by the crash—and delay is "transferred" from south of Northgate to north of Northgate.

Traditional incident delay calculations compute location-specific delay, which includes delay that has been transferred from elsewhere, and do not consider the time "savings" elsewhere that are also related to the incident. In the example, they would measure the delay that occurred north of Northgate but not consider the decrease in delay that occurred south of the incident. Those calculations also assign all of the delay to the incident, rather than calculating how much is from already existing congestion and how much is added by the incident. In contrast, the calculations developed in this project subtract the "benefit" that occurs in one location from the related delay at the incident site, as well as subtract the recurring delay from the total delay, thus obtaining the incident-"caused" delay. This is a different delay measure than the incident delay statistics computed by most scholarly work to date, but the project team believes it is the appropriate measure for estimating the *regional* delay benefits that can be achieved through better incident response.

## THE EFFECTS OF INCIDENT DURATION ON CONGESTION AND DELAY

It is not possible, given current technology, to eliminate all crashes and other incidents. Consequently, incident response is designed to reduce the impacts of the incidents and crashes that do occur. It does this by reducing the duration of those events, the implication being that reducing the duration of an incident will reduce the delays associated with that incident. This section describes the relationship between benefits that can be obtained (in minutes of delay saved) and the duration of incidents.

As noted above, incidents, including crashes, do not, in and of themselves, cause measureable delay. *They cause delay only when the disruption they create causes functional capacity to fall below actual demand*. Therefore, the impact of any given incident is not constant but is a function of where it occurs, when it occurs, and the traffic demand relative to functional roadway capacity at the time it occurs.

At low volumes, even modestly large incidents may create no measurable delay (except for the "rubbernecking slow down" equal to a few seconds as vehicles pass the scene). At moderate volumes (relative to roadway capacity), moderately large incidents lower functional roadway capacity to the point at which queues form, creating significant, measurable congestion. As volumes begin to approach functional capacity, even small incidents can create queuing and a dramatic increase in congestion. However, if volumes have grown to the point at which congestion has already formed, even moderately sized incidents create only a minor increase in the existing congestion. In this last case, the functional capacity of the roadway has already decreased because of the volume-based congestion. Therefore, the incident reduces that functional capacity only slightly more, resulting in only a small increase in congestion. Crashes and other major incidents can cause significant increases in delay during these conditions because they generally reduce functional capacity substantially below simple over-saturated flow capacity.

Once a queue forms—regardless of why—the maximum functional capacity of the roadway is governed by the capacity of the roadway at that queue, which is lower than the capacity under free flow conditions. That queue—and the resulting congestion delay—will remain until the volume approaching the back of the queue drops low enough to allow the queue to dissipate.

As a result, a queue that forms because of an incident that occurs just before the start of a peak period will remain throughout the peak period. It will only dissipate when volumes drop at the end of the peak period, even if the original cause of the queue (the incident) has been cleared. Because of the incident, the queue that would normally have been present during the peak period forms earlier than normal, consequently contains more vehicles than normal, and therefore lasts longer than normal, adding to the delay experienced throughout the peak period.

When volumes are moderate (e.g., outside of the peak periods), the clearance of an incident results in very quick dissipation of the queue it has caused.

However, in both cases, the longer the disruption (incident) lasts, the larger the queue that forms; the longer the queue, the more time that queue will take to dissipate; consequently, the greater the total delay that is created by the incident.

Because of the complex interaction among incident size, duration, traffic volume, and roadway capacity, there is no simple relationship that defines the amount of delay caused by an incident of any specific length. However, for planning and programming purposes, such a value is important. This project determined that growth in delay is roughly linear to the duration of an incident.

This finding was developed from queuing analysis, which explored the effect on queue size and duration of incidents of different sizes and durations (where an "incident" was defined as a given decrease in capacity). Queue size and duration were used as surrogates for vehicle delay. Figure 8 shows the result of a series of these tests, including tests of an incident that is contained on the shoulder and causes only a visual distraction, an incident that blocks one lane, and an incident that blocks two lanes. These incidents were examined occurring off-peak, just before the peak, and mid-way through the peak period.

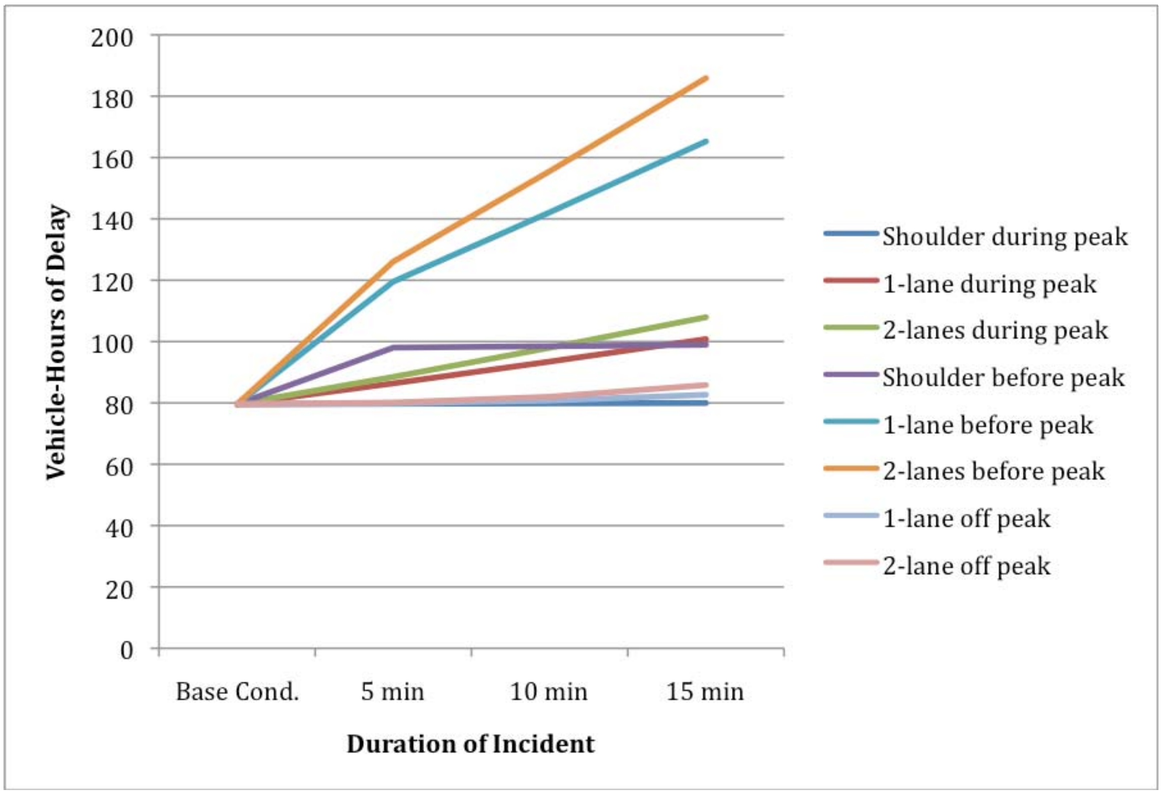


**Figure 8: Changes in Vehicle Delay for Different Incident Blockage Sizes and Durations, Three-Lane Freeway Section**

What can be seen in Figure 8 is that if the incident happens just before the formation of peak period congestion formation, and the incident queue does not dissipate before the formation of peak period congestion, the "added" incident congestion creates an initial asymptotic jump in congestion formation. However, once congestion has formed, the delay relationship increases essentially linearly in relation to the duration of the incident. For incidents that do not affect peak period congestion at all or that occur during the peak, only the linear increase is present. This basic linear[22] relationship remains constant despite modest variations in input traffic volumes that occur over the life of the incident queue. What does change, depending on the size of the incident blockage and the background traffic volume, is the slope of that linear relationship. This same basic linear relationship is present for all sizes of roadway (e.g., two-lane versus three- or four-lane facilities), different traffic volumes, and most[23] incident durations.

Because this relationship is so consistent, dividing the total vehicle delay that incidents add to travel in the Puget Sound region by the total duration of those incidents provides a reasonable measure of the "average delay added per minute of incident." This relationship can then be used to estimate the time savings (in vehicle-hours) that could be gained if "the average incident" could be reduced in duration.

Note that this statistic is a poor estimator of the delay associated with any specific incident. Such a value could be more accurately computed by examining the actual traffic volume at that location, relative to the roadway capacity at that time, and the size of the "blockage" caused by that incident. However, for a general statistic applicable regionwide, none of these basic pieces of information is available. Therefore, this average value is a good unit estimator.

Because the WITS data contains statistics that describe the duration of incidents in the Puget Sound region, and those incidents could be used to identify the added congestion caused by those incidents (the added delay is provided earlier in this chapter),

[22] The relationship is not perfectly linear, but the linear approximation works very well statistically, except for the asymptotic start to the delay function.
[23] Only for extremely long incidents, when starting and ending traffic volume conditions are very different from each other, does this relationship not hold.

it was possible to compute the average delay per minute of incident. WITS also records which incidents close lanes. It was therefore possible to calculate these same two basic statistics for amount of delay caused by lane closing incidents and the total duration of lane closures. This allowed the computation of the average delay per minute of lane closure.

WITS reported 5,463 hours of active incidents in 2006. Of those, 1,700 involved lane closures. Unfortunately, WITS staff do not respond to all vehicle crashes, so it was not possible to determine how long those crashes remained on the roadway. To provide a simple estimate, the research team assumed that crashes were present for 20 minutes at the roadside. While this figure probably underestimates the duration of many crashes, especially those occurring outside of the peak periods, many crashes that occur outside of the peaks create relatively little congestion. Further study is needed to more accurately determine a better crash duration statistic, but the 20-minute value provides an initial baseline value for use by WSDOT.

Using these figures and the delay statistics presented above, it was possible to compute the average delay per minute of incident or crash. These are as follows:

- The average incident that does not involve a lane closure results in 576 vehicle-minutes of delay per minute that the incident is present.
- If the incident closes a lane, the effect of that lane closure results in 814 vehicle-minutes of delay per minute of incident.
- A crash causes 676 vehicle-minutes of delay per minute while that crash is present on the roadside.

Note that because these are average figures, they will significantly underestimate the delay created by an incident in heavy volume conditions and significantly overestimate the delay in low volume conditions. Table 4 shows how dramatically these values change from study segment to study segment.

**Table 4: Differences in the Average Delay per Minute of Incidents for Different Roadway Segments**

| Corridor | Delay Minutes / Minute of Incident | Delay Minutes / Minute of Closure |
|---|---|---|
| I-90 Issaquah EB | 10 | 0 |
| I-90 Bellevue EB | 15 | 39 |
| I-5 Everett SB | 63 | 61 |
| I-90 Issaquah WB | 85 | 53 |
| I-405 North NB | 95 | 268 |
| SR 167 Auburn NB | 139 | 117 |
| I-405 Eastgate NB | 157 | 196 |
| SR 520 Redmond EB | 166 | 311 |
| I-5 N Seattle NB | 185 | 542 |
| I-405 South SB | 210 | 225 |
| I-405 Eastgate SB | 234 | 237 |
| I-5 Seattle CBD NB | 256 | 473 |
| I-90 Seattle WB | 322 | 30 |
| I-5 Everett NB | 323 | 805 |
| I-90 Bellevue WB | 385 | 268 |
| I-405 South NB | 417 | 394 |
| I-405 Kirkland SB | 419 | 812 |
| I-405 Bellevue NB | 420 | 513 |
| I-5 Seattle CBD SB | 433 | 743 |
| I-5 N King NB | 445 | 1220 |
| I-5 Tukwila SB | 464 | 507 |
| SR 167 Auburn SB | 486 | 521 |
| SR 520 Seattle EB | 494 | 811 |
| I-5 South NB | 516 | 960 |
| I-405 Kirkland NB | 551 | 1277 |
| I-90 Bridge WB | 553 | 385 |
| I-90 Seattle EB | 565 | 249 |
| I-5 Lynnwood NB | 609 | 980 |
| I-5 Tukwila NB | 638 | 811 |
| I-405 North SB | 655 | 982 |
| I-5 Lynnwood SB | 682 | 1355 |

| | | |
|---|---|---|
| I-405 Kennydale SB | 782 | 996 |
| SR 167 Renton SB | 824 | 275 |
| I-90 Bridge EB | 831 | 656 |
| I-5 N King SB | 871 | 852 |
| SR 520 Seattle WB | 900 | 1296 |
| I-405 Kennydale NB | 907 | 1235 |
| SR 520 Redmond WB | 919 | 174 |
| I-5 South SB | 1144 | 1493 |
| SR 167 Renton NB | 1652 | 591 |
| I-5 Seattle North SB | 1975 | 2106 |
| I-405 Bellevue SB | 2089 | 1915 |

It is also important to note that these statistics represent *the additional delay* that would not have occurred if an incident had not happened. They do not include delay from normal congestion levels. In addition, they do *not* include the shift in delay from one portion of a corridor to another. (See Figure 1 and the corresponding discussion about how incidents transfer delay from one segment of a corridor to another. This figure is repeated below as Figure 9.)

This approach to measuring incident delay makes our computations very conservative because some individuals (for example those traveling only from A to B in Figure 9) will experience unexpected delay caused by the incident that they would not otherwise have experienced. This is definitely "incident-caused delay." Other travelers will experience a net decrease in delay (e.g., those traveling from C to E) that is also the direct result of the incident. Our "delay per minute of incident" calculation subtracts the improvement in delay from points C to E from the increase in delay from points A to B. This is correct from a region-wide perspective, but it downplays the unexpected delay that some travelers experience.

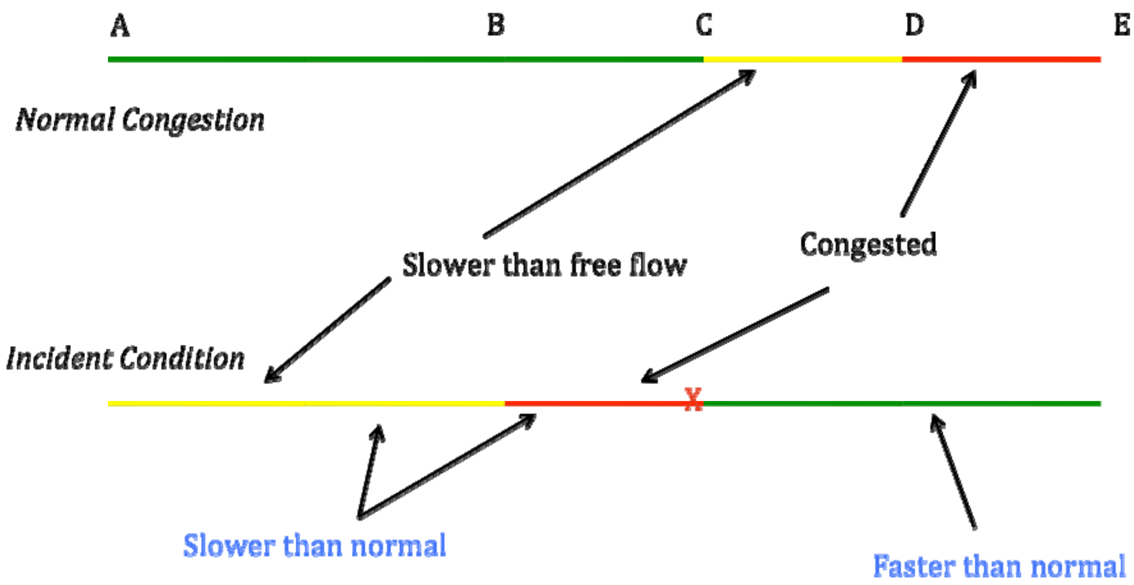


**Figure 9: Shift of Delay from One Group of Travelers to Another under Incident Conditions**

In addition, studies on the value of travel time reliability have shown that travelers value time lost as a result of unexpected delay at considerably higher rates than the time gained when delays are not as bad as expected. (That is, getting to the airport 10 minutes early is not "as good" as getting to the airport 10 minutes late is "bad.") Accordingly, the value of our computed "time lost" due to incidents should probably be weighted more heavily than our "time gained." Because our process weighs the value of these times equally, its estimates of the value of the delay that could be saved by better incident management are conservative.

## <u>THE EFFECTS OF INCIDENTS ON THE END OF PEAK PERIOD CONGESTION</u>

As discussed earlier in this chapter, <u>when an incident's effects are active,</u> traffic congestion lasts longer in both peak periods (assuming that there is congestion during the peak period) than when no incident has occurred. The problem with this statement is understanding when those influences end. That is, the definition of "incident influence" used above means that only incidents whose effects on roadway performance are "still active" are considered when "incident influenced travel time" is computed. If an incident is quickly cleared and the disruption is minimized, how does that affect the experienced travel time?

To analyze the more general impact of incidents and crashes on congestion, another analysis was performed. In this analysis the study team defined when congestion ends at the end of both the AM and PM peak periods. "End of Congestion" was defined as being when travel times for 20 consecutive minutes (four 5-minute periods) were less than travel time at the speed limit plus 5 percent. Three sets of statistics were then computed for all non-holiday Tuesdays, Wednesdays, and Thursdays describing when congestion ended for days during which 1) *any* crash occurred,[24] 2) *any* non-crash incident occurred, or 3) no incident occurred. These statistics were then compared.

One problem with this analysis was that for 11 test sections, AM peak period congestion did not "end" before noon when this definition of congestion was used. A review of the travel times routinely experienced on these routes showed that a variety of traffic flow conditions (e.g., excessive merging at bottlenecks near the end of the corridor, heavy traffic flows influenced by large, heavy truck volumes) frequently kept these road segments operating slightly below the speed limit during late morning and midday periods. Although these routes all operated at or above the speed limit during late night hours and during many midday hours, they routinely operated at speeds lower than the speed limit for reasons other than traffic disruptions during the middle of the day.

[24] The crash must have occurred after 4:00 AM for the morning peak period test, or after 3:00 PM for the evening peak period test.

The result of the above definitional problem was that the "AM peak period" frequently did not end until late in the day. This "starting condition" limited the benefit of the intended analysis. As a result, for the AM peak period on these 11 routes, "end of congestion" was redefined as being sustained speeds within either 10 or 20 percent of the speed limit.

These "lowered expectations" were tested on other corridors but frequently caused the "end of congestion" flag to be set during obviously congested conditions. This was particularly true in the afternoon peak period, when all routes reached travel times within 5 percent of that achieved at the speed limit by a "reasonable" time of day. Consequently, the "slower speed" needed to adjust the "end of congestion" definition was used only for those 11 sections and only for the AM peak period.

The resulting summary statistics for these analyses are shown in tables 5 and 6.[25] The tables are sorted so that the study sections with the "slowest," most congested corridors (as defined by their peak period *median* travel rate—in minutes per mile) are at the top of the table, and the fastest, least congested corridors are at the bottom. Within a given travel rate, routes are sorted by their *mean* travel rate. Both tables show the mean time when congestion ended on days that did not experience reported incidents or crashes, and the mean travel time differences (in minutes) for when "congestion ended" for each corridor when at least one crash or incident had been reported within the study section in the indicated direction of travel. Only the values with statistical significance[26] are presented. All other values are set to zero.

[25] All of the statistics generated from this analysis are shown in Appendix B.
[26] At the 90 percent level of confidence.

