# Secondary Accident Data Fusion for Assessing Long-Term Performance of Transportation Systems

MIDWEST TRANSPORTATION CONSORTIUM

**Final Report**
**March 2007**

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**16. Abstract**

Secondary accident statistics can be useful for studying the impact of traffic incident management strategies. An easy-to-implement methodology is presented for classifying secondary accidents using data fusion of a police accident database with intranet incident reports. A current method for classifying secondary accidents uses a static threshold that represents the spatial and temporal region of influence of the primary accident, such as two miles and one hour. An accident is considered secondary if it occurs upstream from the primary accident and is within the duration and queue of the primary accident. However, using the static threshold may result in both false positives and negatives because accident queues are constantly varying.

The methodology presented in this report seeks to improve upon this existing method by making the threshold dynamic. An incident progression curve is used to mark the end of the queue throughout the entire incident. Four steps in the development of incident progression curves are described. Step one is the processing of intranet incident reports. Step two is the filling in of incomplete incident reports. Step three is the nonlinear regression of incident progression curves. Step four is the merging of individual incident progression curves into one master curve. To illustrate this methodology, 5,514 accidents from Missouri freeways were analyzed. The results show that secondary accidents identified by dynamic versus static thresholds can differ by more than 30%.

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# SECONDARY ACCIDENT DATA FUSION FOR ASSESSING LONG-TERM PERFORMANCE OF TRANSPORTATION SYSTEMS

**Final Report**
**March 2007**


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## PURPOSE OF THE STUDY

The primary purpose of this project is to improve upon the current methodology of classifying secondary accidents by using static thresholds. The improved dynamic threshold methodology will be demonstrated using a freeway accident database from St. Louis, Missouri.

To illustrate the static methodology, Figure 1 shows the progression of an incident and the static queue length and time thresholds superimposed on this progression. Progression refers to the growth and decline of the queue length as the incident progresses through the various stages. In general, the stages of an incident include the onset, the arrival of response teams, the clearance to the shoulder, the completion of clearance, and the normalization of traffic. The progression is a function of both the demand (traffic) and the supply (road capacity). If a subsequent accident falls within the influence of the primary accident, then the subsequent accident is considered a secondary accident, i.e., it occurred because of the queue from the primary accident.

With the demand changing constantly, it is clear that an assumption of static thresholds would not capture field conditions properly. Some would argue that, on average, the total number of secondary accidents can be estimated accurately with static thresholds. That is, the area formed by the static threshold (a rectangle) is the same as the area under the progression curve. For example, Figure 1 shows that the same number of accidents (three) is classified as secondary whether a static (fixed) threshold or an actual incident progression curve is used.

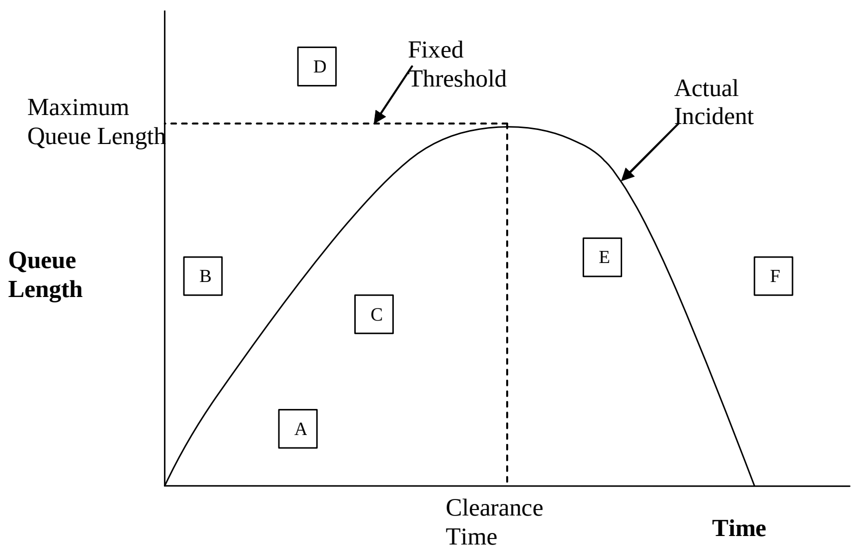


**Figure 1. Static thresholds versus actual incident progression**

However, by definition, secondary accidents differ in cause from primary accidents. Therefore, even if the average number of accidents is captured accurately with static thresholds, the accidents themselves are still misclassified. Referring back to the example in Figure 1, the total number of secondary accidents is estimated correctly using static thresholds, even though accident B is a false positive and accident E is a false negative. The elimination of such type I and type II classification errors is an important motivation for developing dynamic thresholds. Also, it is clear that accidents occurring around the same time as the onset of the primary accident but far from its location should not be classified as secondary. However, this misclassification can occur if a static threshold is used.