**Table 5: Effects of Incidents and Crashes on When Congestion Abates after the Evening Peak Period**

| Study Corridor | Mean PM Peak Travel Rate | Median PM Peak Travel Rate | "Normal" Time When Congestion Abates | Additional Congestion Time After a Non-Crash Incident | Additional Congestion Time After a Crash |
|---|---|---|---|---|---|
| I-405 Bellevue SB - PM Peak | 3.73 | 3.6 | 19:44 | 0:13 | 0:20 |
| I-405 Eastgate SB - PM Peak | 2.73 | 2.6 | 19:12 | 0:00 | 0:15 |
| SR 520 Sea WB - PM Peak | 2.72 | 2.6 | 20:00 | 0:00 | 0:12 |
| I-405 South NB - PM Peak | 2.58 | 2.6 | 20:41 | 0:00 | 0:17 |
| I-5 SeattleN SB - PM Peak | 2.56 | 2 | 18:49 | 0:00 | 0:00 |
| I-405 Kirkland NB - PM Peak | 1.99 | 2 | 19:03 | 0:00 | 0:11 |
| I-5 SeattleCBD NB - PM Peak | 1.96 | 1.8 | 18:53 | 0:00 | 0:00 |
| I-405 Kennydale SB - PM Peak | 1.90 | 1.8 | 19:27 | 0:00 | 0:00 |
| I-5 Nking NB - PM Peak | 1.79 | 1.8 | 18:55 | 0:00 | 0:12 |
| I-5 SeattleCBD SB - PM Peak | 1.72 | 1.8 | 18:20 | 0:00 | 0:31 |
| SR 167 Auburn SB - PM Peak | 1.96 | 1.6 | 18:47 | 0:08 | 0:08 |
| SR 520 Red EB - PM Peak | 1.87 | 1.6 | 19:09 | 0:00 | 0:00 |
| I-5 South SB - PM Peak | 1.76 | 1.6 | 18:08 | 0:00 | 0:19 |
| I-405 North NB - PM Peak | 1.61 | 1.6 | 19:18 | 0:00 | 0:14 |
| I-5 Everett NB - PM Peak | 1.87 | 1.4 | 17:08 | 0:28 | 0:58 |
| I-5 SeattleN NB - PM Peak | 1.74 | 1.4 | 18:34 | 0:00 | 0:00 |
| SR 167 Renton SB - PM Peak | 1.63 | 1.4 | 18:47 | 0:00 | 0:16 |
| I-405 South SB - PM Peak | 1.52 | 1.4 | 19:36 | 0:00 | 0:00 |
| I-90 Bridge WB - PM Peak | 1.73 | 1.2 | 18:25 | 0:34 | 0:48 |
| SR 520 Sea EB - PM Peak | 1.49 | 1.2 | 18:52 | 0:11 | 0:22 |
| I-5 Lynwood NB - PM Peak | 1.38 | 1.2 | 19:00 | 0:00 | 0:00 |
| I-405 Bellevue NB - PM Peak | 1.34 | 1.2 | 18:09 | 0:00 | 0:27 |
| I-90 Seattle WB - PM Peak | 1.13 | 1.2 | 17:29 | 0:00 | 0:00 |
| SR 520 Red WB - PM Peak | 1.49 | 1 | 16:51 | 1:24 | 1:53 |
| I-90 Seattle EB - PM Peak | 1.43 | 1 | 17:07 | 0:00 | 1:05 |
| I-90 Bridge EB - PM Peak | 1.40 | 1 | 18:18 | 0:22 | 0:35 |
| I-5 Nking SB - PM Peak | 1.33 | 1 | 16:47 | 0:29 | 1:57 |
| I-90 Bellevue WB - PM Peak | 1.30 | 1 | 16:13 | 1:21 | 2:10 |
| I-5 Tukwilla SB - PM Peak | 1.19 | 1 | 17:18 | 0:21 | 0:51 |
| SR 167 Renton NB - PM Peak | 1.17 | 1 | 17:22 | 0:27 | 0:57 |
| I-405 Kennydale NB - PM Peak | 1.17 | 1 | 18:05 | 0:17 | 0:23 |
| I-90 Bellevue EB - PM Peak | 1.11 | 1 | 16:35 | 0:00 | 0:00 |
| I-5 Everett SB - PM Peak | 1.10 | 1 | 16:35 | 0:24 | 0:57 |
| I-5 Lynwood SB - PM Peak | 1.10 | 1 | 17:21 | 0:00 | 1:09 |
| I-405 North SB - PM Peak | 1.09 | 1 | 17:40 | 0:00 | 0:46 |
| I-405 Kirkland SB - PM Peak | 1.09 | 1 | 16:55 | 1:00 | 1:21 |
| I-5 Tukwilla NB - PM Peak | 1.07 | 1 | 16:23 | 0:23 | 1:56 |
| SR 167 Auburn NB - PM Peak | 1.05 | 1 | 17:31 | 0:00 | 0:00 |
| I-405 Eastgate NB - PM Peak | 1.04 | 1 | 16:24 | 0:00 | 0:47 |
| I-90 Issaquah EB - PM Peak | 1.01 | 1 | 16:10 | -0:05 | 0:00 |
| I-5 South NB - PM Peak | 1.01 | 1 | 16:05 | 0:00 | 0:45 |
| I-90 Issaquah WB - PM Peak | 1.00 | 1 | 16:05 | 0:00 | 0:00 |

Table 5 shows that congestion in the I-405 southbound corridor through Bellevue normally ends at 7:44 PM when no disruptions occur. If a non-crash incident occurs after 3:00 PM, congestion can be expected to last 13 minutes longer (to 7:57 PM). Congestion in that same study corridor lasts 20 minutes longer than "normal" if a crash has occurred. The very next row in the table shows that in the next section of I-405 downstream of Bellevue (I-405 Eastgate southbound) an incident does not produce a statistically significant change in the time that PM peak period congestion abates. However, crashes on the Eastgate section do have a statistically significant effect, adding 15 minutes to the length of congestion in the evening on this roadway section.

While the nature (size, duration, specific location) of incidents affects exactly how much disruption each causes, and these differences in incident size/duration are not directly accounted for in these tables, some generalizations can be made from these tables. Among these are the following:

- Incidents occurring in the evening peak period have little measurable effect on when peak period congestion abates for 1) very heavily congested roadway sections or 2) very lightly congested sections.
- Crashes extend the evening commute period's congestion more significantly than non-crash incidents and are more likely to affect roadway performance than other kinds of incidents.
- The duration of congestion on a surprising number of corridors is not significantly affected by a crash occurring on that section.

Congestion was extended by non-crash incidents in a statistically significant manner in only three of 18 corridors with a median PM peak period travel rate of 1.4 or greater. In addition, the "end of congestion time" was extended when incidents occurred in less than half (9 of 19) of the study corridors with a median travel rate equal to the speed limit.

**Table 6: Effects of Incidents and Crashes on When Congestion Abates after the Morning Peak Period**

| Study Corridor | Mean AM Peak Travel Rate | Median AM Peak Travel Rate | "Normal" Time When Congestion Abates | Additional Congestion Time After a Non-Crash Incident | Additional Congestion Time After a Crash | Adjusted End of Congestion Travel Time Value[27] |
|---|---|---|---|---|---|---|
| I-405 Kennydale NB - AM Peak | 3.66 | 3.4 | 11:47 | 0:00 | 1:33 | 10% |
| I-405 North SB - AM Peak | 2.82 | 2.4 | 9:56 | 1:27 | 2:09 | |
| I-5 Nking SB - AM Peak | 2.07 | 1.8 | 11:06 | 0:48 | 1:29 | 10% |
| I-5 SeattleCBD NB - AM Peak | 1.91 | 1.8 | 12:15 | 0:00 | 0:00 | No Disruption Free Days |
| I-405 Kirkland SB - AM Peak | 1.76 | 1.8 | 10:16 | 0:56 | 1:14 | |
| SR 520 Sea EB - AM Peak | 1.70 | 1.8 | 11:54 | 6:02 | 6:53 | |
| I-5 Lynwood SB - AM Peak | 1.89 | 1.6 | 10:06 | 1:57 | 1:39 | |
| I-5 South NB - AM Peak | 1.75 | 1.6 | 9:16 | 0:00 | 0:22 | |
| SR 167 Auburn NB - AM Peak | 1.68 | 1.6 | 11:40 | 0:00 | 0:00 | 20% |
| I-405 Eastgate NB - AM Peak | 1.66 | 1.6 | 11:38 | 0:00 | 1:04 | 10% |
| I-5 SeattleN SB - AM Peak | 2.15 | 1.4 | 9:38 | 1:10 | 4:58 | |
| I-405 Kennydale SB - AM Peak | 1.54 | 1.4 | 9:08 | 1:19 | 1:23 | 20% |
| I-405 South SB - AM Peak | 1.45 | 1.4 | 12:46 | 3:12 | 2:17 | 20% |
| SR 167 Renton NB - AM Peak | 1.62 | 1.2 | 9:13 | 1:47 | 1:22 | 20% |
| SR 520 Sea WB - AM Peak | 1.51 | 1.2 | 9:51 | 0:47 | 2:54 | 10% |
| I-5 Tukwilla NB - AM Peak | 1.50 | 1.2 | 10:06 | 0:00 | 0:32 | |
| I-90 Issaquah WB - AM Peak | 1.46 | 1.2 | 9:10 | 0:00 | 0:33 | |
| I-90 Bellevue WB - AM Peak | 1.30 | 1.2 | 9:26 | 0:00 | 0:00 | |
| I-405 Bellevue NB - AM Peak | 1.27 | 1.2 | 11:01 | 3:34 | 5:00 | 10% |
| I-405 South NB - AM Peak | 1.24 | 1.2 | 8:21 | 4:49 | 7:47 | 20% |
| I-90 Seattle EB - AM Peak | 1.96 | 1 | 8:45 | 0:00 | 1:05 | |
| I-90 Seattle WB - AM Peak | 1.20 | 1 | 7:35 | 0:00 | 1:52 | |
| I-90 Bridge EB - AM Peak | 1.18 | 1 | 9:23 | 0:45 | 1:04 | |
| I-405 Bellevue SB - AM Peak | 1.16 | 1 | 8:27 | 7:56 | 11:07 | 10% |
| I-5 Everett SB - AM Peak | 1.15 | 1 | 7:08 | 0:06 | 1:06 | |
| I-90 Bridge WB - AM Peak | 1.15 | 1 | 8:04 | 0:26 | 1:30 | |
| I-5 SeattleCBD SB - AM Peak | 1.10 | 1 | 9:28 | 1:04 | 4:57 | |
| SR 167 Auburn SB - AM Peak | 1.06 | 1 | 8:58 | 7:29 | 9:59 | |
| I-405 Eastgate SB - AM Peak | 1.05 | 1 | 7:22 | 0:00 | 0:32 | |
| SR 167 Renton SB - AM Peak | 1.04 | 1 | 9:42 | 7:33 | 7:30 | |
| I-5 Tukwilla SB - AM Peak | 1.02 | 1 | 7:08 | 0:00 | 0:00 | |
| SR 520 Red WB - AM Peak | 1.02 | 1 | 7:09 | 0:56 | 2:10 | |
| I-405 North NB - AM Peak | 1.02 | 1 | 7:56 | 0:12 | 0:00 | |
| I-5 Everett NB - AM Peak | 1.01 | 1 | 7:05 | 0:00 | 0:14 | |
| I-5 Lynwood NB - AM Peak | 1.01 | 1 | 7:13 | 0:00 | 0:00 | |
| I-5 SeattleN NB - AM Peak | 1.01 | 1 | 7:07 | 0:00 | 0:00 | |

[27] In order to get the "end of congestion" to occur *before* noon after the AM peak period on days *without incidents or crashes* on some study corridors, it was necessary to change the definition of "congestion" from 20 consecutive minutes of average travel times faster than 1.05 times travel time at the speed limit to either 1.10 times travel times at the speed limit (indicated by the value 10%) or 1.20 times travel time at the speed limit (indicated by 20%).

| | | | | | | |
|---|---|---|---|---|---|---|
| I-90 Bellevue EB - AM Peak | 1.01 | 1 | 7:05 | 0:00 | 0:00 | |
| I-5 South SB - AM Peak | 1.00 | 1 | 7:07 | 0:00 | 0:00 | |
| I-405 Kirkland NB - AM Peak | 1.00 | 1 | 7:05 | 0:05 | 0:00 | |
| SR 520 Red EB - AM Peak | 1.00 | 1 | 7:05 | 0:00 | -0:00 | |
| I-90 Issaquah EB - AM Peak | 1.00 | 1 | 7:05 | 0:00 | 0:00 | |
| I-5 Nking NB - AM Peak | 1.00 | 1 | 7:05 | 0:00 | 0:00 | |

The effects of incidents and crashes in the morning peak period described in Table 6 are significantly different in several ways from those shown for the evening peak period in Table 5. The most significant difference is that the heavily congested AM corridors were much more sensitive to incidents than their PM peak period counterparts. In only one of the ten PM peak corridors with median travel rates above 1.6 were congestion durations sensitive to incidents, while four of the six AM peak corridors operating at this level of congestion were sensitive to non-crash incidents, one of the other two study corridors (I-5 Seattle CBD Northbound) had so many disruptions[28] that no comparison could be made, and another section (I-405 Kennydale Northbound—the most congested morning segment) had changes statistically significant at just below the 80th percentile level.

A second difference between the morning and evening periods is the size of the change when incidents and crashes affected the dissipation of congestion. In the evening, when incidents and crashes had an effect, the mean change to the duration of the peak period tended to be between 15 minutes and an hour at most.[29] In the morning peak period, in corridors affected by crashes and other incidents, congestion routinely extended for more than an hour, and in seven cases, multiple hours.

[28] The I-5 Seattle CBD Northbound study segment had only one day among all non-holiday Tuesdays, Wednesdays, and Thursdays in 2006 that did not contain either a crash or a WITS-reported incident. One day was not sufficient to make a statistically significant comparison.

[29] 35 out of 45 statistically significant differences were less than one hour.

However, at the less congested end of the congestion distribution, the morning peak period was similar to the evening peak period. Half of the study corridors with a median travel rate equal to the speed limit had congestion ending times that were not affected by incidents. The majority of these also had a mean travel rate equal to less than 1.01. These same corridors were also reasonably insensitive to congestion caused by crashes.

These observed differences further strengthen the primary finding of this study: the overriding aspect of congestion is the background traffic volume. While there are many differences between the AM and PM peak periods, one of the key differences is that in the morning, the leading (early) shoulder has very low traffic volumes. Therefore, as noted earlier, incidents tend to have little impact early in the AM peak period. In the evening, traffic volumes drop off very rapidly at the end of the peak period. Therefore, congestion frequently abates rapidly at the end of the peak period, simply because traffic volumes are low enough for queues to clear. At the end of the morning peak, traffic volumes stay modest as people make a variety of non-commute trips. Therefore, congestion formed during the AM peak tends to last much longer than congestion formed in the PM peak.

Conversely, significant incidents occurring well before the start of the PM peak period have the potential to cause the entire PM peak period to be congested if they are not cleared quickly, whereas incidents occurring an hour before the start of the AM peak are far less likely to affect the morning commute if they are cleared with even modest speed.

## THE EFFECTS OF WEATHER ON CONGESTION

Another aspect of incident response for which additional information was needed was a better understanding of how weather affects roadway performance. While the entire scope of this topic is too large for this project, it was possible to address parts of it.

The first analysis task involved exploring ways to define “bad weather.” Only with that definition would it be possible to begin to understand how, when, and where bad weather affects roadway performance.

A large number of studies have looked at the effects of various weather phenomena on roadway performance. For example, previous work on the analysis of weather impacts has clearly shown that weather does matter in terms of impacts not only on crashes but also on traffic volumes, highway capacity, and average speed.[30] Cools et al.[31] and Unrau and Andrey[32] found that rainfall (as well as snowfall and wind speed) significantly decreases traffic volumes. Edwards found a small but significant reduction in mean speed due to wet or misty conditions.[33] Kyte et al. found that light rain or snow and heavy rain may have a greater impact, and heavy snow may have a smaller impact, than stated in the 2000 Highway Capacity Manual.[34] Rakha et al. found that although

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[30] Maze, T., M. Agarwal, and G. Burchett. Whether Weather Matters to Traffic Demand, Traffic Safety, and Traffic Operations and Flow. In *Transportation Research Record: Journal of the Transportation Research Board* , No. 1948, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp 170-176.

[31] Cools, M., E. Moons, and G. Wets. Assessing the Impact of Weather on Traffic Intensity. *Transportation Research Board Annual Meeting*. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2008, Paper No. 08-1903.

[32] Unrau, D. and J. Andrey. Driver Response to Rainfall on Urban Expressways In *Transportation Research Record: Journal of the Transportation Research Board* , No. 1980, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp 24-30

[33] Edwards, J. Speed adjustment of motorway commuter traffic to inclement weather. Transportation Research Part F, Vol. 2, No. 1, 1999, pp. 1-14.

[34] Kyte, M., Z. Khatib, P. Shannon, and F. Kitchener. Effects of Environmental Factors on Free-Flow Speed, Fourth International Symposium on Highway Capacity Proceedings, Transportation Research Circular, Transportation Research Board of the National Academies, 2000, pp. 108-119,gulliver.trb.org/publications/circulars/ec018/ec018toc.pdf.

both rain and snow reduce free-flow speed and capacity, jam density is not affected by weather.[35] On the basis of their research, they developed new weather adjustment factors for free-flow speed, speed at capacity, and capacity for use in the Highway Capacity Manual.

None of these or other papers appears to answer the basic question posed to the research team: what quantifiable effect does bad weather have on roadway performance?

In examining this question, the research team discovered a number of key problems. One problem is that the effects of bad weather, such as rain or snow, is not restricted to the time when precipitation is falling. For example, the effects of snow last long after the snow has fallen—IF the snow sticks to the pavement. However, snow may have very limited effect if the ground is warm enough to melt the snow as it lands. Similarly, while heavy thunder showers can reduce speeds markedly rain falls, the spray thrown up by tires after even light rain can also slow vehicles for quite a while after the rain has fallen.

## The Effects of Snow

The case study review of I-90 described near the beginning of this chapter illustrates the difficulties posed by the fact that the impacts of weather result from a combination of weather variables AND traffic variables. On I-90, snow fell equally on both the eastbound and westbound directions. However, extreme delays occurred in only one direction. Those delays occurred because other factors also played a part in the performance of the roadway.

[35] Rakha, H., M. farzaneh, M. Arafeh, and E. Sterzin. Inclement Weather Impacts on Freeway Traffic Stream Behavior. In Transportation Research Record: Journal of the Transportation Research Board , No. 2071, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp 8-18.

While the westbound direction showed modest delays in the evening, with moderate delays occurring between 6:00 and 9:00 PM, the eastbound section experienced an unusually heavy day of congestion prior to the snowfall, and then a major additional pulse of congestion starting at 8:00 PM and lasting well into the morning hours. Exacerbating the eastbound congestion was additional traffic returning home from a Monday Night football game played in front of 65,000 fans in downtown Seattle.

## The Effects of Rain

Because of the limited number of days and hours during which snow fell in 2006, it was difficult to develop an analytical approach that describes the effects of snow on roadway performance. However, rain falls frequently in the area. For rain, the best descriptor of rain's effects on roadway performance is whether measurable rain fel within the last hour.

The results uniformly showed that the occurrence of rain leads to a statistically significant increase in the amount of congestion, but only during periods of moderately high traffic volume. That is, rain does not cause congestion uniformly throughout the day. The probability of congestion forming as a result of rain is a function of the underlying level of vehicular demand. And given the time series nature of traffic flow, time of day and day of week can be used as surrogates for vehicular demand winhen estimating the probability of congestion forming.

Rain causes the roadway to operate just a little less efficiently than it would otherwise.[36,37] The result, as observed in our data set, is that for a given a normal commute

[36] Edwards, J. Speed adjustment of motorway commuter traffic to inclement weather. *Transportation Research Part F*, Volume 2, No. 1, 1999, pages 1-14.

period, the roadway is likely to break down a little earlier than it would otherwise under conditions of similar demand but dry roadways.[38] Because the roadway breaks down earlier than it would if rain had not occurred, the queues grow larger than they otherwise would, and consequently last longer. The moderate rate at which rain falls in Seattle (or more accurately, the region's frequently wet roadways) does not *cause* congestion; it simply lowers the amount of traffic volume that can a given roadway can handle before it becomes congested. Therefore, the roadway breaks down earlier in the commute period than it would otherwise.

Figure 10 illustrates this trend for SR 520 Seattle westbound crossing the Evergreen Point Floating Bridge. The red line shows the probability of a traveler experiencing congestion on this corridor on a dry day. The blue line illustrates the probability of a traveler being in congestion if rain has fallen within the last hour. State Route 520 westbound into Seattle is one of the more congested roadway segments in the region. It experiences congestion during both the AM and PM peaks, as well as periodically in the middle of the day.

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[37] Rakha, H., M. Farzaneh, M. Arafeh, and E. Sterzin. Inclement Weather Impacts on Freeway Traffic Stream Behavior. In Transportation Research Record: Journal of the Transportation Research Board, No. 2071, Transportation Research Board of the National Academies, Washington, D.C., 2008, pages 8-18.

[38] The amount of rainfall likely determines the degree to which roadway efficiency declines, but an analysis confirming this has not been completed for this study.

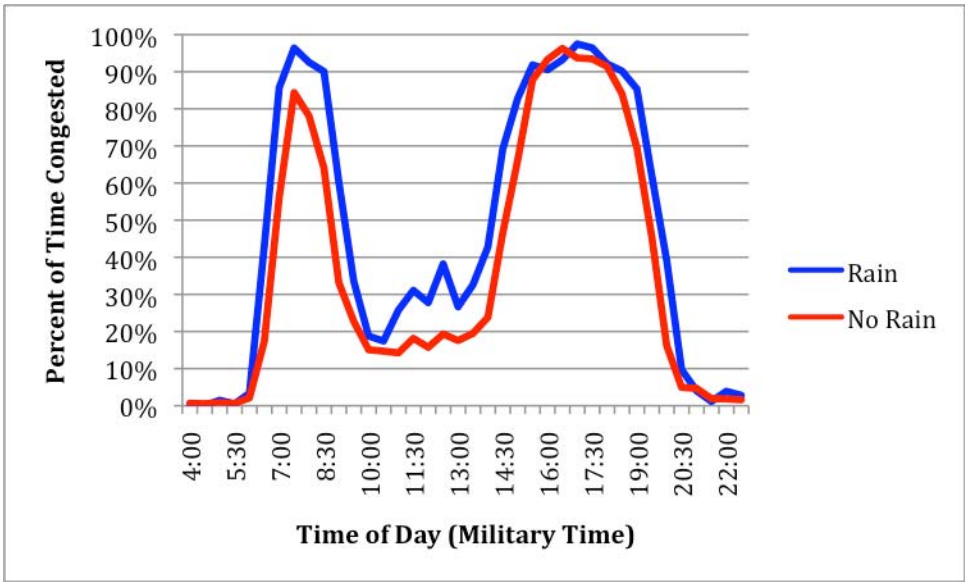


**Figure 10: The Probability of Being in Congestion: Rain versus No Rain SR 520 Westbound from Bellevue to Seattle**

Figure 11 shows one of the less congested roadway sections in the region. In this case, only one peak period (the AM) routinely experiences congestion. Therefore, in the morning when volumes are high, if rain falls, the probability of congestion forming in the next hour increases. However, after the peak period ends, the fact that rain has fallen has no discernible impact on the formation of congestion. Although falling rain may increase accident rates during off-peak times (see a later discussion on accident rates and the presence of rain), congestion caused by that increase in accident rates is no more likely to occur than congestion from other sources.

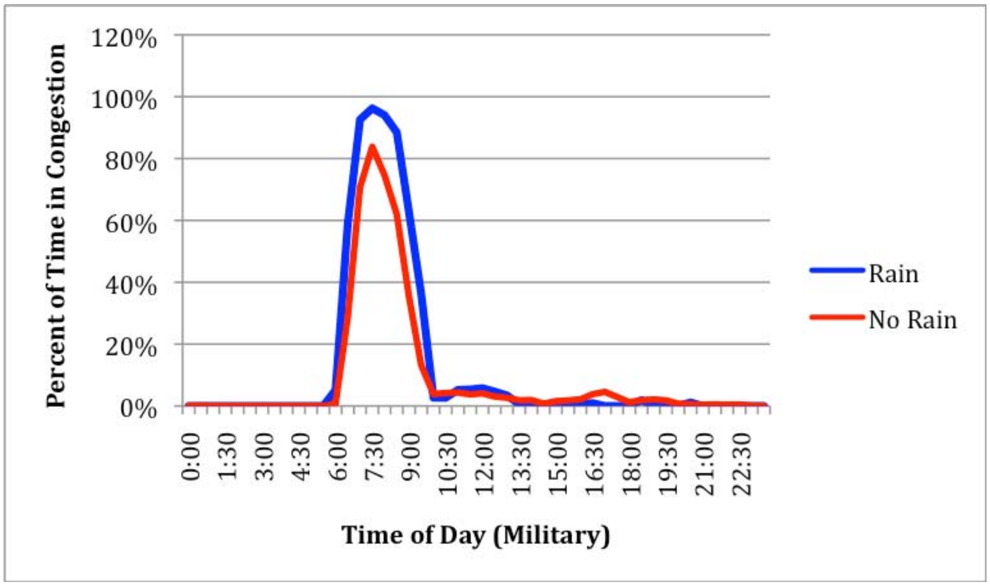


**Figure 11: The Probability of Being in Congestion: Rain versus No Rain**
**I-90 Westbound from Issaquah to Bellevue**

The greater probability of congestion early in the peak period on a rainy day and the longer queues that result from that early start to congestion also mean longer travel times. Figure 12 illustrates how mean travel times increase along with an increased probability of being in congestion. This graph shows the probability of congestion having formed by time of day when the roadway is dry (red) or has been rained on in the last hour (blue). It also shows the *change in mean travel time* when rain has fallen (black), where the travel time increase is shown on the right hand axis. As can be seen in this figure, at no time does the mean travel time decrease with statistical significance when rain is present. Interestingly, Figure 12 also shows that the declining volumes at the end of the commute period quickly moderate the travel time effects of the congestion developed as a result of early queue formation in the rain. That is, even though the queues are longer and the travel times worse in the peak period, the mean travel time for a trip starting at the end of the commute period is only marginally worse than normal, and by the end of the peak period, travel times are nearly the same as normal, regardless of whether rain has fallen.

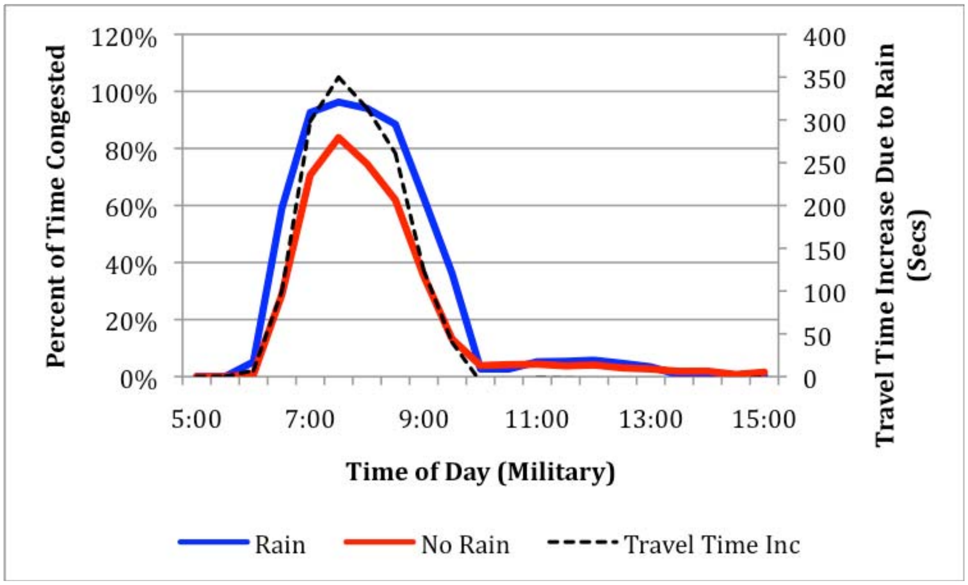


**Figure 12: The Correspondence of an Increase in Mean Travel Times with the Increase in Probability of Congestion Due to Rain I-90 Westbound from Issaquah**

While the effects shown in Figure 12 were observed fairly universally for all roadway segments studied, further analysis of the 42 study segments revealed two significant differences in the effects of rain between less congested and more congested roadway segments. First, on the more congested segments, enough volume exists during the middle of the day that rain causes an increased likelihood of congestion forming during midday periods. On less congested roadway segments this is not the case. The project team believes that on road segments that operate near capacity during midday, the decreasing roadway efficiency caused by wet roadways is sufficient to create congestion, irrespective of increases in crash rates caused by the wet pavement.[39] On less heavily traveled (and therefore less congested) roadway segments, the modest loss of efficiency caused by wet pavement does not create conditions that result in congestion, except on rare occasions when major crashes occur.

The second significant difference between heavily congested and less heavily congested roadway segments is that on the most congested segments, the probability of congestion during the heart of the peak period approaches 100 percent. As a result, rain does not increase the probability of congestion forming during those periods. On less congested roadways, there are lower volume commute periods (e.g., the workdays near major holidays) when congestion may not form. Rainfall on those lower volume work days may decrease roadway performance to a degree sufficient for congestion to form.

Figure 13 illustrates the effects of rain on a moderately congested roadway segment (there are no "uncongested" freeway segments in the Seattle region). Figure 14 illustrates how rain affects a heavily congested segment. In this figure, it is easy to see that the probability that congestion will form does not change significantly during the core of the PM peak period. However, during the early portion of the PM peak, travel times do increase when rain falls. This is because queues form earlier than normal and are, therefore, longer than normal at later points in the day.

Interestingly, Figure 13 shows the travel time increases in the rain briefly moderated just after the midpoint of the PM peak period. The increases in travel time caused by rain approach zero shortly before 6:00 PM. (18 on the X-axis of the graph), only to rebound by 6:30 PM. This outcome does not represent a lack of effect from the

[39] Additional analysis is required to determine the effects of the increased accident rates versus the simple effect of wet pavements.

rain on commute times. Instead, it is an artifact of the roadway segmentation used for this specific analysis. On this particular roadway segment, the normal queue extended roughly to the end of the roadway analysis segment at the peak of the PM peak period. This maximum queue length occurred at roughly 6:00 PM. Because the section already was fully congested, estimated travel times for the segment did not increase **on the study section** under rainy condition, and thus travel times did not increase. Instead, travel times increased on the upstream section of the roadway (in this case the SR 520 Redmond westbound study section) because the queue from the first section extended back onto the second. Thus, **travelers** did experience slower trip times, but the reported travel time **on this section** was not worse. As the "extra long queue" moderated toward the end of the peak period, travel times on the Seattle test section again increased, simply because the normal queue was once again shorter than the length of the entire roadway section.

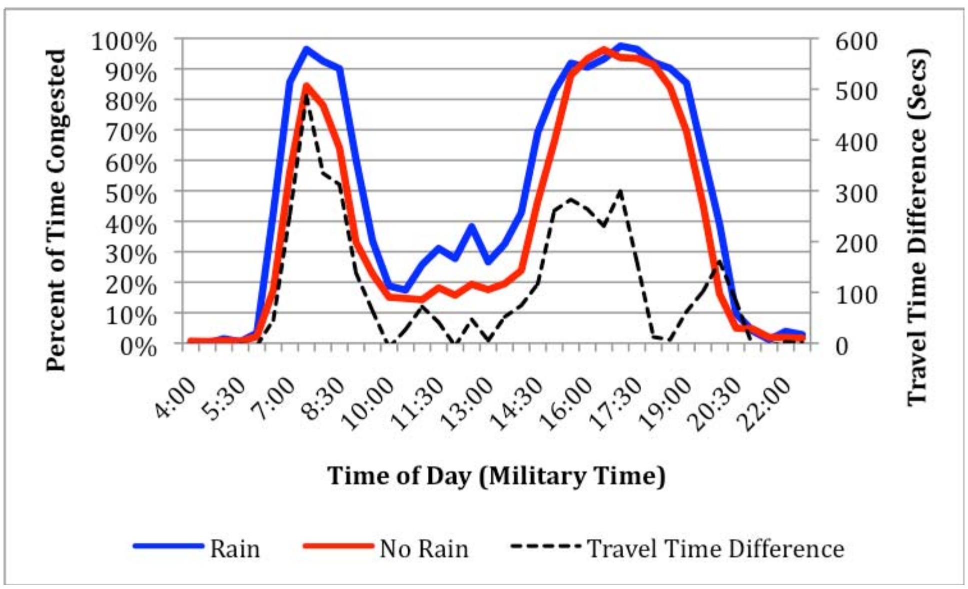


**Figure 13: The Correspondence of an Increase in Mean Travel Times with the Increase in Probability of Congestion Due to Rain SR 520 Westbound: Bellevue toward Seattle**

Another way to look at the effect of rain was to compute the probability that a given test section of roadway was operating in each Regime[40] for each time slice of a day. Probabilities were computed for days when rain occurred within the last hour and when the same roadway was dry at that same time of day. For the regimes that represent varied speed (i.e., those regimes in which traffic is not at free flow speed), the mean, median, and standard deviation of that speed were also determined.

The SR 520 roadway sections were used to illustrate the findings from these analyses. In tables 7 and 8 it can be seen that rain did not change the percentage of time that travel occurred in regimes 1 and 2. That is, at low volumes, modest amounts of rain ("Seattle rain") had no measurable effect on average facility performance. For example, on SR 520 Seattle westbound, between 5:00 AM and 6:00 AM, with no rain, Table 7 shows that the percentage of travel in combined regimes 1 and 2 was almost 100 percent, regardless of the weather condition. We see this effect across all four corridors of SR 520 for both Regime 1 and Regime 2.

However, when conditions approached roadway capacity—Regime 3—the effects of rain became apparent. Rain caused a significant decrease in the percentage of time the roadway spent in Regime 3 (near capacity volumes, with still free flowing speeds) and a commensurate increase in Regime 4 (congested) travel. For example, in the 7:00 AM to 8:00 AM hour, if it did not rain, westbound SR 520 operated in Regime 3 21 percent of the time; however, if rain had fallen in the last hour, westbound SR 520 operated in Regime 3 only 5 percent of the time. Similarly, between 4:00 PM and 5:00 PM on the Seattle section eastbound, if no bad weather had occurred recently, the probability of

[40] See the discussion of the Regime variable in the previous chapter of this report.

traveling in Regime 3 was 30 percent and in Regime 4 was 63 percent. Once rain began to fall, however, the probability of traveling in Regime 4 jumped to almost 81 percent, while Regime 3 dropped to around 14 percent.

**Table 7: The Percentage of Travel by Time of Day That Occurs in Specific Regimes Given Different Weather Conditions[41]—AM Peak**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | SR 520 Sea WB | 5 - 6 AM | | | SR 520 Sea WB | 7 - 8 AM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2656.00 | 409.00 | 528.00 | N | 2724.00 | 339.00 | 477.00 |
| Regime 1 | 63.10% | 61.12% | 62.69% | Regime 1 | 0.29% | 0.00% | 0.00% |
| Regime 2 | 36.71% | 37.90% | 36.55% | Regime 2 | 1.06% | 0.00% | 0.00% |
| Regime 3 | 0.00% | 0.00% | 0.00% | Regime 3 | 20.96% | 4.72% | 7.34% |
| Regime 4 | 0.15% | 0.98% | 0.76% | Regime 4 | 73.64% | 93.81% | 91.61% |
| Regime 5 | 0.04% | 0.00% | 0.00% | Regime 5 | 4.04% | 1.47% | 1.05% |
| | | | | | | | |
| | SR 520 Sea EB | 6 - 6 AM | | | SR 520 Sea EB | 7 - 8 AM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2536.00 | 409.00 | 528.00 | N | 2556.00 | 318.00 | 459.00 |
| Regime 1 | 77.21% | 82.40% | 81.82% | Regime 1 | 0.04% | 0.00% | 0.00% |
| Regime 2 | 22.67% | 17.60% | 18.18% | Regime 2 | 0.82% | 0.00% | 0.00% |
| Regime 3 | 0.00% | 0.00% | 0.00% | Regime 3 | 8.49% | 1.89% | 3.49% |
| Regime 4 | 0.08% | 0.00% | 0.00% | Regime 4 | 89.63% | 98.11% | 96.51% |
| Regime 5 | 0.04% | 0.00% | 0.00% | Regime 5 | 1.02% | 0.00% | 0.00% |
| | | | | | | | |
| | SR 520 Red WB | 5 - 6 AM | | | SR 520 Red WB | 7 - 8 AM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2643.00 | 409.00 | 538.00 | N | 2711.00 | 339.00 | 487.00 |
| Regime 1 | 68.63% | 67.48% | 68.96% | Regime 1 | 0.44% | 0.00% | 0.00% |
| Regime 2 | 31.37% | 32.52% | 31.04% | Regime 2 | 2.73% | 0.59% | 0.62% |
| Regime 3 | 0.00% | 0.00% | 0.00% | Regime 3 | 92.48% | 72.27% | 78.64% |
| Regime 4 | 0.00% | 0.00% | 0.00% | Regime 4 | 4.02% | 27.14% | 20.74% |
| Regime 5 | 0.00% | 0.00% | 0.00% | Regime 5 | 0.33% | 0.00% | 0.00% |
| | | | | | | | |
| | SR 520 Red EB | 6 - 6 AM | | | SR 520 Red EB | 7 - 8 AM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2643.00 | 409.00 | 528.00 | N | 2643.00 | 409.00 | 528.00 |
| Regime 1 | 51.46% | 52.32% | 52.27% | Regime 1 | 60.00 | 60 | 60.00 |
| Regime 2 | 48.35% | 46.45% | 46.78% | Regime 2 | 60.00 | 60 | 60.00 |
| Regime 3 | 0.00% | 0.00% | 0.00% | Regime 3 | 0.00 | 0 | 0.00 |
| Regime 4 | 0.00% | 0.00% | 0.00% | Regime 4 | 0.00 | 0 | 0.00 |
| Regime 5 | 0.19% | 1.22% | 0.95% | Regime 5 | 53.00 | 49 | 49.00 |

Because speeds could vary in Regime 3 (they were allowed to range between 42 and 58 mph), there was also a drop in average speed within Regime 3. Figure 14 shows how mean speed was at its slowest in this Regime when rain had fallen recently. Figure 14 also shows how this change in speed was partly dependent on how long it had been

41 The value of "N" in Table 6 is the number of 5-minute time periods included in that one-hour period for each analysis.

since rain had fallen. The variable used in this figure was actually an inclusive variable. It was set to "rain" if any rain had fallen in the past 1, 2, 4, or 8 hours. In the figure, as the time period since rain last fell increases, the speed gradually increases back to where the Regime was before rain began. This same time effect can be seen in the percentage shift from Regime 3 travel to Regime 4 travel. This is illustrated in Figure 15.

**Table 8: The Percentage of Travel by Time of Day That Occurs in Specific Regimes Given Different Weather Conditions[42]—PM Peak**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | SR 520 Sea WB | 4 - 5 PM | | | SR 520 Sea WB | 7 - 8 PM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2675.00 | 429.00 | 514.00 | N | 2636.00 | 393.00 | 521.00 |
| Regime 1 | 0.00% | 0.00% | 0.00% | Regime 1 | 0.95% | 0.00% | 1.54% |
| Regime 2 | 0.11% | 0.00% | 0.00% | Regime 2 | 21.85% | 13.49% | 13.82% |
| Regime 3 | 1.79% | 0.70% | 0.58% | Regime 3 | 7.66% | 1.53% | 3.65% |
| Regime 4 | 97.72% | 99.07% | 99.22% | Regime 4 | 58.19% | 73.79% | 66.22% |
| Regime 5 | 0.37% | 0.23% | 0.19% | Regime 5 | 11.34% | 11.20% | 14.78% |
| | | | | | | | |
| | SR 520 Sea EB | 4 - 5 PM | | | SR 520 Sea EB | 7 - 8 PM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2624.00 | 416.00 | 502.00 | N | 2599.00 | 381.00 | 517.00 |
| Regime 1 | 0.00% | 0.00% | 0.00% | Regime 1 | 1.23% | 4.20% | 4.45% |
| Regime 2 | 0.50% | 0.00% | 0.00% | Regime 2 | 76.49% | 70.87% | 69.63% |
| Regime 3 | 30.49% | 13.94% | 14.34% | Regime 3 | 1.19% | 0.00% | 0.19% |
| Regime 4 | 62.73% | 80.53% | 80.28% | Regime 4 | 9.08% | 12.07% | 0.00% |
| Regime 5 | 6.29% | 5.53% | 5.38% | Regime 5 | 12.00% | 12.86% | 0.58% |
| | | | | | | | |
| | SR 520 Red WB | 4 - 5 PM | | | SR 520 Red WB | 7 - 8 PM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2690.00 | 429.00 | 525.00 | N | 2645.00 | 393.00 | 537.00 |
| Regime 1 | 0.19% | 0.23% | 0.19% | Regime 1 | 2.38% | 3.31% | 2.42% |
| Regime 2 | 61.12% | 31.70% | 35.81% | Regime 2 | 89.91% | 84.48% | 85.29% |
| Regime 3 | 6.88% | 1.63% | 2.10% | Regime 3 | 0.08% | 0.00% | 0.00% |
| Regime 4 | 31.60% | 66.20% | 61.71% | Regime 4 | 7.60% | 11.45% | 11.73% |
| Regime 5 | 0.22% | 0.23% | 0.19% | Regime 5 | 0.04% | 0.76% | 0.56% |
| | | | | | | | |
| | SR 520 Red EB | 4 - 5 PM | | | SR 520 Red EB | 7 - 8 PM | |
| | No Bad Weather | Precip 1 hour | Precip 2 hour | | No Bad Weather | Precip 1 hour | Precip 2 hour |
| N | 2689.00 | 428.00 | 513.00 | N | 2642.00 | 393.00 | 521.00 |
| Regime 1 | 0.04% | 0.00% | 0.00% | Regime 1 | 1.51% | 1.02% | 0.19% |
| Regime 2 | 2.31% | 1.40% | 1.17% | Regime 2 | 78.73% | 68.96% | 73.13% |
| Regime 3 | 2.86% | 1.64% | 2.34% | Regime 3 | 0.00% | 0.00% | 0.00% |
| Regime 4 | 90.03% | 90.65% | 91.81% | Regime 4 | 14.72% | 22.14% | 18.81% |
| Regime 5 | 4.76% | 6.31% | 4.68% | Regime 5 | 5.03% | 7.89% | 7.87% |

[42] The value of "N" in Table 7 is the number of 5-minute time periods included in that one-hour period for each analysis.