**Literature Review for Estimating Secondary Accidents**

Several studies have discussed secondary accidents, but many have not directly addressed the extraction process. For instance, several studies have addressed the magnitude and impact of incident delays, including Garib et al. (1997), Giuliano (1989), Skabardonis et al. (1996), Morales (1987), Sullivan (1997), Smith et al. (2003), Lindley (1987), and Lee et al. (2003). Moreover, Karlaftis et al. (1999) examined the primary crash characteristics that influence the likelihood of secondary crash occurrence. The authors suggested that clearance time, season, type of vehicle involved, and lateral location of the primary crash were the most significant factors. The economic benefit of reducing secondary crashes for the Hoosier Helper freeway service patrol program was also discussed.

At least two studies exemplify the use of static (fixed) thresholds for classifying secondary accidents. For example, Raub (1997) discussed the extraction of secondary accidents. In this study, a methodology was presented for the temporal and spatial analysis of incidents on urban arterials in order to identify the secondary crashes. For his analysis, Raub (1997) assumed an accident effect duration of 15 minutes, plus clearance time. He also assumed a distance of effect of less than 1,600 meters (1 mile). In other words, if an accident occurred within these temporal and spatial boundaries, the accident was considered to be secondary. Raub (1997) found that more than 15% of the crashes reported by police may be secondary in nature. He also found that such crashes result from external distractions instead of internal distractions or driver perception error.

More recently, Moore et al. (2004) examined secondary accident rates on Los Angeles freeways using accident records from the California Highway Patrol's First Incident Response Service tracking system, as well as data from loop detectors on Los Angeles freeways. The authors defined secondary accidents as accidents occurring upstream of the initial incident, in either direction, within or at the boundary of the queue formed by the initial incident. A static threshold of 3,218 meters (2 miles) and 2 hours was used for forming this boundary. Several levels of filters served to eliminate erroneous data.

## DATASET: MEDIA TRAFFIC REPORTS

Traffic management centers and traffic news agencies can provide wide spatial coverage of incidents and can track the incidents over time. These agencies can use information from aircraft, elevated traffic cameras, Motorist Assist, emergency management (fire, police, ambulance, and HAZMAT), and motorist calls. The agencies can also monitor and update this information throughout the course of an incident. Such intranet traffic information can be independent from police information; therefore, such information can complement the police accident database.

Combining the police accident database and intranet traffic reports helps incorporate much information about the incidents. By analyzing individual traffic reports in detail, the reporting times of the incident and the dynamic locations of the back of the queue can be found. The difference between the incident's initial and final times gives an estimate of the total duration of the incident, and the distance from the location of the incident to the back of the queue gives an estimate of the length of the roadway affected by the incident.

However, the intranet reports need to be processed significantly in order for them to be usable. The methodology for processing such reports is as follows. Pages of traffic reports are downloaded daily at regular intervals, e.g., three minutes. A Unix script has been written to perform this automatically. These reports are then consolidated and parsed so that pieces of information are extracted into specific fields, such as incident reporting time, incident type, and incident description. An important task is to extract the traffic information for a particular highway along a particular direction in the sequence reported on a particular day. A computer program then stores the information pertaining to a single incident through multiple reports in a single day.

Since no unique identifier is associated with the information pertaining to a particular incident, the lines containing information related to a particular incident must be extracted through the use of keywords present in those lines and absent in other lines. This process can be difficult, since traffic reports are human-generated and can include syntax variability and errors. For example, consider the primary route under examination to be eastbound on Interstate 70. In the intranet traffic reports, eastbound can be expressed as "EB," "E/B," or "east," and Interstate 70 can be "70," "I70," or "I-70." Descriptions of the route can also be expressed in phrases such as "eastbound lanes of 70" or "east and westbound lanes of 70."