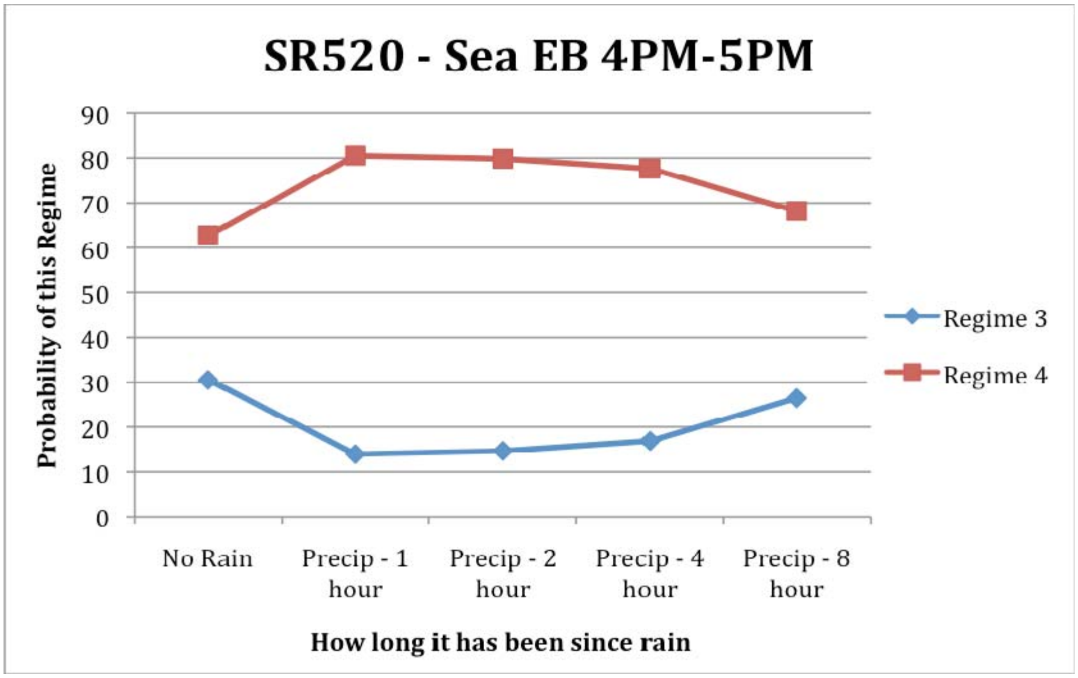


**Figure 14: Percentage of Time Spent in Regimes 3 and 4**
**Eastbound on SR 520 Seattle Section**

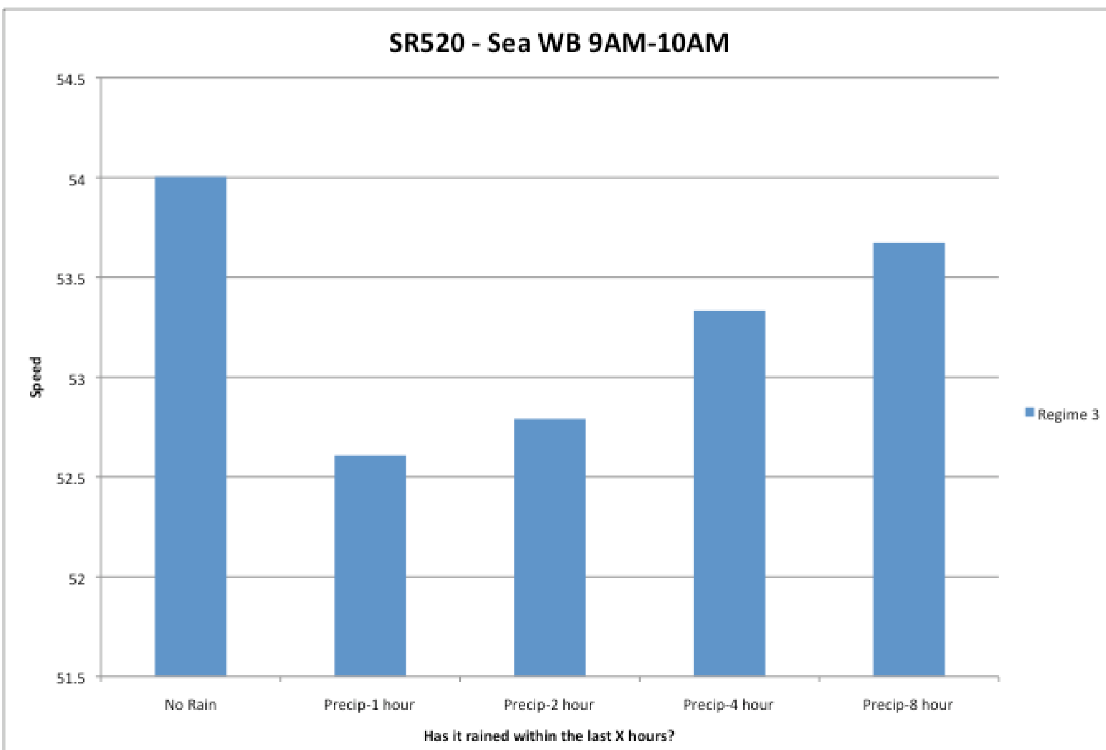


**Figure 15: Mean Travel Speed within Regime 3**
**SR 520 Westbound Seattle Section 9:00 AM – 10:00 AM**

Regime 4 also experiences a much sharper change in speed than Regime 3. In a normal Regime 4 condition, without rainfall, SR 520 Redmond eastbound between 4:00 PM and 5:00 PM had a mean speed of 38.8 mph. When precipitation had fallen in the last hour, however, the mean speed for Regime 4 dropped to 35.6 mph.

One limitation with the above analysis is best explained with an example. If rain fell between 3:00 and 4:00 PM, the time periods between 3:00 and 5:00 PM were assumed to be "rain affected" (within one hour of when measurable rain has fallen). Therefore, travel times occurring at 4:55 that day were "rain affected," whereas travel times at 5:05 were considered "dry" trips. The limitation with this analysis is that the rain may have created a queue that affected the 5:05 dry trip, but for the analysis we ignored that possibility, thus slightly underestimating the potential impacts of rain on travel time.

## The Effects of Wind

Research[43] (and most drivers' personal experience) has shown that high winds frequently cause motorists to drive more slowly and carefully, as wind can affect vehicle handling. Under high winds, many drivers slow slightly. As with rain, this more cautious approach to driving under heavy wind conditions can negatively affect the relationship of vehicle volume and speed, causing the roadway to operate less efficiently. Given high enough traffic volumes, this loss of efficiency results in congestion, whereas

[43] Cools, M., E. Moons, and G. Wets. Assessing the Impact of Weather on Traffic Intensity. Transportation Research Board Annual Meeting. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2008, Paper No. 08-1903.

Unrau, D. and J. Andrey. Driver Response to Rainfall on Urban Expressways In Transportation Research Record: Journal of the Transportation Research Board, No. 1980, Transportation Research Board of the National Academies, Washington, D.C., 2006, pages 24-30.

under normal circumstances congestion would not form.  Under these conditions, wind will result in statistically significant increases in travel time.

An analysis of roadway performance and wind data in the Seattle region supported these basic findings.  However, the analytical tests performed on the Seattle test corridors showed that travel times in all test corridors were not equally affected by wind.  In fact, in many corridors, wind did not have any statistically significant effect on travel times.  In other corridors, wind had a very high impact on roadway performance. Table 9 gives examples of how wind affects various corridors differently, even though the corridors are directly connected.  Table 9 also gives examples of the results of the sensitivity tests performed with different wind speeds to separate “windy” from “not windy” conditions.

As can be seen in Table 9 the SR 520 Evergreen Point Floating Bridge is affected by even relatively moderate winds (10 mph sustained wind speeds).  This is because the bridge is a 2-mile-long floating span.  The roadway is two lanes in each direction with no shoulders.  In even moderate wind, a driver crossing the bridge can feel the bridge sway. The wind also can create spray, as wind-driven waves break against bridge.  The result is that drivers slow down.  Because the bridge operates near capacity 12 to 14 hours each weekday, these wind effects are sufficient to cause congestion.

**Table 9: Example Effects of Wind on Travel Times by Corridor (in seconds)**

| Route | Mean Travel Time AM Peak | | Difference | Statistically Significant? | Mean Travel Time PM Peak | | Difference | Statistically Significant? |
|---|---|---|---|---|---|---|---|---|
| | With Wind[a] | Without Wind[b] | | | With Wind[a] | Without Wind[b] | | |
| I-5 Everett – Southbound | 190 | 207 | -17 | No | 191 | 209 | -18 | No |
| I-5 North King – Southbound | 759 | 690 | 68 | Yes | 400 | 422 | -22 | No |
| I-5 North Seattle – Southbound | 751 | 606 | 145 | Yes | 926 | 686 | 239 | Yes |
| I-5 South Northbound | 1671 | 1073 | 598 | Yes | 649 | 649 | 0 | No |
| SR 520 Seattle Westbound | 1020 | 638 | 382 | Yes | 1548 | 1052 | 495 | Yes |
| I-90 Bridge Eastbound | 425 | 410 | 15 | No | 543 | 437 | 106 | Yes |
| I-90 Seattle Eastbound | 198 | 169 | 29 | Yes | 151 | 115 | 36 | Yes |
| SR 520 Seattle Westbound 10 mph Wind Speed | 781 | 626 | 154 | Yes | 1093 | 1049 | 44 | Yes |
| I-90 Bridge Eastbound 10 mph Wind Speed | 434 | 407 | 27 | No | 431 | 441 | -10 | No |
| I-90 Seattle Eastbound 10 mph Wind Speed | 174 | 169 | 5 | No | 107 | 118 | -12 | No |

a Sustained wind speed is greater than 16 mph.
b Sustained wind speed is less than or equal to 16 mph.

The I-90 Lacey V. Murrow Memorial Bridge, located nearby to the south, also is affected by wind, but to a lesser extent than the SR 520 bridge. This is most likely due to a combination of factors, including the facts that the I-90 bridge is more modern, has full shoulders, and sits higher off the water (and, therefore, experiences less wind-driven spray). Interestingly, the evening commute across the I-90 bridge is affected by wind, whereas the morning commute is not, even though traffic volumes are similar in both periods. Part of this is because the definition of the test section that included the I-90 bridge also included a large segment of non-bridge travel across Mercer Island. Back-ups on the bridge affecting eastbound traffic actually create some free flow conditions on the island itself, decreasing the travel time impact of the wind. However, wind-caused back-ups significantly affect the upstream section of eastbound I-90 (the Seattle section also shown in Table 9). This explains why the I-90 Seattle section is statistically affected by wind in the morning, even though it does not include the bridge itself. At more moderate wind speeds (e.g., 10 mph sustained winds), none of the I-90 segments shows a statistically significant change in expected travel time.

Looking at the I-5 segments included in Table 9, it can be seen that wind affects some corridors in some peak periods, but not all corridors nor all peak periods within all corridors. In general, high peak-period volumes relative to their capacity make roadway segments more likely to be affected by high winds. Other reasons that a roadway may be susceptible to winds are that the road segment is exposed to high levels of wind (the I-5 North Seattle segment crosses the Ship Canal Bridge, an exposed portion of road where wind is often felt) or that the segment is immediately upstream of another segment that is wind affected. (The I-5 North King segment is upstream of the I-5 North Seattle segment. The I-5 Everett segment is considerably farther north and does not experience spillback from North King or North Seattle segments, except in very extreme cases.)

Figure 16 illustrates how wind affects the SR 520 bridge westbound, while Figure 17 illustrates the I-90 eastbound bridge section. Both figures show that the primary effects of wind are in the peak periods when traffic volumes are highest. If the same graphs were presented with higher wind speeds, more impacts would be seen in the middle of the day, especially on SR 520.

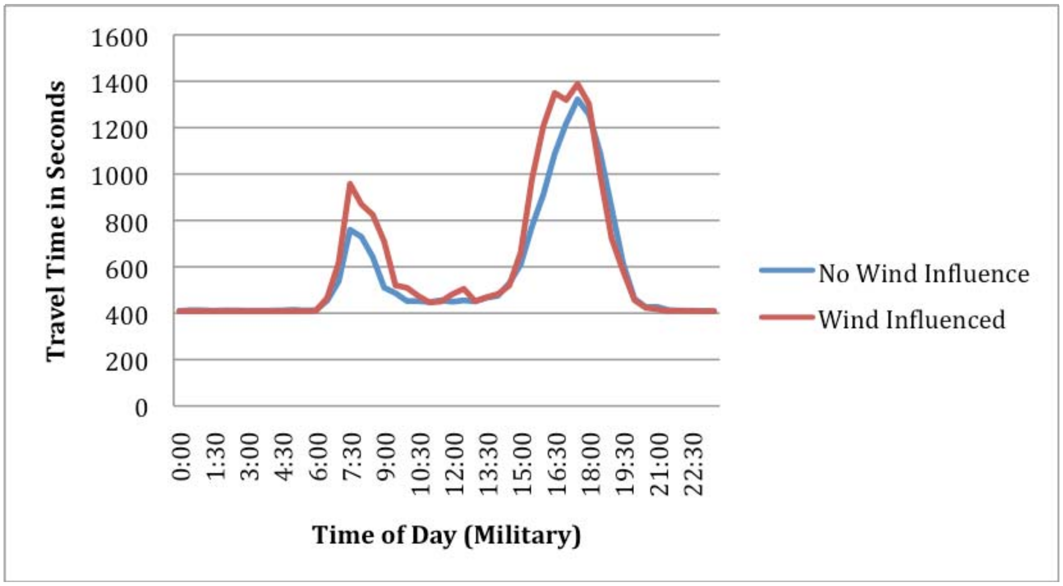


**Figure 16: Mean Travel Times by Time of Day in Wind and No-Wind Conditions**
**SR 520 Westbound: Bellevue toward Seattle**

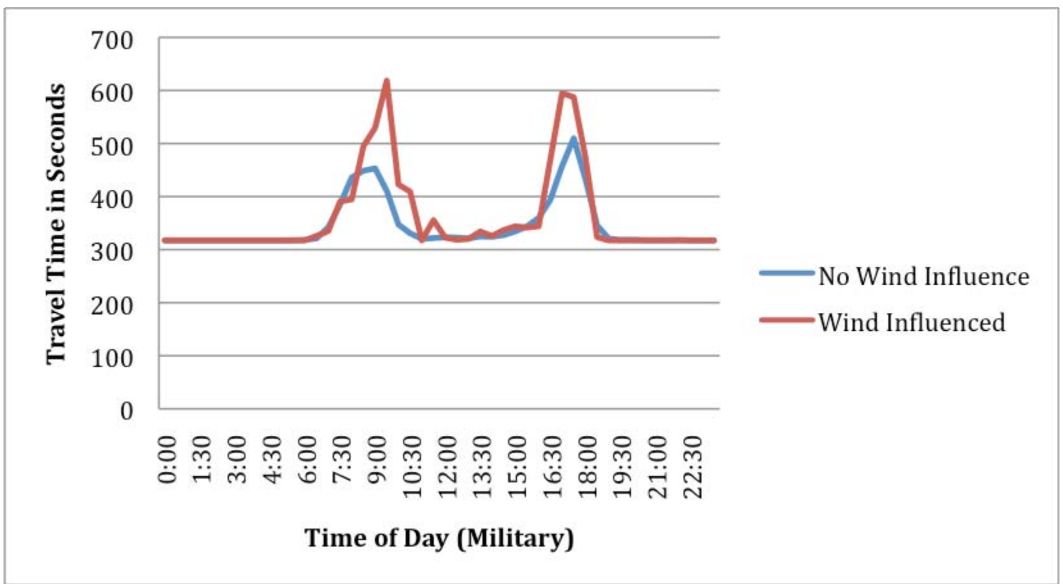


**Figure 17: Mean Travel Times by Time of Day in Wind and No-Wind Conditions**
**I-90 Bridge Section Eastbound: Seattle toward Bellevue**

In Figure 17, wind appears to have a significant effect on expected travel times during the later portion of the AM peak period, but not on the earlier portion of the peak. This helps explain why the difference in mean travel times shown in Table 9 is not statistically significant.

In summary, the analysis of the impacts of bad weather on congestion formation on Seattle freeways identified the following major conclusions:

- Small disruptions, such as those caused by moderate amounts of rain or even spray from wet pavements, only cause congestion when they occur in combination with sufficient volume relative to the available capacity.
- Precipitation can affect roadway performance as long as the roadway remains wet.
- The probability that bad weather will significantly affect roadway performance on any given roadway section is a function of the expected demand/capacity condition of that road section and the significance of the weather event (e.g., light rain versus a heavy thundershower).
- Bad weather also increases the probability of crashes occurring, which further increases the probability of significantly increased travel times.

Given Seattle's relatively benign climate, most weather impacts in the Seattle region are small, at least in terms of the changes in vehicle speed and throughput that they directly cause. During most parts of the day, on most roadway segments, the travel time changes that these small differences in speed create are not statistically significant. *However, when those small speed changes occur in combination with large traffic volumes, especially during the beginning shoulder of a peak period, those small changes can result in congestion that will, in turn, generate much more significant increases in expected travel times.*

The use of rain variables that account for the continuing presence of spray from wet roadways suggests that spray has as much of an impact on roadway performance as moderate rainfall itself. Similarly, except in the case of heavy snowfall (when poor visibility affects drivers' behavior), the major impacts of snow are the result of snow accumulation, not the snowfall itself. Anecdotal evidence of this same effect was also apparent for ice formation in Seattle. The project team attempted to compute times when black ice formation might be present by using humidity and temperature data from the Sea-Tac weather station. However, these factors did not result in successful identification of ice formation in the informal tests conducted during the winter of 2008. Therefore, we conclude that using regional weather station data is not an effective way to accurately determine the presence of snow and ice on roadways.

The effects of wind are similar to those of rain. High winds cause motorists to drive more cautiously. (The degree to which they adjust their behavior for a given wind condition is a function of the roadway section: How wide are the lanes? Are there shoulders? How exposed is the roadway section to wind?) This in turn reduces the functional capacity of the roadway during high wind conditions. These effects do not appear to be as uniform as the effects of rain, since geographic differences in terrain and geometric differences in roadway right-of-way appear to play bigger roles in determining the effects of wind on roadway performance than they do in the case of rain.

Where wind is significant and traffic volumes are light, travel times increase only marginally, in direct proportion to the slowing that individual vehicles exhibit under windy conditions. However, when volumes are high, the reduced functional roadway capacity resulting from motorists' voluntary slowing can create congestion that would not occur under average weather conditions. That congestion frequently becomes self-sustaining during peak periods; that is, the queue itself creates a further decrease in functional roadway capacity, which further increases the length of the queue and increases travel times on the roadway section.

## ROADWAY CONDITIONS PRESENT WHEN INCIDENTS CREATE CONGESTION

Congestion is caused by a combination of factors involving traffic volume (demand), driver behavior, and roadway characteristics (as measured in terms of operational roadway capacity). Recent research has shown that driver behavior, especially in combination with roadway configuration changes (e.g., uphill grades, sharp curves) can produce congestion under volume conditions lower than conventional traffic flow theory would suggest. The presence of various driver distractions is thought to be a major cause of these slowdowns. Incidents—both those that close lanes and those that simply create visual interest—are a key source of distractions. Larger, lane blocking incidents are also the direct cause of lost roadway capacity.

In the SHRP2 L03 report, work performed by Dowling and Associates showed that the instability of speeds on urban freeways rises dramatically (as measured by the standard deviation of speeds) at traffic volumes that are much lower than roadway capacity. The SHPR2 L03 results did not indicate that modest volumes equal congestion but that the probability of congestion forming increases dramatically at relatively modest volumes. Figure 18 shows how the mean value of the inverse of speed (expressed as minutes per mile) and the standard deviation of that value change on U.S. 101 freeway southbound in the Bay Area near San Francisco.

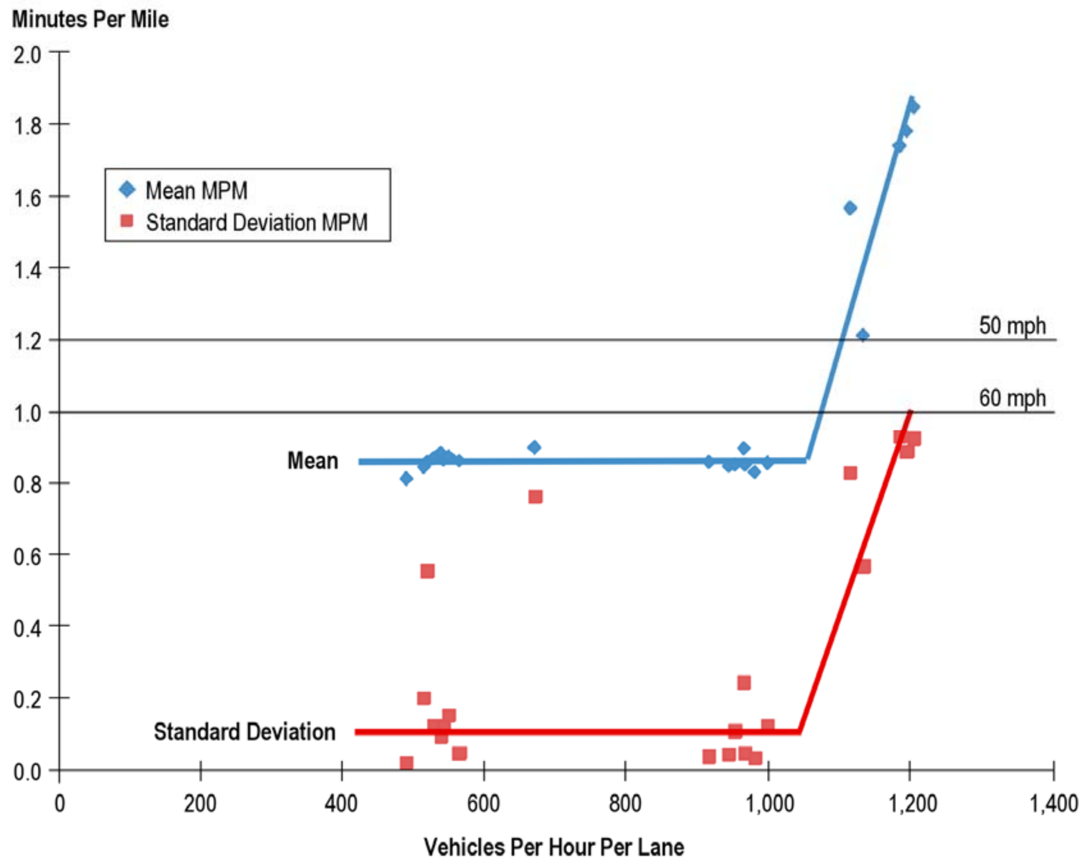


**Figure 18: Volume per Lane versus Mean and Standard Deviation of Speed Expressed as Minutes per Mile**

Consequently, this project looked at the probability of congestion forming (as measured by at least one detector location reporting average speeds below 45 mph for a 5-minute period). Analysis of Puget Sound freeway data showed that on six-lane freeways (three lanes in each direction), congestion is unlikely (< 20 percent) to form at volume/capacity (V/C) ratios of below 0.8 if no disruption event occurs. On smaller freeways (two lanes in each direction) congestion forms more than 20 percent of the time at V/C ratios as low as 0.5 or 0.6. Table 10 illustrates these findings.