Figure 2 illustrates the result of this processing. The information pertaining to a single incident is tracked throughout the incident, giving the queue length as the incident progresses. Though the processing of intranet traffic reports is laborious, a valuable incident dataset is produced.

### Processing the Traffic Reports

Each day's traffic reports for the specified segment and direction are scanned for incidents. Work zones and other activities are also included in the traffic reports, and they are filtered out. Upon identifying an incident, the location and time are logged, as well as subsequent updates of the queue length, incident clearance, and incident normalization information. Table 1 demonstrates how the data is entered. Each column represents an incident. The first six rows give information about the incident location and the time it was reported, and the subsequent rows record each new traffic update. For these particular incidents, the traffic updates varied in terms of number of updates and the time difference between updates.

3:03 PM EB I-70 BETWEEN CASS AND THE ENTRANCE TO THE KING BRIDGE, THE RIGHT LANE IS BLOCKED BY AN OVERTURNED TRASH TRUCK. ;
4:02 PM EB I-70 BETWEEN CASS AND THE ENTRANCE TO THE KING BRIDGE, THE RIGHT LANE IS BLOCKED BY AN OVERTURNED TRASH TRUCK...TRAFFIC BACKS UP NEAR SALISBURY. ;
4:35 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP NEAR ADELAIDE..BROADWAY TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. ;
4:42 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP TO EAST OF GRAND...BROADWAY TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. EB EADS BRIDGE TRAFFIC IS ALSO BACKED UP GETTING INTO ILLINOIS. ;
5:00 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP TO EAST OF GRAND...4TH ST TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. EB EADS BRIDGE IS ALSO JAMMED FROM MISSOURI END OF THE BRIDGE INTO ILLINOIS. ;
5:04 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP TO WEST OF ADELAIDE..4TH ST TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. EB EADS BRIDGE IS JAMMED FROM MISSOURI END OF THE BRIDGE INTO ILLINOIS. ;
5:12 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP TO WEST OF ADELAIDE..4TH ST TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. EB EADS BRIDGE JUST HEAVY ON THE ILLINOIS END. ;
EADS BRIDGE JUST HEAVY ON THE ILLINOIS END. ;
5:37 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE CLOSED, DUE TO AN OVERTURNED TRASH TRUCK..TRAFFIC BACKS UP TO EAST OF ADELAIDE..4TH ST TRAFFIC GETTING ONTO KING BRIDGE ALSO BLOCKED. EB EADS BRIDGE JUST HEAVY ON THE ILLINOIS END. ;
5:41 PM EB I-70 ENTRANCE RAMP TO KING BRIDGE HAS BEEN REOPENED...BUT TRAFFIC STILL BACKS UP TO EAST OF ADELAIDE..4TH ST AT THE KING BRIDGE ALSO REOPENED. ;

**Figure 2. Example intranet traffic report**

**Table 1. Sample data entry form**

| **Incident ID** | 70EB_01 | 70EB_02 | 70EB_03 |
|---|---|---|---|
| **Date** | 9-May-03 | 9-Sep-03 | 6-Oct-03 |
| **First report time** | 6:35 AM | 5:04 PM | 5:44 AM |
| **Clearance time** | 7:09 AM | 5:36 PM | 5:58 AM |
| **Start location (Location 00)** | West Florissant # 245.7 | Riverview Dr # 243.48 | Cypress # 235.69 |
| **Time 00** | 6:20 AM | 4:50 PM | 5:15 AM |
| **Location 01** | Kingshighway # 244.71 | Bermuda # 241.06 | Rte.180 # 234.25 |
| **Time 01** | 6:39 AM | 5:21 PM | 6:20 AM |
| **Location 02** | Goodfellow # 243.24 | West Florissant # 245.7 | Rte.180 # 234.25 |
| **Time 02** | 6:55 AM | 5:25 PM | 6:36 AM |
| **Location 03** | Jennings Station # 242.92 | West Florissant # 245.7 | |
| **Time 03** | 7:11 AM | 5:36 PM | |
| **Location 04** | Goodfellow # 243.24 | | |
| **Time 04** | 7:22 AM | | |

The location of the incident report usually refers to the closest exit, cross road, or landmark (e.g., Blanchett Bridge). In case the location is reported as between two known reference points, the mile marker between the reference points is also recorded. For example, if an incident is reported as ”North/South of I-70,” then the mile marker of I-70 is noted as the incident location. Or, if the incident is reported as ”Between I-70 and Dorsett,” then the mile marker between I-70 and Dorsett is noted as the incident location. For a short backup, the length of the queue is considered to be 0.5 miles or mid-point between the exits, whichever is smaller.