**Table 10: Percentage of Periods When at Least One Detector in a Corridor Falls Below 45 mph—No Disruptions Present**

| V / C | SR 167 Auburn NB | I-5 Tukwila NB | SR 520 Seattle WB | SR 520 Redmond WB | SR 520 Redmond EB | I – 405 Kennydale NB* | I – 405 Kennydale SB* |
|---|---|---|---|---|---|---|---|
| 0.4 | 1% | 0% | 2% | 4% | 0% | 10% | 2% |
| 0.5 | 2% | 1% | 4% | 2% | 3% | 21% | 4% |
| 0.6 | 23% | 1% | 13% | 1% | 9% | 33% | 26% |
| 0.7 | 62% | 3% | 33% | 2% | 18% | 32% | 73% |
| 0.8 | 82% | 19% | 52% | 4% | 39% | 41% | 84% |
| 0.9 | 83% | 31% | 71% | 2% | 62% | 49% | 90% |
| 1 | 63% | 13% | 69% | 3% | 100% | 35% | 88% |

However, if an incident occurs, and particularly if a lane is closed by an incident, the disruption to traffic flow can produce congestion at surprisingly low V/C ratios. For example, on most corridors, if a lane closing incident occurs, speeds fall below 45 mph roughly 75 percent of the time if the V/C ratio is equal to or greater than 0.3. Crashes have effects similar to those caused by lane closures. While this speed reduction affects only a small section of roadway, that slowdown can be viewed as a significant safety hazard, and at higher levels of traffic volume they can create significant traffic delay.

These findings agree with theoretical expectations. Table 11 shows how previous research[44] described the effects of incidents on functional roadway capacity. These values suggest that for any given V/C ratio, roadways with larger capacity simply have more "absolute capacity to spare" and therefore experience a lower proportional loss of

[44] Blummentritt, C.W., Pinnel, C., and McCasland, W.R., "Guidelines for Selection of Ramp Control Systems," *NCHRP Report 232*, Transportation Research Board, Washington, DC, May 1981.

capacity than smaller roadways, even if the absolute loss of capacity due to incidents is higher. The presence of extra lanes means that loss of part of a lane removes less absolute capacity.

**Table 11: Percentage of Capacity Reduction by Type of Incident and Size of Roadway**

| Nature of Incident | 2-Lane Roadway (One Direction) | 3-Lane Roadway | 4-Lane Roadway |
|---|---|---|---|
| Shoulder | 25 % | 16% | 11% |
| Blocking One Lane | 68% | 47% | 44% |
| Blocking Two Lanes | 100% | 78% | 66% |

The combination of real performance data and previously published findings indicates that even minor traffic incidents can create congestion whenever the V/C ratio reaches about 0.7 for a two-lane (one-direction) freeway or 0.8 on a three-lane or larger freeway. Slightly larger incidents cause congestion at even lower volumes.

Because the goal is to clear incidents before congestion occurs (the largest travel time and safety benefits accrue when incidents can be cleared before congestion occurs), incident response actions—even for minor incidents—are likely to be cost-beneficial whenever V/C ratios exceed about 0.6 for two-lane roads and 0.7 for larger roads, especially when those V/C conditions occur at the beginning of a rise in traffic volume (e.g., at the beginning of a peak period).

Unless they are in response to large traffic disruptions, which tend to occur infrequently, incident response actions taken in V/C conditions lower than these rates are unlikely to result in travel time savings of sufficient value to outweigh the cost of the incident response.

## THE EFFECTS OF INCIDENTS ON CRASH RATES

While the major focus of this project was on the delays caused by incidents, a secondary interest was whether those increases in congestion cause crash (accident) rates to increase. If this is in fact the case, then faster removal of incidents from the roadway and the expected faster removal of the associated queues will also decrease the crash rate for a facility. This analysis effort explored whether the probability of a "secondary crash" occurring was higher than that of a crash occurring otherwise. This was investigated by comparing the probability of a crash occurring during periods when "nothing" was occurring (no incident, crash, or rain had already influenced traffic on a corridor) and during periods when a previous incident or crash had influenced travel on that corridor.

Table 12 shows the results for all study corridor segments in the AM peak, midday, and PM peak periods. While additional statistical analysis should be performed, a useful but simple summary of these results is that *the probability of a crash occurring roughly doubles when an incident has influenced travel conditions*. Table 12 shows that in the AM peak period, if travel times have been affected by an incident of any kind, the probability of a crash occurring increases by an average factor of 2.97. In the PM peak, crash rates increase by an average of 2.66.

**Table 12: Ratio of the Probability of a Crash Occurring under Different Conditions (Incident Affected Crash Probability / No Event Present Crash Probability)**

| Corridor | AM Peak | Midday | PM Peak |
|---|---|---|---|
| SR 520 Sea EB | 2.67 | 4.91 | 1.38 |
| I-405 South NB | 2.06 | 1.72 | 1.01 |
| I-5 South NB | 2.06 | 3.08 | 1.91 |
| I-90 Bridge EB | 2.55 | 0.77 | 2.64 |
| I-405 North SB | 1.77 | 1.78 | 2.06 |
| I-405 North NB | 3.86 | 2.28 | 1.29 |

| | | | |
|---|---|---|---|
| SR 167 Auburn NB | 0.00 | 3.10 | 0.00 |
| SR 520 Sea WB | 3.12 | 4.92 | 1.91 |
| SR 520 Red WB | 3.20 | 5.31 | 4.37 |
| SR 520 Red EB | 10.04 | 0.96 | 1.71 |
| SR 167 Auburn SB | 19.87 | 1.15 | 1.90 |
| I-5 Lynnwood NB | 2.00 | 11.27 | 2.25 |
| I-5 Lynnwood SB | 2.30 | 0.97 | 1.00 |
| I-5 Everett NB | 1.08 | 2.89 | 1.37 |
| I-5 Everett SB | 2.24 | 1.07 | 1.79 |
| I-5 N. King NB | 0.00 | 5.08 | 5.08 |
| I-5 N. King SB | 1.83 | 11.90 | 11.90 |
| I-5 N. Sea NB | 1.29 | 0.87 | 1.48 |
| I-5 N. Sea SB | 2.42 | 2.36 | 3.57 |
| I-5 Sea CBD NB | 2.80 | 2.77 | 1.62 |
| I-5 Sea CBD SB | 2.57 | 3.66 | 1.68 |
| I-5 Tukwila NB | 2.58 | 2.38 | 6.65 |
| I-5 Tukwila SB | 0.00 | 5.24 | 2.35 |
| I-5 South SB | 1.01 | 1.51 | 1.31 |
| SR 167 Renton NB | 3.83 | 1.06 | 6.32 |
| SR 167 Renton SB | 7.32 | 1.44 | 2.01 |
| I-90 Issaquah EB | 0.00 | 0.00 | 0.92 |
| I-90 Issaquah WB | 3.66 | 0.00 | 0.00 |
| I-90 Bridge WB | 4.16 | 0.00 | 0.81 |
| I-90 Seattle EB | 5.30 | 3.79 | 14.46 |
| I-90 Seattle WB | 6.03 | 0.00 | 1.83 |
| I-90 Bellevue EB | 0.00 | 0.00 | 0.93 |
| I-90 Bellevue WB | 3.44 | 4.79 | 5.47 |
| I-405 Kennydale NB | 1.69 | 1.54 | 3.46 |
| I-405 Kennydale SB | 1.43 | 1.52 | 1.48 |
| I-405 Eastgate NB | 2.79 | 1.00 | 0.69 |
| I-405 Eastgate SB | 0.00 | 6.22 | 1.96 |
| I-405 South SB | 3.40 | 0.72 | 2.03 |
| I-405 Bellevue NB | 1.63 | 2.45 | 1.40 |
| I-405 Bellevue SB | 2.87 | 3.89 | 2.32 |
| I-405 Kirkland NB | 2.40 | 2.13 | 1.25 |
| I-405 Kirkland SB | 1.31 | 2.01 | 2.21 |
| | | | |
| Mean all segments | 2.97 | 2.73 | 2.66 |
| Median all segments | 2.41 | 2.07 | 1.86 |

Like any average, the mean value of these ratios tells only part of the story. However, the distribution of the these ratios gives us significant confidence in the basic conclusion that the occurrence of an incident significantly increases the chance of a crash occurring. Of the 42 corridor sections, 31 showed a probability of a crash occurring that was at least 1.5 times greater than the rate when incidents or other major disruption events had not occurred. Eight of the 11 corridors that did not show this increase had no routine AM peak congestion, meaning that most “incident influenced” congestion occurring on those corridors was very small and occurred under light traffic conditions. As a result, the “influence” of the incident was often only a visual distraction, not the formation of a queue at an unexpected location—one of the expected causes of secondary crashes. Finally, many of the these very light traffic corridors had limited numbers of crashes, in several cases resulting in 0.0 expected crashes under any traffic condition during that particular time of the day.

Table 12 shows that in the PM peak, 27 of the 42 test corridors had an increase in the probability of a crash occurring that was at least 1.5 times greater than the rate when incidents had not occurred. In the midday periods, 22 of the corridor segments had increased crash rates of greater than 2.0, another five had increases of greater than 1.5, five experienced no crashes, and only five saw declines in crash rates under incident conditions.

## THE EFFECTS OF RAIN ON CRASH RATES

The light rain experienced in the region appears to have effects similar to incidents in terms of the creation of congestion. For this reason, the project team also investigated the effect rain has on crash rates. This analysis, done as part of the SHRP2

L03 project, paid specific attention to the statistical validity of the results. It examined crash rates only on SR 520 but for all days of the year and for the four roadway segments analyzed elsewhere in this project. (SR 520 was divided into east and west of the I-405 interchange; there is much lower congestion east of the interchange than west of the interchange.)

For the analysis the intervals were divided into those with rain (15703) and those without rain (89,417) (out of 105,120 = 365 × 24 × 12 intervals). These counts were the same for all four segments, since the weather indicator came from just one location (Sea-Tac). Given the distance between Sea-Tac and the 520 corridor, the rain indicator may have been erroneous in some situations, but this indicator was all we had. These measurement intervals were also classified by their accident indicator, which should have been accurate for each of the four segments. The resulting cross-classifications are shown in tables 13 through 15.

**Table 13: Accident/Rain Cross-Classification for Seattle 520 Westbound**

| | Rain | | |
|---|---|---|---|
| Accident | no | yes | Total |
| No | 89239 | 15644 | 104883 |
| Yes | 178 | 59 | 237 |
| Total | 89417 | 15703 | 105120 |

**Table 14: Accident/Rain Cross-Classification for Seattle 520 Eastbound**

| | Rain | | |
|---|---|---|---|
| Accident | no | yes | Total |
| No | 89196 | 15633 | 104829 |
| yes | 221 | 70 | 291 |
| Total | 89417 | 15703 | 105120 |

**Table 15: Accident/Rain Cross-Classification for Redmond 520 Westbound**

| | Rain | | |
|---|---|---|---|
| Accident | no | yes | Total |
| no | 89358 | 15686 | 105044 |
| yes | 59 | 17 | 76 |
| Total | 89417 | 15703 | 105120 |

**Table 16: Accident/Rain Cross-Classification for Redmond 520 Eastbound**

| | Rain | | |
|---|---|---|---|
| Accident | no | yes | Total |
| No | 89365 | 15687 | 105052 |
| yes | 52 | 16 | 68 |
| Total | 89417 | 15703 | 105120 |

Because accidents are rare events, it is reasonable to treat their occurrence from time interval to time interval as independent events, with probability $p_1$ when there is no rain and with probability $p_2$ when there is rain. The number $X_1$ of accidents observed over the $n_1$ no rain intervals can be treated as having a binomial distribution with parameters $n_1$ and $p_1$. This distribution is very well approximated by a Poisson distribution with a mean ($\lambda_1$) equal to $n_1 * p_1$. We express this distributional relation as

$$X_1 < \text{Pois}(\lambda_1 = n_1 \, p_1).$$

Similarly we write

$$X_2 < \text{Pois}(\lambda_2 = n_2 \, p_2),$$

where $X_2$ is the accident count over the $n_2$ intervals with rain.

Estimates of $p_1$ and $p_2$ are easily obtained as $\hat{p}_i = X_i / n_i$ for $i$ =1, 2, respectively, with the resulting estimate $\hat{p}_1 / \hat{p}_2$ for $p_1 / p_2$. 100γ% confidence intervals for $p_1 / p_2$ are obtained by the exact method (Clopper-Pearson) as explained in Scholz[45]. Computationally, confidence intervals xL, xU are obtained in the statistical software package "R" via the commands.

xL =(1/qbeta((1 + gam)/2, X2 + 1, X1) − 1) □ n2/ n1

and

xU =(1/qbeta((1 – gam)/2, X2 + 1, X1) − 1) □ n2/ n1

where gam = $\gamma$ = .95, X1 = $X_1$, X2 = $X_2$, n1 = $n_1$, and n2 = $n_2$. qbeta denotes the beta distribution quantile function that is intrinsic to R.

The resulting estimates and 95th percentile confidence bounds for $p_1/ p_2$ are shown in Table 17 and graphically illustrated in Figure 19. Note that in each case an aggregated analysis was performed for all four segments combined. The analysis results in that case are labeled "520 Corridor."

**Table 17: Estimates and 95th Percentile Confidence Intervals for $p_1/p_2$**

| Segment | Estimate | Lower Bound | Upper Bound |
|---|---|---|---|
| Sea520WB | 0.530 | 0.393 | 0.724 |
| Sea520EB | 0.554 | 0.422 | 0.736 |
| Red520WB | 0.609 | 0.350 | 1.115 |
| Red520EB | 0.571 | 0.321 | 1.071 |
| 520 Corridor | 0.553 | 0.462 | 0.664 |

Note that the estimates for $p_1/ p_2$ are consistently around .53 to .61. The confidence intervals for the Seattle 520 westbound and Seattle 520 eastbound segments do not contain the value 1, and we can reject the hypothesis $p_1 = p_2$ in those situations at

[45] Scholz, F.W. (2007), "Confidence Bounds & Intervals for Parameters Relating to the Binomial, Negative Binomial, Poisson and Hypergeometric Distributions With Applications to Rare Events," notes for Stat 498B, Industrial Statistics, University of Washington, Seattle, Washington.

significance level α = .05. For the segments Redmond 520 westbound and Redmond 520 eastbound these intervals do contain 1, and the same hypothesis cannot be rejected at that significance level. However, this weaker form of evidence in those two cases is probably due to the fact that there were fewer accidents on those segments. The combined analysis rejects the hypothesis $p_1 = p_2$ quite strongly. On the basis of that analysis we can be 95 percent confident that the true ratio $p_1/ p_2$ is in the interval (.462, .664). This interval is the tightest of all intervals because of the combined number of involved accidents. This indicates that the accident rate during rain is almost twice as high as during periods without rain.

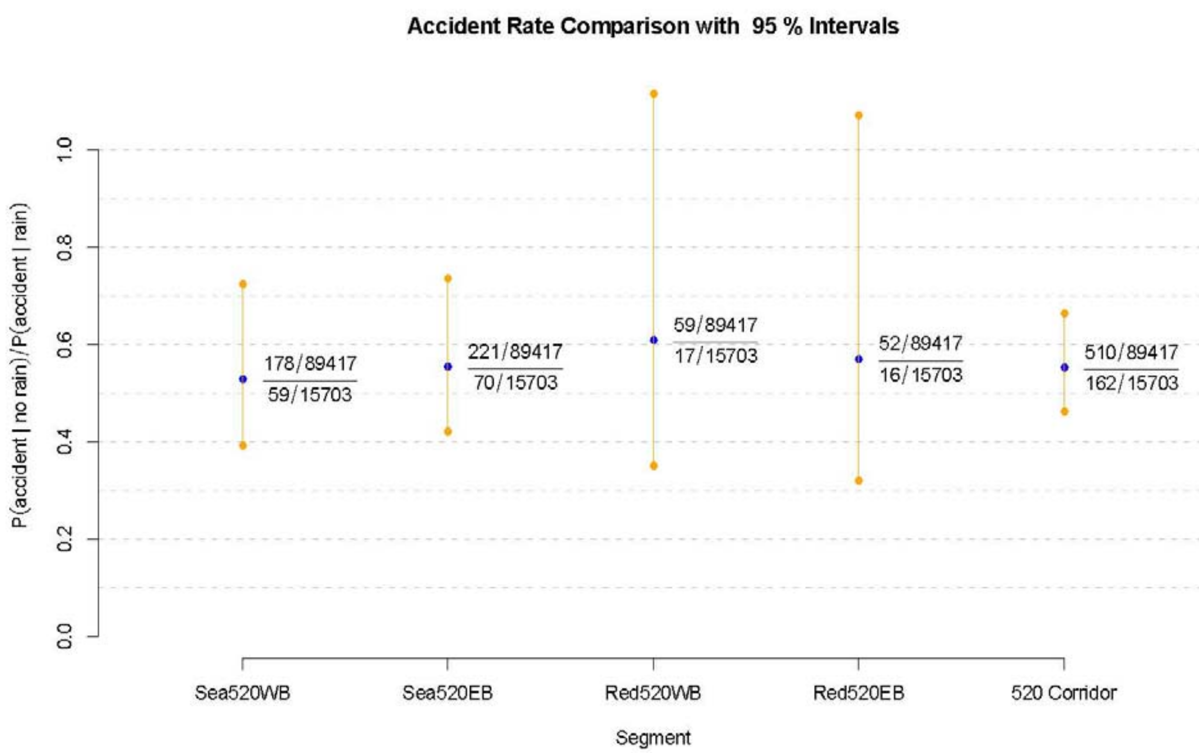


**Figure 19: Estimates and 95th Percentile Confidence Intervals for $p_1 / p_2$**

## ESTIMATING THE FREQUENCY OF INCIDENTS IN AREAS WITH LIMITED INCIDENT RESPONSE

The next problem this project faced was that before WITS begins operating along a stretch of roadway, WSDOT has no information on the number of non-crash incidents that take place along that stretch of roadway. Without such a number, it is difficult to estimate the benefits that can be gained from beginning incident response activities. While it is logical that higher traffic volumes on any given stretch of roadway will yield larger numbers of incidents, no work has been done to develop a relationship that could estimate the number of incidents that can be expected along a roadway.

Consequently, this project tested the statistical relationship among volume, vehicle miles of travel, and crash rates against the number of incidents recorded by WITS within the Puget Sound study area. In this study, an examination of the relationship between volume or vehicle miles of travel and the number of incidents recorded by WITS did not reveal any statistically consistent relationship. Instead, a stronger correlation was found between the annual number of vehicle crashes and the number of incident responses (see Figure 20).

Importantly, the incidents reported by WITS primarily occurred during weekdays in the peak periods, with a smaller number occurring mid-day and on weekends. This is because the commute peaks are the primary periods when WITS resources are deployed. Crash data, on the other hand, were obtained from state accident records collected 24 hours per day, 365 days of the year. Therefore, the time periods of the two statistics shown in Figure 20 (total annual crashes and total incident response actions reported from WITS) are not actually the same.