In Table 1, every row with location information also contains an additional numerical value after the "#" symbol. This numerical value represents a continuous log point of the location. Continuous log points are part of the reference system employed by the Missouri Department of Transportation (MoDOT). In this system, the continuous log point reflects the actual distance of the road from its origin point. For example, the origin point of I-70 eastbound is the state line in St. Louis. For I-70 westbound, the origin point is in the western-most part of Missouri in Kansas City. For the present project, continuous log points were used to cross-reference the MoDOT accident database. A continuous log table was created for all the reference points (exits, cross roads, and landmarks) for each freeway in each direction.

The distances between reference points were measured using the online mapping tool of the Center for Agricultural, Resource, and Environmental Systems (CARES) website (http://www.cares.missouri.edu). Figure 3 shows a screenshot from the website. This mapping tool can measure the distance between any two points in the state of Missouri. The functions of this website can be accessed through the menu buttons. The top menu buttons navigate through the map, while the bottom menu buttons, such as "feature info," "geographic coordinate," and "distance," provide information about the selected point(s) or an area. In Figure 3, the "distance" button is selected, and a segment of I-270 between I-70 and Rte. D has been traced with successive mouse clicks. The calculated distance of this path is shown on the right-hand side of the map in both miles and feet. These distances are transformed into the continuous log format, and a lookup table is created. Thus, the locations named in the incident reports are translated into log points.