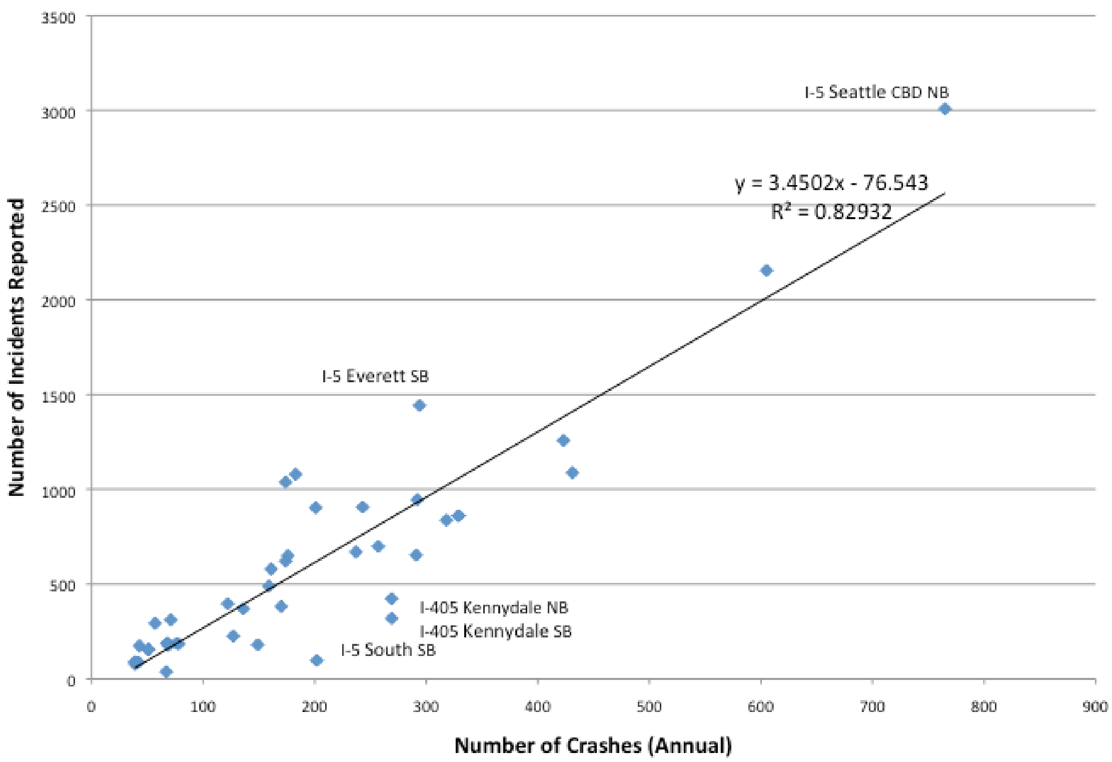


**Figure 20: Relationship of Annual Number of Crashes to Annual Reported Number of Incidents**

Nevertheless, this relationship was more statistically robust (in terms of R-squared) than that produced by similar analyses that compared only peak period, peak direction crashes and reported incidents or that compared incident rates with volume or VMT (see Figure 21). The project team is convinced that several factors explain why the annual number of (primarily peak period) incidents correlates better to annual number of crashes than to either annual VMT, peak period VMT, or peak period crashes. We believe the following:

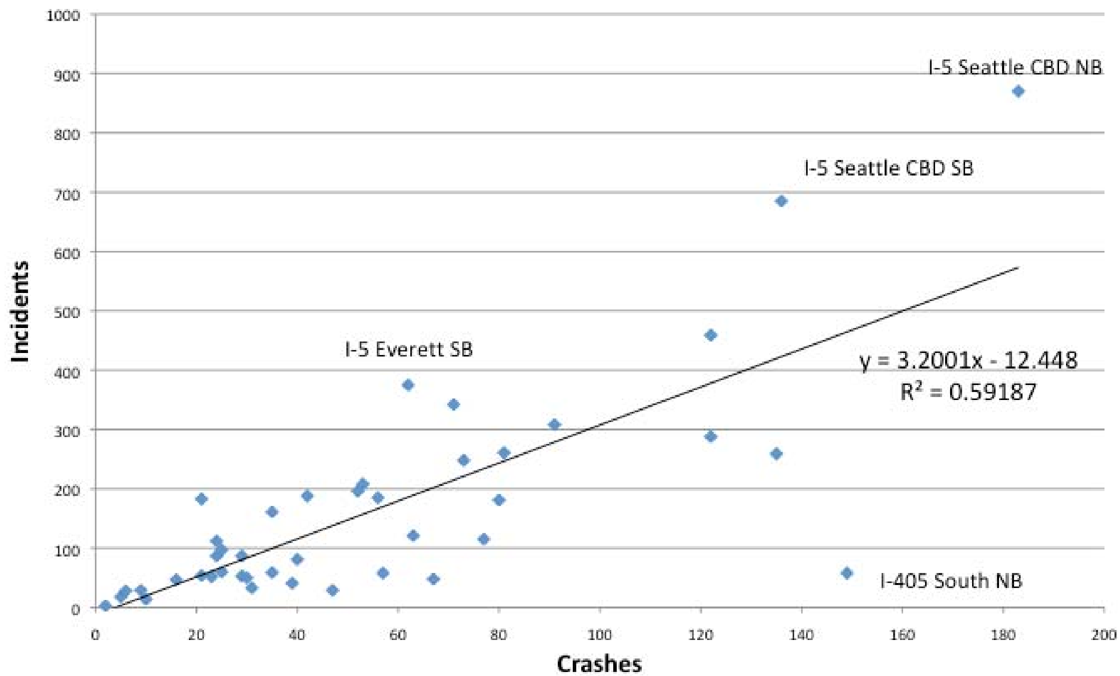


**Figure 21: PM Peak Period Relationship of Number of Incidents versus Number of Crashes**

- The annual number of (primarily peak period) incidents correlates well to the annual number of crashes because incidents and crashes are in fact related. The factors that cause crashes also influence the number of incidents that warrant a WITS response, but there is more to this relationship than the simple explanation of "more crashes in the peak period equals more incidents in the peak period."
- Volumes correlate less well to the annual number of incidents because geometric conditions (presence versus lack of shoulders, frequency of interchanges, the frequency and nature of traffic merge/diverge movements) play a major role—on top of but overshadowing volume—in determining whether crashes and incidents occur. Note that many of the outliers shown in figures 20 and 21 can be directly traced to unusual, "temporary" conditions (e.g., I-405 in the south end has narrowed lanes and very limited shoulders because of ongoing construction, increasing the number of crashes relative to the number of incidents).

- Peak period crashes correlate less well to peak period incidents than do annual number of crashes to annual number of incidents because, once deployed, WITS staff respond to incidents on both sides of a freeway. That is, they see and respond to debris and disabled vehicles in the off-peak direction of travel as they return to the start of their roving area in order to detect and respond to incidents occurring in the peak direction. (Many of these incidents likely occur during other periods but are not noted until an incident response vehicle is on duty to see them.) This artificially increases the number of incidents that occur in "off-peak" directions for which there is no corresponding increase in the number of crashes. (Where significant differences in volume by direction exist, the peak direction/off-peak direction crash ratio ranges from 3 to 1 up to 15 to 1. But the peak to off-peak incident rate only ranges from 1 to 1 up to 2 to 1.)

  Note that these "additional incident responses" are quite valuable, as they remove potential incident- and crash-causing hazards, even though those hazards are unlikely to cause congestion *at that time* in the off-peak direction. Removing hazards during the off-peak has significant incident delay reduction benefits for the *next* peak period movement because the potential cause of delay has been removed before it can cause a more serious incident or crash.

The project team believes that the basic linear relationship of incidents to crashes is valid statewide. (That is, roadway segments subject to higher numbers of crashes are more likely to benefit from incident response.) This means that given the annual number of vehicle crashes along a particular roadway segment, it is possible to predict the future annual frequency of incidents to which WITS staff will respond.

The difficulty with the regression equation illustrated in Figure 20 is not that it is "Seattle centric" but that, given a particular number of crashes, site-specific conditions will cause roadways to be either more or less likely to experience incidents. For example, roadways with wide shoulders, easy access to exit ramps, and no routine congestion are likely to have fewer significant incidents per crash than predicted by the equation. Roadways with limited shoulders, a lack of access to services (places to get fuel, fix a flat tire, fix an overheating engine), or where other conditions tend to cause incidents are likely to have a higher number incidents per crash.

For the prediction of potential benefits from incident response on new roadway sections, the project team concludes that this basic linear relationship is a reasonable initial estimate of incident rates. However, we recommend that the predicted incident rate be assumed to be the maximum expected rate of incident occurrence unless some type of construction activity or other geometric limitation exists on that roadway.

## THE VALUE (COST) OF INCIDENTS AND THUS INCIDENT RESPONSE

### The Value of Time

Given the various results from above, it is possible to estimate

- the savings (in minutes) from improvements in incident response (i.e., the amount of time saved as a result of better incident response actions)
- the number of incident response actions that can be expected in areas where incident response is not currently occurring.

By applying a value to time, it is then possible to develop estimates of the value of time savings that can be obtained from incident response improvements, as well as to estimate the benefits that can be obtained from new incident response efforts.

The dollar values per vehicle minute of delay were based on values of time previously developed by WSDOT[46]: $21.90 per hour for passenger cars and $57.40 for trucks (comprising a mix of heavy- and medium-duty vehicles). To convert these into a

[46] Assessing Cost of Travel Annual Update, by the Urban Planning Office and Freight Office, WSDOT, April 2009, internal WSDOT document

single value that can be applied throughout the state, the research team was assumed that trucks make up 10 percent of the traffic stream.

By using the average amount of delay caused per minute of incident (see "The Effects of Incident Duration on Congestion and Delay" above), the researchers computed the following cost per minute of incidents for three types of traffic disruptions:

Incident[47] = $244 / minute of incident
Closure = $345 / minute of lane closure
Crash = $286 / minute of crash duration[48]

Note that, like the delay per minute of incident statistics upon which these values were based, these figures are simple averages. For times when and locations where volumes are high for long periods of the day, delays will be longer than reported above, and as a result, these values will underestimate the actual value of incident clearance. For times when and locations where lower volumes result in lower delays per minute of incident, these values will overestimate incident response benefits. These differences in the value of incident response can be seen in Table 18, which shows the difference in the dollar value of incident response benefits by study segment in the AM and PM peak periods.

[47] This includes all incidents reported in the WITS database. "Closure" incidents are a subset of those incidents that involve the closure of one or more lanes.
[48] The time it takes to clear crashes is not recorded in the state crash reporting system, and WSDOT's Incident Response team does not respond to many crashes in the Puget Sound region, especially many of those occurring in off-peak periods. Therefore, the duration of the "incident event" is not known for many crashes. To compute a per-minute-of-duration value, it was necessary to assume a duration for each crash event. This value was selected to be 20 minutes for this computation. This was the only computation for which this specific assumption was required.

**Table 18: Differences in the Average Cost per Minute of Incidents for Different Roadway Segments**

| Corridor | Cost / Minute of Incident[49] | Cost / Minute of Closure[34] |
|---|---|---|
| I-90 Issaquah EB | $4.18 | $0.00 |
| I-90 Bellevue EB | $6.55 | $16.70 |
| I-5 Everett SB | $26.78 | $25.94 |
| I-90 Issaquah WB | $35.93 | $22.59 |
| I-405 North NB | $40.23 | $113.72 |
| SR 167 Auburn NB | $58.97 | $49.79 |
| I-405 Eastgate NB | $66.75 | $83.32 |
| SR 520 Redmond EB | $70.57 | $132.07 |
| I-5 N Seattle NB | $78.62 | $229.92 |
| I-405 South SB | $89.25 | $95.48 |
| I-405 Eastgate SB | $99.14 | $100.54 |
| I-5 Seattle CBD NB | $108.56 | $200.74 |
| I-90 Seattle WB | $136.66 | $12.83 |
| I-5 Everett NB | $136.79 | $341.52 |
| I-90 Bellevue WB | $163.13 | $113.73 |
| I-405 South NB | $176.76 | $167.18 |
| I-405 Kirkland SB | $177.84 | $344.43 |
| I-405 Bellevue NB | $178.29 | $217.44 |
| I-5 Seattle CBD SB | $183.49 | $315.07 |
| I-5 N King NB | $188.87 | $517.26 |
| I-5 Tukwila SB | $196.69 | $214.80 |
| SR 167 Auburn SB | $206.13 | $221.12 |
| SR 520 Seattle EB | $209.43 | $343.73 |
| I-5 South NB | $218.79 | $407.24 |
| I-405 Kirkland NB | $233.70 | $541.46 |
| I-90 Bridge WB | $234.35 | $163.32 |
| I-90 Seattle EB | $239.60 | $105.60 |
| I-5 Lynnwood NB | $258.31 | $415.44 |
| I-5 Tukwila NB | $270.63 | $343.96 |
| I-405 North SB | $277.63 | $416.49 |
| I-5 Lynnwood SB | $289.09 | $574.74 |
| I-405 Kennydale SB | $331.77 | $422.28 |
| SR 167 Renton SB | $349.40 | $116.45 |

[49] These costs do not consider the differences in truck percentage occurring on these different roads, either in total or in relation to peak period traffic. All values assume a 10 percent truck mix.

| | | |
|---|---|---|
| I-90 Bridge EB | $352.51 | $278.30 |
| I-5 N King SB | $369.48 | $361.44 |
| SR 520 Seattle WB | $381.61 | $549.47 |
| I-405 Kennydale NB | $384.51 | $523.67 |
| SR 520 Redmond WB | $389.58 | $73.81 |
| I-5 South SB | $485.00 | $633.30 |
| SR 167 Renton NB | $700.40 | $250.53 |
| I-5 Seattle North SB | $837.33 | $893.22 |
| I-405 Bellevue SB | $885.74 | $812.07 |

Similarly, the value of time and thus delay will vary with the truck percentage and truck make-up (long haul or local delivery) from one corridor to another. In reality, these values also vary by time of day. These differences are not accounted for in Table 18. Given a more detailed, site-specific analysis, truck percentages could be varied according to measured truck and car volumes, and the dollar value of time could be varied accordingly by hour of the day and mapped to the delay occurring in each hour. This would provide a more accurate estimate of the value of time savings. However, since the data required to make detailed, site-specific delay by mode calculations are not readily available throughout the state, the above simplified estimates are the best available mechanism at this point in time.

## Safety Benefits

Savings from reductions in reduced congestion formation are only a portion of the value of improved incident response. Although this study did not attempt to quantify the safety benefits of incident response, they are important to consider when the benefits from incident response are examined. As noted above, this study found that the probability of a crash occurring roughly doubles when an incident has influenced travel conditions. At a minimum, shortening the length of an incident's duration decreases the duration of congestion linearly. Where quick incident response can prevent congestion from forming or can clear an incident before it can trigger early congestion formation during a commute peak, the reduction in the time during which additional crashes may occur is very significant.

Even if incidents are cleared at times when and locations where the incident will not cause congestion to form, the incident management action still has considerable value because 1) it removes the distraction the incident causes and 2) it removes debris and other road hazards that can create dangerous conditions. For example, when an incident response team member stops on the side of the freeway in the off-peak travel direction to remove a piece of debris or help a stranded motorist, that recorded incident does not directly “reduce delay” because the “incident” recorded in WITS occurs at a time when and in a direction where it causes no delay. However, that debris retrieval and/or motorist assistance removes hazards that have the potential to cause significant problems later. In addition, effective incident scene management is an important aspect of WSDOT’s incident management efforts because it makes the incident scene a safer working environment for first responders.

Note that none of the values of these safety benefits were included in the dollar value of incident management presented earlier in this report.

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

### When and Where Incident Response Makes Sense

To determine where incident response makes economic sense, the dollar value of incident response must be compared with the cost of providing incident response, and locations must be selected where sufficient incidents occur. These same three criteria can be used to help prioritize different cost beneficial incident management activities.

Statistics obtained from WSDOT indicate that, on average, WSDOT incident response costs around $50 per hour to provide.[50] This value includes the cost of labor and equipment. These costs vary somewhat, depending on the type of equipment deployed, as well as a variety of other factors. Larger, more capable response trucks (heavier tow trucks) cost more but can also more quickly clear a greater percentage of incidents without having to call (and wait) for additional incident response resources.

To obtain a positive benefit to cost ratio at this basic rate and at the "average benefits rate" discussed in the previous section (e.g., $244/minute of incident) requires one incident response action for each five hours of incident response activity if only travel time savings are included. However, this is only true if the basic conditions under which the $244/minute benefit value are maintained, i.e., traffic volumes are high enough

[50] This dollar value was obtained from WSDOT staff. As with many average costs, this figure is useful for a simplified statewide analysis. It is not, however, representative of incident management costs at all locations throughout the state. In some cases, incident management can be done less expensively because of specific efficiencies gained though cooperation with other agencies. In other cases, it will be much more expensive, for example because of an inability to deploy incident management resources efficiently as a result of geographic constraints or temporal constraints due to changing traffic conditions that affect when and where incident response can be effectively applied.

to generate the delay savings estimated. Safety benefits could be added on top of this value, but this study did not attempt to compute the dollar value of those benefits.

The next section provides some basic guidance about when roadway volumes are high enough for fast incident response to either help prevent congestion from forming or significantly limit the scope of that congestion.

## The Roadway Conditions That Need to Be Present for Incident Response to Be Effective at Reducing Congestion

Both the analysis of real performance data and previously published findings indicate that even minor traffic incidents can create congestion whenever the V/C ratio reaches about 0.7 for a two-lane (one-direction) freeway or 0.8 on a three-lane or larger freeway. Larger incidents cause congestion at even lower volumes.

Because the goal is to clear incidents before congestion occurs (the largest travel time and safety benefits accrue when incidents can be cleared before congestion occurs), incident response actions—even for minor incidents—are likely to be cost-beneficial whenever V/C ratios exceed about 0.6 for two-lane roads and 0.7 for larger roads, especially when those V/C conditions occur at the beginning of a rise in traffic volume (e.g., at the beginning of a peak period).

Unless they are in response to large traffic disruptions, which tend to occur infrequently, incident response actions taken in V/C conditions lower than these rates are unlikely to result in travel time savings of sufficient value to outweigh the cost of the incident response.

## RECOMMENDATIONS

By combining the equation illustrated in Figure 20 with the $50 per hour cost of incident response, and assuming that the application of incident response resources results in a 2.5-minute savings in incident duration per non-crash incident and a 5-minute reduction in the duration of crash-involved incidents, it is possible to estimate the following:

> Roadway segments that produce roughly 45 crashes per year in one direction of travel will exhibit enough savings in travel time from incident response to warrant the deployment of incident response on the basis of travel time savings alone.

Two additional constraints need to be applied to that basic statement.

- The 45 crashes need to occur within a limited geographic area (roughly a 5- to 7-mile stretch of freeway).
- Roving incident response activities are only financially warranted during times when volumes exceed a V/C ratio of 0.6 on two-lane (in one direction) roadways or 0.7 on three-lane or larger roads.

The first of these constraints helps identify locations where sufficient, concentrated crash and incident activity takes place to warrant routine incident response deployment. The second constraint ensures that sufficient volume is present to produce delay savings. This second constraint may mean that active (roving) incident response patrols are warranted during only relatively limited hours of the day in some locations. The second constraint may also be relaxed if the roadway lacks shoulders or has other right-of-way constraints that 1) make disabled vehicles particularly hazardous to both those involved and other motorists, or 2) limit the ability of disabled vehicles to move sufficiently far off the right-of-way to limit the hazard they create.

In some locations across the state, short duration commute peaks (less than two hours) may create labor utilization issues in deploying incident response teams. In other locations, incident response deployment may be best associated with recreational traffic movements. For example, incident response deployed during peak weekend travel movements on I-5 through Centralia/Chehalis during many Thursday and Friday evenings and on many Sundays probably show a significant benefit/cost ratio.

In rural areas subject to heavy recreational traffic volumes, incident response teams may have significant benefit/cost ratios in terms of travel savings if those resources can be cost effectively deployed during periods when traffic volumes meet the V/C criteria identified above. Unfortunately, at those locations the statewide average of $50/hour to provide incident response services may be the least applicable because of the need to move both specialized equipment and trained incident response personnel to locations so remote.

Consequently, additional analysis is required to determine whether it is possible to cost effectively deploy incident response team resources in more remote recreational areas, given the distances involved, as well as the unique timing of the peaking of those recreational traffic volumes, and the unique vehicle types operating on those roads. (For example, light duty incident response trucks may not be able to effectively handle large recreational vehicles, which may make up a significant portion of disabled vehicles on a recreational route.)

WSDOT might be able to reduce the cost of providing incident response in these areas by using different approaches to labor utilization. It could also develop unique working relationships (such as the fast tow truck response previously used in the Olympic region) to gain access to existing incident response equipment already deployed in the area, rather than paying to redeploy its own equipment from the urban areas where that equipment is most commonly stationed. Whether these strategies make financial and operational sense will depend on the specifics of resource and budget availability. Currently permissible and/or potential labor utilization strategies (location, training, and equipment needs) that might be used in these areas were not examined as part of this study.

# APPENDIX A
# VARIABLE DEFINITIONS

This appendix describes the variables that are present in the data sets developed as part of the analysis of congestion causes performed by the University of Washington's Washington State Transportation Center (TRAC-UW.) This work was performed as part of the SHRP2 L03 project.

As noted in the main report, raw data were obtained from a variety of sources. Time, date, and location information (state route and mile post) were used to combine the various data items. Data were stored in a flat file record format, where each record in a file represents all data present for a specific 5-minute interval in the year 2006 for a given direction for a given study segment. Consequently, each file contains 105,120 records of data. Because a separate file is used for each direction for each study corridor, there are 42 of these summary files produced for the SHRP2 L03 project.

The primary data storage and analysis system was Microsoft Excel. (Note, the 2007 version – or later – is needed for this effort, because the number of records present in each file exceeds the allowable limit for earlier versions of Excel.) For a wide variety of analyses, these records were also read into various statistical packages (SPSS, SAS, R, etc…) which allowed efficient computation of statistical tests.

While a more capable database management system would be far more useful in the long term, the use of Excel allowed far easier development, testing, and analysis of derived statistics. Many of the statistics present in the analysis database are dependent on one or more data items from one or more prior time periods on that roadway segment. In Excel it was relatively easy to create these variables, test the variables, and visually examine how the variables reacted to changing traffic conditions (e.g., high/low volume, high/low speeds, etc.)  It was also possible to easily find and examine how new test variables changed over time, given multiple different secondary inputs. It is also easy to identify specific anomalies (e.g., time periods with large amounts of congestion, but no traffic disruptions noted by a newly computed test variable, and track the performance of that computation over time.) This process allowed the research team to identify specific computational techniques that did not work consistently. It also produced a better analysis database.

Note that the actual Excel computational formulas are not all included in these final datasets. Including all of the computations causes Excel to exceed the number of computations allowed in a single file. This causes unstable behavior within Excel. Consequently, once a computational variable was determined to work as intended, the data resulting from that latest series of computations was converted from an active Excel formula (i.e., recomputed each time variables were recomputed within Excel) to a constant. This was normally accomplished by simply saving the dataset as a CSV file and re-importing those values into a new Excel file. In other cases, especially cases were very complex logical processes were necessary to compute new row values, a separate "computational spreadsheet" was used to produce one or more new columns of data. These were then cut-and-pasted into the primary analysis spreadsheets.