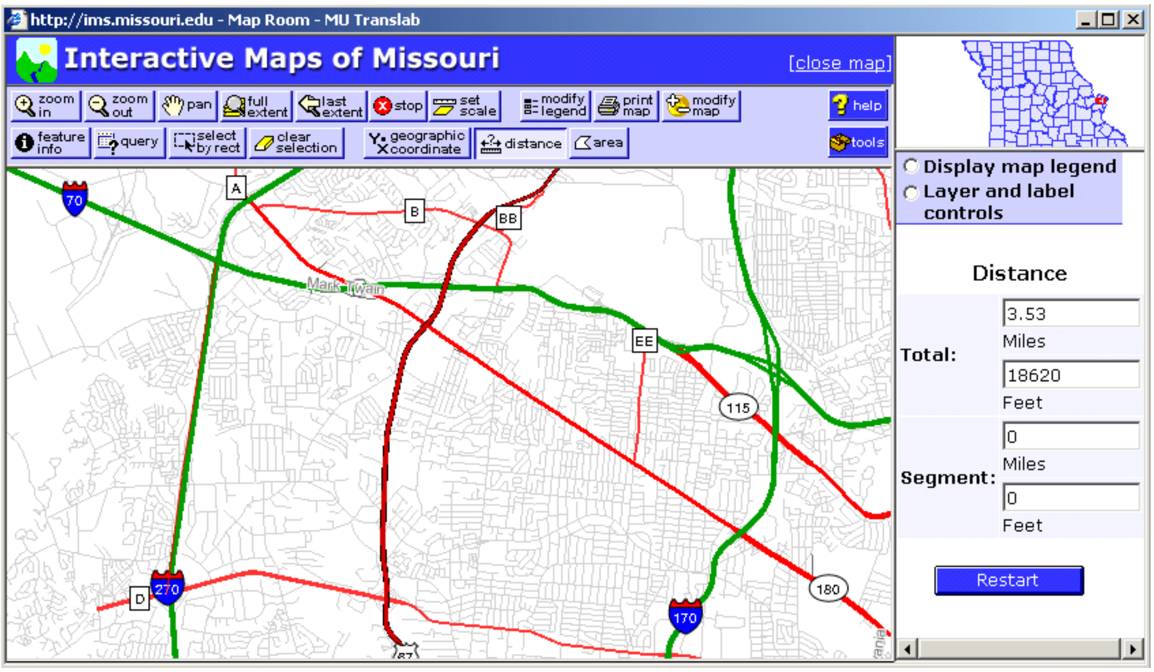


**Figure 3. Log point translation using the CARES website**

## METHODOLOGY

Using the media traffic reports as described above, a total of 480 incident reports were extracted for I-70 and I-270 in Missouri. I-70 and I-270 are two major freeways in the St. Louis area, and I-70 is a major East-West corridor in the United States. The reports were collected between January 2003 and first week of February 2004. All of these reports contained some sort of traffic backup or queue information. For these incident reports, the amount of traffic information varied from complete coverage of the entire incident to the reporting of just the incident backup. The reports can be classified into three types based on the completeness of the information, as shown in Figure 4. The categories, labeled “a,” “b,” and “c,” are defined as follows:

- a-type. These incident reports have complete information about the incident, thus producing incident progression curves (IPC), i.e., parabolic-shaped curves showing the variation of queue length throughout an incident.
- b-type. These incident reports lack some information at the end of the report. The incompleteness can be due to the traffic helicopter finishing its drive-time operations, which are typically the morning and afternoon rush hours. Despite the missing information, the decreasing trend of the queue is present, and estimating the missing portion seems to be possible. The b-type curve in Figure 4 illustrates this category.
- c-type. In this category, there is some uncertainty as to whether the incident queue will increase or decrease. This can be seen in the c-type curve of Figure 4. The shape of the IPC is difficult to predict using this category of reports.

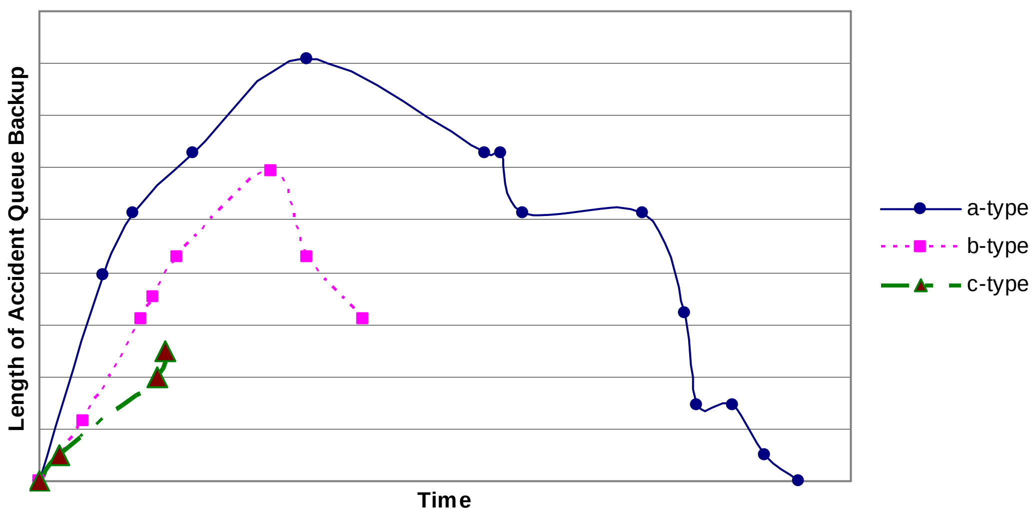


**Figure 4. Categories of incident information**

### Filling in Incomplete Incident Report Data

Since detailed incident data was difficult to obtain, it was desirable to use the incomplete traffic reports rather than discard them completely. Since category “b” reports contain the decreasing trend information of the queue, the time of traffic normalization can be estimated. However, for category “c” reports, neither the clearance time nor the rate of the queue reduction is known. Therefore, the reports from categories “a” and “b” were used in this project, and the reports from category “c” were discarded. An additional check had to be performed because of the elimination of the category “c” data. This check involved comparing the type “a” and “b” reports to the type “c” reports. If the reports proved to be different in nature, then the elimination of type “c” data would bias the results. For example, if type “c” reports are incomplete because they are less severe than types “a” and “b,” then a systematic bias has been introduced into the IPCs, thus overestimating the effects of the incidents.