The following variables can be found in the final data sets developed and used in the SHRP2 L03 project by TRAC-UW. In some datasets, specific variables were not computed. When this occurs, the term "empty" is included in the variable name column, indicating that this variable does not exist for the spreadsheet being examined.

| Column | Variable Name | Definition |
|---|---|---|
| A | link_name | Roadway and Direction |
| B | direction | East, West, North or South |
| C | Date | Date (M/D/Yr) |
| D | Time | 0:00 to 23:55 in 5 minute increments |
| E | Decimal Time | Time expressed as a decimal |
| F | Hour | The hour of the day |
| G | Day of Week | Numeric day with 1=Sunday to 7=Saturday |
| H | Month | Numeric month with 1=January to 12=December |
| I | Day | Numeric day from 1 to 31 of each month |
| J | [route]_[segment]_TT[dir] | Travel Time [direction] on [route], [segment] section |
| K | avg_occupancy | Average Occupancy from Operation Archive |
| L | avg_vht | Average VHT from Operation Archive |
| M | avg_volume | Do not use, not a good value |
| N | Accident Severity | Severity of Accident (1 = PDO, 2 = injury, 3 = fatal) |
| O | Accident | Accident Variable, equal 1 when an accident occurred |
| P | Accident Severity (Calc) | The total number of 5-minute time periods during which a queue, influenced by a given accident lasts. (Value exists only for the first five minute period during which the accident occurs.) |
| Q | Max_closure_length | Maximum duration closure of lane(s) from Operation Archive |
| R | Closure Severity | The total number of 5-minute time periods during which a queue, influenced by a given lane closure lasts. (Value exists only for the first five minute period during which the closure occurs.) |
| S | Max_incident_length | Maximum duration of incident from Operation Archive |
| T | Incident Severity | The total number of 5-minute time periods during which a queue, influenced by a given incident lasts. (Value exists only for the first |

| | | |
|---|---|---|
| | | five minute period during which the incident occurs.) |
| U | Accident Rubbernecking | Has a value of 1 whenever there is an accident on the other side of the road |
| V | Incident Rubbernecking | Has a value of 1 whenever there is an incident on the other side of the road |
| W | Delay Variable | Computed Vehicle delay (Actual Travel time – Free Flow Travel Time) * Maximum Section Volume |
| X | IF Variable | Variable describing "event effects present" during that five-minute time period:<br>0- No cause of congested noted in available variables<br>1- ONLY Acc Queue Extended is present<br>2- ONLY Inc Queue Extended is present<br>3- ONLY Preciphour is present (it has rained in the past hour)<br>4- BOTH Acc Queue Extended and Inc Queue Extended are present<br>5- BOTH Acc Queue Extended and Preciphour are present<br>6- BOTH Inc Queue Extended and Preciphour are present<br>7- All three variables are present<br><br>Note: This variable is based on the 5+15 queue extended methodology[1] |
| Y | Max_occupancy | Maximum Occupancy from Operation Archive |
| Z | Max_speed | Maximum Speed from Operation Archive |
| AA | Max_volume | Maximum Volume from Operation Archive |
| AB | Min_speed | Minimum Speed from Operation Archive |
| AC | Min_volume | Minimum Volume from Operation Archive |
| AD | Sum_vht | Sum of the VHT from Operation Archive |
| AE | Sum_vmt | Sum of the VMT from Operation Archive |
| AF | Accident -5+20 | Associated with Accident variable (Column O) – time periods back 5 minutes and ahead 15 minutes from an accident (the variable is slightly misnamed.) |
| AG | Acc Queue Extended[1] | Associated with Accident variable (Column O) – time periods extended from accident time period according to queue extended method (see end note) |
| AH | Inc -5+20 | Associated with Max_incident_length variable (Column Q) |
| AI | Inc Queue Extended[1] | Associated with Max_incident_length variable (Column Q) |

| | | |
|---|---|---|
| AJ | Closure -5+20 | Associated with Max_closure_length variable (Column P) |
| AK | Closure Queue Extended[1] | Associated with Max_closure_length variable (Column P) |
| AL | Acc + Closure -5+20 | Associated with the combination of Accident & Max_closure_length variables (Column O and P) |
| AM | Acc + Closure Queue Extended[1] | Associated with the combination of Accident & Max_closure_length variables (Column O and P) |
| AN | Acc + Inc -5+20 | Associated with the combination of Accident & Max_incident_length variables (Column O and Q) |
| AO | Acc + Inc Queue Extended[1] | Associated with the combination of Accident & Max_incident_length variables (Column O and Q) |
| AP | Acc + Inc + AccRub -5+20 | Associated with the combination of Accident, Max_incident_length & Accident Rubbernecking variables (Column O, Q, and R) |
| AQ | Acc + Inc + AccRub Queue Extended[1] | Associated with the combination of Accident, Max_incident_length & Accident Rubbernecking variables (Column O, Q, and R) |
| AR | Acc. + Inc. + Rub -5+20 | Associated with the combination of Accident, Max_incident_length, Accident Rubbernecking & Incident Rubbernecking variables (Column O, Q, R, and S) |
| AS | Acc. + Inc. + Rub Queue Extended[1] | Associated with the combination of Accident, Max_incident_length, Accident Rubbernecking & Incident Rubbernecking variables (Column O, Q, R, and S) |
| AT | Space Mean Speed | Average Speed derived from Travel Time and Segment Length |
| AU | Rounded Speed 5.0 | Rounded Average Speed (Column AT) to the nearest 5.0 mph |
| AV | Rounded Speed 2.5 | Rounded Average Speed (Column AT) to the nearest 2.5 mph |
| AW | Rounded Speed 2.0 | Rounded Average Speed (Column AT) to the nearest 2.0 mph |
| AX | Regime | The condition of the road segment (minimum speed observed and maximum volume observed) (1 = lots of capacity left, 2 = less than one lane of capacity, 3 = minimal capacity left, speed slowed slightly, 4 = congestion present, 5 = recovery underway) |

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|---|---|---|
| AY | Holiday | Has a value of 1 on the following days: Jan 2, Feb 20, May 29, July 3, July 4, Sep 4, Nov 10, Nov 23, Nov 24, Dec 25, Dec 26 |
| AZ | Rain | 1 if NOAA WeatherType of Rain (RA), Mist(BR), Drizzle(DZ), T-storm(TS), or Haze(HZ) for the most recent time period reported (0 otherwise) |
| BA | Heavy_Rain | 2 if Rain as defined above with NOAA hourly precipitation > 0.125 inches (0 otherwise) |
| BB | Wind | 3 if NOAA Wind speed greater than 19 mph (0 otherwise) |
| BC | Snow | 4 if NOAA WeatherType of Snow(SN), Freezing(FZ), Sm Hail(GS), Hail(GR), Ice Pellet(PL) or Squall(SQ) for the most recent time period reported (0 otherwise) |
| BD | Fog | 5 if NOAA WeatherType of Fog(FG) OR NOAA Visibility < 0.25 (0 otherwise) |
| BE | Wind-Speed | Wind speed (in knots) directly from NOAA data for the most recent time period reported |
| BF | Wind-Gusts | Wind speed for gusting winds (in knots) directly from NOAA data for the most recent time period reported |
| BG | Precip_hour | Hourly precipitation (in inches and hundredths) from the most recent reported hourly NOAA data |
| BH | Precip_2hours | Sum of last 2 hours of precipitation |
| BI | Precip_4hours | Sum of last 4 hours of precipitation |
| BJ | Precip_8hours | Sum of last 8 hours of precipitation |
| BK | Hours_since_rain | Number of hours since last reported precipitation of any amt |
| BL | R2-R4_5 min | Tells us that there was a change from Regime 2 to Regime 4 within the last 5 minutes |
| BM | R2-R4_10 min | Tells us that there was a change from Regime 2 to Regime 4 within the last 10 minutes |
| BN | R2-R4_15 min | Tells us that there was a change from Regime 2 to Regime 4 within the last 15 minutes |
| BO | R3-R4_5 min | Tells us that there was a change from Regime 3 to Regime 4 within the last 5 minutes |
| BP | R3-R4_10 min | Tells us that there was a change from Regime 3 to Regime 4 within the last 10 minutes |
| BQ | R3-R4_15 min | Tells us that there was a change from Regime 3 to Regime 4 within the last 15 minutes |
| BR | Number_of_2ndary_events_Accidents | Uses the “Severity” (duration) variable and then looks to see how many accidents and incidents occur within the duration (time the queue is present) of the accident in question. |

| | | |
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| BS | Numb_Sec_Rubnking_Accidents | Uses the "Severity" (duration) variable and then looks to see how many accident and incident rubbernecking events occur within the duration (time the queue is present)of the accident in question. |
| BT | Number_of_2ndary_events_Closures | Uses the "Severity" (duration) variable and then looks to see how many accidents and incidents occur within the duration (time the queue is present) of the closure in question. |
| BU | Numb_Sec_Rubnking_Closures | Uses the "Severity" (duration) variable and then looks to see how many accident and incident rubbernecking events occur within the duration (time the queue is present) of the closure in question. |
| BV | Number_of_2ndary_ events_Incidents | Uses the "Severity" (duration) variable and then looks to see how many accidents and incidents occur within the duration (time the queue is present) of the incident in question. |
| BW | Numb_Sec_Rubnking_ Incidents | Uses the "Severity" (duration) variable and then looks to see how many accident and incident rubbernecking events occur within the duration (time the queue is present) of the incident in question. |
| BX | 5+5 Queue Extended Crash[1] | The queue extended variable (1 = influence is present) using the 5 minute follow on period as the basis for computation) crashes only |
| BY | 5+5 Queue Extended Incident[1] | The queue extended variable (1 = influence is present) using the 5 minute follow on period as the basis for computation) incidents only |
| BZ | 5+5 Queue Extended Closure[1] | The queue extended variable (1 = influence is present) using the 5 minute follow on period as the basis for computation) closures only |
| CA | 5+5 Queue Extended Rubernecking[1] | The queue extended variable (1 = influence is present) using the 5 minute follow on period as the basis for computation) either rubbernecking variable is a active |
| CB | 5+5 Queue Extended Incident or Accident[1] | The queue extended variable (1 = influence is present) using the 5 minute follow on period as the basis for computation) if an incident or accident has occurred |
| CC | Mainline IF Variable 5+5 | Sets a value 1-8 (see column X definition for what each value means) indicating what influences are present to "cause" congestion. – Examines only WITHIN segment variables – and does NOT include construction effects |

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| | | This version of the "IF" variable is based on the 5+5 Queue Extended computations and the variables in columns BX through CB |
| CD | Construction variable | 1: Construction<br>2: All lanes closed<br>3: 520 weekend closures<br>4: Construction happens in two locations at one time in the same segment. |
| CE | IF 5+5 Construction Included | Variable describing "event effects present" during that five-minute time period. Uses the 5+5 Queue Extended variables as input AND includes notifications of construction traffic management activities<br>0- No cause of congested noted in available variables<br>1- ONLY Inc Queue Extended is present<br>2- ONLY Acc Queue Extended is present<br>3- ONLY Preciphour is present (it has rained in the past hour)<br>4- BOTH Acc Queue Extended and Inc Queue Extended are present<br>5- BOTH Inc Queue Extended and Preciphour are present<br>6- BOTH Acc Queue Extended and Preciphour are present<br>7- All three variables are present<br>8- Ramp congestion, but no cause for ramp congestion is known<br>9- Construction activity going on<br>10- Construction activity plus ramp congestion<br>11- Construction activity plus an incident queue extended<br>12- Construction activity plus an accident queue extended<br>13- Construction activity plus rain<br>14- Construction activity plus an accident and incident queues extended<br>15- Construction activity plus an incident queue extended and rain<br>16- Construction activity plus an accident queue extended and rain<br>17- Construction activity plus an accident and incident queues extended and rain |
| CF | Delays caused by ramps / downstream queues ($1^{st}$ | A non-zero value is present when loop detectors at a ramp have lane occupancy |

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| | location) | greater than 35 percent. (This is used as a measure that queues have formed on the ramp and are likely to cause congestion on the connecting roadway.) Uses the same variable definitions as in column CE. The name in the header row changes from dataset to dataset to describe the specific ramp and/or downstream segment. There are three columns allocated for these "external to the road segment" variables CF, CG, and CH. |
| CG | Delays caused by ramps / downstream queues (2nd location) | See CF definition |
| CH | Delays caused by ramps / downstream queues (3rd location) | See CF definition |
| CI | IF – Single Cause (5+5) | Combines the "causes" defined in the variables in CE, CF, CG, and CH. The effects are cumulative. So that a "1" on the mainline and a "2" on a connecting ramp means this variable would become a "4" (both accident and incident effects.) |
| CJ | Rounded | Converts the "Time" variable to half hour increments (0 for 0:00 through 0:25, 0.5 for 0:30 through 0:55, 1 for 1:00 through 1:25 to allow easy aggregation of results on a half hour basis. |
| CK | CrashVSVolume | Is a three category variable. The variable is set to 0 when no known "disruption" is affecting roadway performance. It is set to the value "1" when a crash is affecting roadway performance. It is set to a "2" when some other (non-crash) is influencing roadway performance. (The value is "1" when a crash influences performance, even if other factors also influence that performance.) |
| CL | IncidentVsVolume | Is similar to the CrashVSVolume variable, except that the value "1" is used to indicate that an incident reported by WSDOT's incident response team is influencing roadway performance. A "2" indicates some disruption other than something reported by WITS is influencing roadway performance. |
| CM | Queue Duration Incidents | The number of 5 minute time periods during which the roadway is influenced (traffic is slower than the fastest travel time observed |

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| | | during an incident) for a defined incident. One value exists for each incident for which there is a valid travel time. That value is placed in the row that corresponds to the first occurrence of the incident. |
| CN | Queue Duration Crashes | The number of 5 minute time periods during which the roadway is influenced (traffic is slower than the fastest travel time observed during a crash) for a defined crash. One value exists for each crash for which there is a valid travel time. That value is placed in the row that corresponds to the first occurrence of the crash. |
| CO | Queue Duration Closures | The number of 5 minute time periods during which the roadway is influenced (traffic is slower than the fastest travel time observed during an incident) for a defined incident involving a lane closure. One value exists for each closure for which there is a valid travel time. That value is placed in the row that corresponds to the first occurrence of the closure. |
| CP | Queue Duration Incidents & Crashes | The number of 5 minute time periods during which the roadway is influenced (traffic is slower than the fastest travel time observed during an incident) for any defined incident or crash. One value exists for each incident or crash for which there is a valid travel time. That value is placed in the row that corresponds to the first occurrence of each incident or crash. |
| CQ | Rubbernecking Influence Duration 5+5 | The number of 5 minute time periods during which the roadway is influenced (traffic is slower than the fastest travel time observed during an rubbernecking event) for a defined rubbernecking event. One value exists for each rubbernecking event for which there is a valid travel time. That value is placed in the row that corresponds to the first incidence of the rubbernecking event. |
| CR | When Congestion Ends AM[ii] | This variable places a "1" in the first row which defines a "non-congested" condition during the AM peak period. "Not Congested is defined as being four consecutive rows where travel times are faster than 1.05 times travel at the speed limit. i.e., faster than 57.15 mph.) For the AM time period, this event can not take |

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| | | place prior to 7 AM. It can occur any time AFTER 7 AM. The row selected is the FIRST row in which the four consecutive rule is observed. Congestion due to a "late occurring" incident may cause congestion after this occurrence. This congestion is ignored by this variable. |
| CS | Incident Effected AM – 4 AM Start | If ANY incident occurs after 4 AM on a given day, this variable is set to "1" at the time the first incident occurs. It remains set to "1" for the rest of the day. |
| CT | Crash Effected AM – 4 AM Start | If ANY crash occurs after 4 AM on a given day, this variable is set to "1" at the time the first crash occurs. It remains set to "1" for the rest of the day. |
| CU | Selection AM | The section variable is set to "1" if the day is a Tuesday, Wednesday, or Thursday, AND it is not a designated holiday AND the "When Congestion Ends AM" variable is set to "1" |
| CV | Effected Inc Vs Crash Vs Nothing AM | This categorical variable is set to "0" unless: a crash has occurred (value = 1) or an incident has occurred (value = 2). When both an incident and crash have occurred, the value is set to "1" |
| CW | When Congestion Ends PM | This variable places a "1" in the first row which defines a "non-congested" condition during the PM peak period. "Not Congested is defined as being four consecutive rows where travel times are faster than 1.05 times the travel time at the speed limit. i.e., faster than 57.15 mph.) For the PM time period, this event can not take place prior to 4 PM. It can occur any time AFTER 4 PM. The row selected is the FIRST row in which the four consecutive rule is observed. Congestion due to a "late occurring" incident may cause congestion after this occurrence. This congestion is ignored by this variable. |
| CX | Incident Effected PM – 4 PM Start | If ANY incident occurs after 3 PM on a given day, this variable is set to "1" at the time the first incident occurs. It remains set to "1" for the rest of the day. |
| CY | Crash Effected PM – 4 PM Start | If ANY crash occurs after 3 PM on a given day, this variable is set to "1" at the time the first crash occurs. It remains set to "1" for the rest of the day. |

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|---|---|---|
| CZ | Selection PM | The section variable is set to "1" if the day is a Tuesday, Wednesday, or Thursday, AND it is not a designated holiday AND the "When Congestion Ends PM" variable is set to "1" |
| DA | Effected Inc Vs Crash Vs Nothing PM | This categorical variable is set to "0" unless: a crash has occurred (value = 1) or an incident has occurred (value = 2). When both an incident and crash have occurred, the value is set to "1" |

Footnotes:

[1] Queue Extended Influence: assumes that once an incident has occurred, any travel time increase along the corridor is associated with the (potential) queue that forms as a result of that incident, and thus all travel in the corridor is "affected" by that incident until the queue has fully dissipated. Mathematically, this method assumes that any increase in travel time that occurs while an incident is active is associated with that incident. That is, if travel times increase over the travel time experienced at any time during an incident, that longer travel time is caused (at least in part) by the incident, even if other events are occurring in the corridor. (See example below.) An incident is defined as being "active" in two ways 1) the incident is actually recorded as taking place within that specific 5-minute period. 2) a trip that entered the test section in the time period immediately prior to that incident occurring or immediately after that incident stopped occurring.

These time periods are indicated as 5+5 in the variable names in the study spreadsheet. They account for the fact that a trip starting at 7:00 but requiring 10 minutes to traverse a section, may be adversely affected by an incident which occurs during the 7:05 time period. Conversely, the queue caused an incident occurring and cleared in the 7:05 time period, might not grow to the point where the loop sensors used in this analysis "notice" that queue until the 7:10 time period. These additional 10 minutes were referenced internally as the "time extended" incident period. The "Queue extended" incident period uses these measures of "extended" duration within which to find the base travel time against which continued queuing is measured. (See two paragraphs below for the definition of how this process works.)

The initial test of the "time extension" variable was 5 minutes prior and 15 minutes after an incident, PLUS the (minimum) 5-minute period containing the incident. This initial set of analyses was called 5+20. The variables created and used in these initial computations are still present in the data set and are stored in columns AF through AS. The 15 minute extension was determined to be too lenient. That is, it was unclear that the delays beginning 15 minutes after the incidents had been cleared were related to the incident. This led to the adoption of the 5+5 rule. The 5+20 variables were not used in any of the published analyses, but have been left in the analysis data set to allow future analysis should they be of interest.

The Queue Extended computation begins by determining the fastest corridor travel time experienced in the five minute period before the disruption occurs through 5 minutes after that disruption is reported to have ended. All subsequent travel periods are assumed to be "influenced" by that disruption until corridor travel times return to (are equal to or faster than) the fastest time observed during the "5+5" time period (5 minutes prior to the incident through 5 minutes after the disruption.) By changing the definition of "disruption" and reapplying these basic rules, the influence of any combination of disruptions can be indicated. This approach does mean that for the analytical purposes of this project – the "influence" of any disruption lasts at least 15 minutes.

In off-peak conditions (where low volume exists – or in other words there is considerable unused roadway capacity), this approach is an excellent measure of incident effects. If the incident occurs at the beginning of peak period conditions, the approach is likely to associate all of the peak period congestion with the incident. This is assumed to be acceptable based on the concept that the incident condition combined with the growing peak period traffic volume will cause congestion to form earlier than would otherwise have occurred on that particular peak period, and the increased congestion will cause travel times to remain elevated later into the tail end of the peak period. While this is a "liberal" measure of the congestion caused by a given incident, and may overstate the extent of any given incident's congestion causing influence, it does replicate the "lasting influence" that an incident can have on roadway performance. An example of how the "Queue Extended Influence Area" works and why it is used is as follows.

On Thursday, February 23, 2006 at 2:30 PM, on SR 520 westbound headed into the city of Seattle, traffic is flowing slightly better than normal (travel time = 494 seconds versus an annual mean travel time of 549 seconds for the 2:30 PM time period.) A lane closing incident, which takes 17 minutes to clear, occurs. During that incident, travel times through the corridor slow to 738 seconds. After the incident is cleared, congestion begins to clear out, but does not return to its pre-incident condition, before increasing traffic volumes associated with the start of the PM peak period cause travel times to again degrade. (That is, the queue formed by the incident has yet to fully clear and thus PM peak period congestion occurs earlier than normal, because the incident caused queue has reduced the roadway's capacity, making it unable to serve the volumes associated with the beginning of the PM peak shoulder period.) Travel times in the PM peak are thus slower than normal throughout the peak period, and do not return to "pre-incident" conditions until well after the PM peak period ends. (Maximum travel time on this day in the "traditional" PM peak is 1,787 seconds at 6:05 PM.) Before the PM peak ends, a two-car, injury collision occurs (at 6:50 PM) within the roadway analysis segment. Travel speeds (already bad) degrade considerably after the accident (reaching 2,960 seconds, or an average speed of 8.5 mph for the 7 mph road segment), and don't return to pre-accident conditions (still much slower than the original pre-incident conditions) until 8:05 PM. However, once again, before the queue can fully dissipate, a second injury accident occurs at 8:35 PM. Travel times again climb, despite the lower traffic volumes experienced at 8:30 in the evening, peaking this time at just over 1,900 seconds. Only after this accident and its resulting queue is cleared, do travel times finally return to a point faster than that found at 2:35 PM, just prior to the first incident. This occurs at 10:10 PM. Further contributing to congestion on this day are two other factors, 1) a higher travel demand than normal caused by a University of Washington's men's basketball game (the team was #17 in the country at the time) which occurred that evening at the University basketball arena located at the western end of this analysis corridor. (the game was a 10,000 person sell out event, and started at 7:30 PM), and 2) the fact that it rained off and on that afternoon and evening. (The 6:50 PM accident notes rain and wet pavement conditions, while the 8:35 PM accident notes dry pavement and overcast conditions.)

The reality of this day is that a variety of events helped cause the congestion experienced by travelers. However, the "instigating event" appears to have been the original lane blocking incident. Without that event and the extended queues it creates, it is possible that neither rear-end accident would have occurred. (Although it is impossible to directly tie the rear-end collisions with a specific queue length.) On the other-hand, delays would have been considerably smaller without the two accidents and without the added travel demand caused by the basketball game. Similarly, the rain may very well have also contributed to the cause of congestion on the corridor as well as the occurrence of both of the accidents, as well as to the time it took for the roadway to recover from all three events. Consequently, we believe that the "queue extended influence" variable works as defined – it indicates that a given event is likely to have influenced – but not totally caused – the level of congestion experienced on the roadway.

The "queue extended" approach successfully tracks the existence of that queue to that instigating event. What remains is to determine how to describe the relative importance of that event versus the contributions of the other causal factors.

[1] – A discussion concerning the "When Congestion Ends" variable - Considerable testing went into the selection of the time period at which "congestion" was described as "ending." The project team was concerned that variations in speed both over time and over the length of the study section might give false indications that free flow travel had returned to the study section, when what was really being measured was a temporary improvement in conditions caused by random fluctuations in traffic density. Consequently, it was decided that the determination of when congestion abated must include both the facts that speeds were free flow throughout the study section and that they remained so for long enough to ensure that the observation was not just a temporary change in conditions. After testing the variation of travel times at the end of the peak periods on multiple study sections, it was determined that 20 minutes of consecutive travel times below a set value ensured that flow remained in a fluid state. However, while 20 minutes of fluid flow are required, the "end point" for congestion is indicated as the first of those 20 minute periods. The selection of the speed at which congestion ended was set based on the available data. The analysis data set had three measures of "speed" – maximum speed in the segment, minimum speed in the segment, and travel time through the segment. Travel time was selected as the variable of choice for two reasons, 1) on longer test sections, it more effectively replicates the travel conditions experienced by motorists – when compared to maximum and minimum speed values selected from different locations within that segment, but within a single time slice. 2) travel time effectively accounts for the importance of different speed measurements along the length of the segment, while minimum and maximum values can shift from one location to another from one time slice to another. Thus use of travel time moderates the importance of any one slow speed measurement, while the 20-minute requirement ensures that fluctuations in the observed travel times do not artificially cause the procedures to end congestion too quickly.
Tests were made using 5 percent, 10 percent and 20 percent increases in travel times, corresponding to average segment speeds of 57, 54, and 48 mph. Each of these travel time increases can be achieved in a variety of ways, ranging from modest slowing throughout the section, to a more substantial slowing at any one speed measurement location with a section. Tests of these speeds indicated that on most corridors, the slower travel times were frequently met during the middle of the traditional peak periods. As a result, they were assumed to be too lenient a travel time measure. (That is, one location of moderate congestion - speeds below 40 mph – could occur while travel times remained fast enough to meet the 10 percent increase criteria. Thus, it was necessary to select the more stringent criteria of only a five percent increase in travel times. When combined with the 20 minute requirement, this gave results which matched local experts general impressions in all cases except 11 corridors during the AM peak period. These corridors all experienced some level of routine vehicle slowing during the middle of the day, and thus frequently never reached "the end of congestion" as defined by the 5 percent and 20 minute rules until after the PM peak had ended. As a result, for those 11 routes, for the AM peak, either the 10 or 20 percent rules were applied in order to ensure that congestion "ends" prior to noon on days when no-incident occurs. The lowest percentage increase which ended mean travel time prior to noon for days in which no incident occurred was selected for each of these 11 corridors. (That is, if the mean "congestion end" time point for non-disrupted days occurred prior to noon based on a 10 percent increase in travel time, that value was used. The 20 percent value was only used if the 10 percent value forced congestion to end after noon.)

## APPENDIX B
## STATISTICS RELATED TO THE END OF CONGESTION

Two sets of statistical comparisons were made regarding the end of congestion. One was made assuming a normal distribution. The other was made using the Anderson-Darling K-sample test,[51] a non-parametric test which allows comparison of two populations with skewed distributions. The resulting tables for AM and PM periods are shown on the following pages. The results are generally very similar, with many of the observed differences easily attributable to how these two types of tests treat the importance of outliers given the total number of data points in samples being tested.

In the tables that follow, green cells indicate statistically significant differences at the 95 percent confidence level. Yellow cells indicate differences at the 90 percent confidence level. Red numbers indicate a negative value.

**Table B-1: P-Values For Comparing The Ending Time of Congestion Under Disruption Versus Non-Disruption Conditions**

| Route | AM Peak Period Crash Influenced | AM Peak Period Incident Influenced | AM Either Crash or Incident Influenced | PM Peak Period Crash Influenced | PM Peak Period Incident Influenced | PM Either Crash or Incident Influenced |
|---|---|---|---|---|---|---|
| I-405 Bellevue NB | 0.00 | 0.00 | 0.00 | 0.00 | 0.40 | 0.01 |
| I-405 Bellevue SB | 0.00 | 0.00 | 0.00 | 0.03 | 0.20 | 0.11 |
| I-405 Eastgate NB | 0.01 | 0.21 | 0.03 | 0.00 | 0.47 | 0.02 |
| I-405 Eastgate SB | 0.01 | 0.20 | 0.01 | 0.03 | 0.49 | 0.11 |
| I-405 Kennydale NB | 0.00 | 0.16 | 0.00 | 0.01 | 0.25 | 0.01 |
| I-405 Kennydale SB | 0.00 | 0.06 | 0.00 | 0.63 | 0.32 | 0.60 |
| I-405 Kirkland NB | 0.68 | 0.00 | 0.01 | 0.07 | 0.62 | 0.04 |
| I-405 Kirkland SB | 0.02 | 0.01 | 0.03 | 0.00 | 0.00 | 0.00 |
| I-405 North NB | 0.00 | 0.03 | 0.00 | 0.00 | 0.55 | 0.01 |

[51] Scholz, F.W. and M. A. Stevens. K-Sample Anderson-Darling Tests. Journal of the American Statistical Association, Vol 82, No. 399, 1987, pp. 918-924.

| | | | | | | |
|---|---|---|---|---|---|---|
| I-405 North SB | 0.00 | 0.00 | 0.00 | 0.00 | 0.44 | 0.01 |
| I-405 South NB | 0.00 | 0.02 | 0.00 | 0.11 | 0.34 | 0.24 |
| I-405 South SB | 0.01 | 0.01 | 0.00 | 0.48 | 0.32 | 0.43 |
| I-5 Everett NB | 0.00 | 0.61 | 0.00 | 0.00 | 0.01 | 0.00 |
| I-5 Everett SB | 0.00 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 |
| I-5 Lynnwood NB | 0.45 | 0.69 | 0.70 | 0.21 | 0.19 | 0.12 |
| I-5 Lynnwood SB | 0.01 | 0.01 | 0.01 | 0.00 | 0.21 | 0.00 |
| I-5 Nking NB | 0.69 | 0.51 | 0.77 | 0.09 | 0.54 | 0.13 |
| I-5 Nking SB | 0.03 | 0.02 | 0.04 | 0.00 | 0.06 | 0.00 |
| I-5 SeattleCBD NB | 0.55 | 0.51 | 0.00 | 0.42 | 0.54 | 0.00 |
| I-5 SeattleCBD SB | 0.00 | 0.48 | 0.00 | 0.55 | 0.50 | 0.54 |
| I-5 SeattleN NB | 0.55 | 0.51 | 0.00 | 0.42 | 0.54 | 0.00 |
| I-5 SeattleN SB | 0.00 | 0.24 | 0.00 | 0.01 | 0.11 | 0.06 |
| I-5 South NB | 0.08 | 0.49 | 0.30 | 0.00 | - | 0.00 |
| I-5 South SB | 0.05 | 0.04 | 0.05 | 0.15 | 0.40 | 0.25 |
| I-5 Tukwila NB | 0.10 | 0.24 | 0.23 | 0.00 | 0.00 | 0.00 |
| I-5 Tukwila SB | 0.00 | 0.55 | 0.00 | 0.00 | 0.01 | 0.00 |
| I-90 Bellevue EB | 0.69 | 0.69 | 0.85 | 0.01 | 0.16 | 0.02 |
| I-90 Bellevue WB | 0.29 | 0.06 | 0.07 | 0.00 | 0.00 | 0.00 |
| I-90 Bridge EB | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| I-90 Bridge WB | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.00 |
| I-90 Issaquah EB | 0.69 | 0.69 | 0.85 | 0.66 | 0.29 | 0.60 |
| I-90 Issaquah WB | 0.00 | 0.51 | 0.00 | - | - | - |
| I-90 Seattle EB | 0.00 | 0.37 | 0.00 | 0.10 | 0.35 | 0.17 |
| I-90 Seattle WB | 0.00 | 0.05 | 0.00 | 0.63 | 0.30 | 0.58 |
| SR 167 Auburn NB | 0.17 | 0.41 | 0.31 | 0.41 | 0.46 | 0.53 |
| SR 167 Auburn SB | 0.00 | 0.00 | 0.00 | 0.10 | 0.39 | 0.23 |
| SR 167 Renton NB | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 |
| SR 167 Renton SB | 0.00 | 0.00 | 0.00 | 0.16 | 0.20 | 0.12 |
| SR 520 Red EB | 0.46 | 0.65 | 0.69 | 0.44 | 0.63 | 0.67 |
| SR 520 Red WB | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| SR 520 Sea EB | 0.00 | 0.00 | 0.00 | 0.01 | 0.25 | 0.02 |
| SR 520 Sea WB | 0.00 | 0.12 | 0.00 | 0.05 | 0.53 | 0.11 |

**Table B-2: Comparison of Ending Time of Congestion AM Peak Period**

| Route | Non-Event End of Congestion Time | Added Time if Incident Occurs | Added Time if Crash Occurs | Z Score for Incident Comparison | Z Score for Crash Comparison |
|---|---|---|---|---|---|
| I-405 Kennydale NB - AM Peak[52] | 11:47 | 0:34 | 1:33 | 1.265 | 3.368 |
| I-405 North SB - AM Peak | 9:56 | 1:27 | 2:09 | 2.209 | 3.101 |
| I-5 Nking SB - AM Peak[2] | 11:06 | 0:48 | 1:29 | 2.472 | 3.321 |
| I-5 SeattleCBD NB - AM Peak | 12:15 | -0:42 | 1:20 | #DIV/0![53] | #DIV/0![3] |
| I-405 Kirkland SB - AM Peak | 10:16 | 0:56 | 1:14 | 2.590 | 2.732 |
| SR 520 Sea EB - AM Peak | 11:54 | 6:02 | 6:53 | 4.820 | 5.752 |
| I-5 Lynwood SB - AM Peak | 10:06 | 1:57 | 1:39 | 3.048 | 2.659 |
| I-5 South NB - AM Peak | 9:16 | 0:12 | 0:22 | 1.204 | 2.344 |
| SR 167 Auburn NB - AM Peak[54] | 11:40 | 0:51 | 0:59 | 1.318 | 1.576 |
| I-405 Eastgate NB - AM Peak[2] | 11:38 | 0:16 | 1:04 | 1.100 | 2.368 |
| I-5 SeattleN SB - AM Peak | 9:38 | 1:10 | 4:58 | 2.650 | 7.531 |
| I-405 Kennydale SB - AM Peak[4] | 9:08 | 1:19 | 1:23 | 1.674 | 2.083 |
| I-405 South SB - AM Peak[4] | 12:46 | 3:12 | 2:17 | 3.171 | 2.782 |
| SR 167 Renton NB - AM Peak[4] | 9:13 | 1:47 | 1:22 | 2.765 | 2.513 |
| SR 520 Sea WB - AM Peak[2] | 9:51 | 0:47 | 2:54 | 1.694 | 3.412 |
| I-5 Tukwilla NB - AM Peak | 10:06 | 0:14 | 0:32 | 1.103 | 1.778 |
| I-90 Issaquah WB - AM Peak | 9:10 | 0:09 | 0:33 | 0.521 | 4.616 |
| I-90 Bellevue WB - AM Peak | 9:26 | 0:13 | -0:06 | 1.607 | -0.781 |
| I-405 Bellevue NB - AM Peak[2] | 11:01 | 3:34 | 5:00 | 5.252 | 7.928 |
| I-405 South NB - AM Peak[4] | 8:21 | 4:49 | 7:47 | 2.478 | 10.562 |
| I-90 Seattle EB - AM Peak | 8:45 | 0:05 | 1:05 | 0.317 | 5.102 |
| I-90 Seattle WB - AM Peak | 7:35 | 0:42 | 1:52 | 1.238 | 8.146 |
| I-90 Bridge EB - AM Peak | 9:23 | 0:45 | 1:04 | 3.806 | 5.876 |
| I-405 Bellevue SB - AM Peak[2] | 8:27 | 7:56 | 11:07 | 8.517 | 27.434 |
| I-5 Everett SB - AM Peak | 7:08 | 0:06 | 1:06 | 1.975 | 2.398 |
| I-90 Bridge WB - AM Peak | 8:04 | 0:26 | 1:30 | 2.048 | 3.518 |
| I-5 SeattleCBD SB - AM Peak | 9:28 | 1:04 | 4:57 | 2.387 | 8.190 |
| SR 167 Auburn SB - AM Peak | 8:58 | 7:29 | 9:59 | 8.068 | 30.022 |
| I-405 Eastgate SB - AM Peak | 7:22 | 0:07 | 0:32 | 1.294 | 5.227 |
| SR 167 Renton SB - AM Peak | 9:42 | 7:33 | 7:30 | 7.033 | 4.957 |
| I-5 Tukwilla SB - AM Peak | 7:08 | 0:05 | 7:51 | 0.719 | 1.026 |
| SR 520 Red WB - AM Peak | 7:09 | 0:56 | 2:10 | 2.266 | 2.888 |
| I-405 North NB - AM Peak | 7:56 | 0:12 | 1:47 | 1.882 | 1.562 |
| I-5 Everett NB - AM Peak | 7:05 | 0:01 | 0:14 | 1.202 | 1.928 |
| I-5 Lynwood NB - AM Peak | 7:13 | -0:01 | 0:20 | -0.403 | 0.709 |
| I-5 SeattleN NB - AM Peak | 7:07 | 0:04 | -0:02 | 1.332 | #DIV/0![55] |

52 Uses a 10 percent travel time increase as the point where "congestion has abated" rather than the 5 percent norm.
53 Too few non-disrupted days occur to compute a test statistic.
54 Uses a 20 percent travel time increase as the point where "congestion has abated" rather than the 5 percent norm.
55 Too few crash days occur to compute a test statistic.

| | | | | | |
|---|---|---|---|---|---|
| I-90 Bellevue EB - AM Peak | 7:05 | -0:00 | -0:00 | -1.380 | #DIV/0![5] |
| I-5 South SB - AM Peak | 7:07 | 0:08 | -0:00 | 1.047 | -0.204 |
| I-405 Kirkland NB - AM Peak | 7:05 | 0:05 | -0:00 | 1.882 | -1.686 |
| SR 520 Red EB - AM Peak | 7:05 | -0:00 | -0:00 | -0.267 | -2.015 |
| I-90 Issaquah EB - AM Peak | 7:05 | -0:00 | -0:00 | -1.381 | #DIV/0![5] |
| I-5 Nking NB - AM Peak | 7:05 | -0:00 | -0:00 | -1.324 | -1.324 |

**Table B-3: Comparison of Ending Time of Congestion PM Peak Period**

| | Non-Event End of Congestion Time | Added Time if Incident Occurs | Added Time if Crash Occurs | Z Score for Incident Comparison | Z Score for Crash Comparison |
|---|---|---|---|---|---|
| I-405 Bellevue NB - PM Peak | 18:09 | 0:07 | 0:27 | 1.264 | 3.927 |
| I-405 Bellevue SB - PM Peak | 19:44 | 0:13 | 0:20 | 1.943 | 2.629 |
| I-405 Eastgate NB - PM Peak | 16:24 | 0:05 | 0:47 | 0.351 | 2.221 |
| I-405 Eastgate SB - PM Peak | 19:12 | 0:00 | 0:15 | 0.064 | 2.377 |
| I-405 Kennydale NB - PM Peak | 18:05 | 0:17 | 0:23 | 2.323 | 2.006 |
| I-405 Kennydale SB - PM Peak | 19:27 | -0:01 | 0:00 | -0.195 | 0.137 |
| I-405 Kirkland NB - PM Peak | 19:03 | 0:01 | 0:11 | 0.246 | 2.196 |
| I-405 Kirkland SB - PM Peak | 16:55 | 1:00 | 1:21 | 4.686 | 4.849 |
| I-405 North NB - PM Peak | 19:18 | -0:05 | 0:14 | -0.799 | 3.236 |
| I-405 North SB - PM Peak | 17:40 | -0:11 | 0:46 | -0.919 | 3.611 |
| I-405 South NB - PM Peak | 20:41 | 0:21 | 0:17 | 0.940 | 1.698 |
| I-405 South SB - PM Peak | 19:36 | -0:03 | 0:05 | -0.336 | 0.776 |
| I-5 Everett NB - PM Peak | 17:08 | 0:28 | 0:58 | 2.174 | 4.216 |
| I-5 Everett SB - PM Peak | 16:35 | 0:24 | 0:57 | 2.979 | 4.441 |
| I-5 Lynwood NB - PM Peak | 19:00 | 0:08 | -0:07 | 1.320 | -1.082 |
| I-5 Lynwood SB - PM Peak | 17:21 | 0:12 | 1:09 | 0.922 | 7.154 |
| I-5 Nking NB - PM Peak | 18:55 | 0:04 | 0:12 | 0.741 | 2.092 |
| I-5 Nking SB - PM Peak | 16:47 | 0:29 | 1:57 | 2.424 | 6.575 |
| I-5 SeattleCBD NB - PM Peak | 18:53 | -0:06 | 0:13 | -0.490 | 1.020 |
| I-5 SeattleCBD SB - PM Peak | 18:49 | 0:06 | 0:13 | 0.271 | 0.520 |
| I-5 SeattleN NB - PM Peak | 18:34 | 0:05 | 0:07 | 0.726 | 1.093 |
| I-5 SeattleN SB - PM Peak | 18:20 | 0:16 | 0:31 | 1.513 | 2.481 |
| I-5 South NB - PM Peak | 16:05 | 0:00 | 0:45 | 0.000 | 1.914 |
| I-5 South SB - PM Peak | 18:08 | 0:09 | 0:19 | 1.179 | 2.168 |
| I-5 Tukwilla NB - PM Peak | 16:23 | 0:23 | 1:56 | 2.329 | 5.897 |
| I-5 Tukwilla SB - PM Peak | 17:18 | 0:21 | 0:51 | 2.083 | 4.972 |
| I-90 Bellevue EB - PM Peak | 16:35 | 0:21 | 1:02 | 1.131 | 1.433 |
| I-90 Bellevue WB - PM Peak | 16:13 | 1:21 | 2:10 | 2.078 | 8.804 |
| I-90 Bridge EB - PM Peak | 18:18 | 0:22 | 0:35 | 3.196 | 4.751 |
| I-90 Bridge WB - PM Peak | 18:25 | 0:34 | 0:48 | 2.921 | 4.299 |
| I-90 Issaquah EB - PM Peak | 16:10 | -0:05 | -0:05 | -2.858 | #DIV/0![56] |
| I-90 Issaquah WB - PM Peak | 16:05 | 0:00 | 0:00 | 0.000 | 0.000 |
| I-90 Seattle EB - PM Peak | 17:07 | -1:02 | 1:05 | #DIV/0![57] | 6.457 |
| I-90 Seattle WB - PM Peak | 17:29 | 0:19 | 0:07 | 1.274 | 0.219 |
| SR 167 Auburn NB - PM Peak | 17:31 | -0:08 | -0:31 | -0.641 | #DIV/0![6] |
| SR 167 Auburn SB - PM Peak | 18:47 | 0:08 | 0:08 | 1.799 | 2.716 |
| SR 167 Renton NB - PM Peak | 17:22 | 0:27 | 0:57 | 1.973 | 4.550 |
| SR 167 Renton SB - PM Peak | 18:47 | 0:08 | 0:16 | 1.293 | 2.853 |
| SR 520 Red EB - PM Peak | 19:09 | 0:05 | -0:07 | 0.835 | -0.841 |
| SR 520 Red WB - PM Peak | 16:51 | 1:24 | 1:53 | 2.652 | 7.432 |

[56] Too few crash days occur to compute a test statistic.

[57] Too few incident days occur to compute a test statistic.

| | | | | | |
|---|---|---|---|---|---|
| SR 520 Sea EB - PM Peak | 18:52 | 0:11 | 0:22 | 1.654 | 3.232 |
| SR 520 Sea WB - PM Peak | 20:00 | -0:01 | 0:12 | -0.206 | 1.727 |