The similarity among the reports in terms of the time of occurrence (time of day) was investigated by comparing temporal frequency distributions. A chi-squared test was employed to determine the goodness-of-fit of the distributions. Table 2 shows the temporal distributions of complete versus incomplete incident reports. Due to the paucity of data during the off-peak periods, larger bins were used for those times. The chi-squared test shows that the distributions are similar at a confidence level greater than 95%.

**Table 2. Distribution of incidents based on time of day**

| Bin | Hours | a-type and b-type combined | c-type |
|---|---|---|---|
| 1 | 06:00–07:00 | 13 | 32 |
| 2 | 07:00–08:00 | 25 | 55 |
| 3 | 08:00–09:00 | 18 | 41 |
| 4 | 09:00–15:00 | 26 | 56 |
| 5 | 15:00–16:00 | 12 | 35 |
| 6 | 16:00–17:00 | 19 | 48 |
| 7 | 17:00–18:00 | 27 | 45 |
| 8 | 18:00–06:00 | 6 | 22 |
| | Totals | 146 | 334 |

*Dataset for Ground Truth Testing*

Out of 480 incidents, 49 incident reports were category “a,” while 97 were category “b.” A methodology was devised for completing the category “b” reports. To test the methodology for completing category “b” reports, a test dataset was constructed by taking the complete incidents and then artificially eliminating information towards the end of the report. This dataset thus tried to replicate the incomplete data to provide the ground truth for testing the methodology. Since the queue may not decrease linearly with time, second-, third-, and fourth-order polynomials were tested for modeling the incomplete accidents.

*Estimated Values for Queue Dissipation*

Table 3 shows the estimated durations based on different polynomial models. The column “Duration at Chop Point” lists the time at which the data was artificially deleted in order to mimic the incomplete category “b” reports. The column “Actual Duration” indicates the time from the accident occurrence to the normalization of traffic. In the columns listed under “Predicted Duration Based on,” the total duration times estimated using second, third and fourth degree models are presented. Among these three estimation models, the second order proved to be the most reliable because it was able to estimate all accidents, while the fourth order was the least reliable because 7 out of 22 cases produced negative values. The negative values and other errors are shown as “n/a” in Table 3.

**Table 3. Estimated durations based on different polynomial models**

| Id | Number of reports used | Duration at chop point (min.) | Actual duration (min.) | Predicted duration based on | | |
|---|---|---|---|---|---|---|
| | | | | Second order (min.) | Third order (min.) | Fourth order (min.) |
| 1 | 5 | 61 | 70 | 69.34 | 0.04 | n/a |
| 2 | 5 | 96 | 108 | 113.15 | 98.22 | 95.20 |
| 3 | 5 | 57 | 79 | 82.08 | 65.46 | 59.67 |
| 4 | 5 | 69 | 77 | 82.96 | 74.88 | 77.23 |
| 5 | 5 | 26 | 49 | 33.59 | 29.32 | 27.16 |
| 6 | 5 | 94 | 127 | 128.26 | 104.59 | 29.12 |
| 7 | 7 | 66 | 118 | 112.51 | 78.40 | 75.26 |
| 8 | 6 | 110 | 187 | 146.21 | n/a | 124.61 |
| 9 | 4 | 34 | 69 | 42.96 | 42.80 | n/a |
| 10 | 6 | 108 | 135 | 126.79 | 138.86 | 100.51 |
| 11 | 4 | 43 | 58 | 55.19 | 56.63 | n/a |
| 12 | 6 | 45 | 48 | 49.91 | 46.25 | 46.68 |
| 13 | 9 | 121 | 139 | 160.92 | 146.78 | 127.27 |
| 14 | 4 | 40 | 60 | 62.82 | 41.99 | 41.72 |
| 15 | 9 | 89 | 108 | 119.45 | 112.72 | 95.39 |
| 16 | 8 | 195 | 213 | 254.94 | 259.51 | 204.42 |
| 17 | 8 | 72 | 76 | 81.16 | 82.81 | 78.17 |
| 18 | 7 | 133 | 172 | 173.25 | 174.35 | 159.58 |
| 19 | 9 | 84 | 88 | 103.66 | 93.40 | 96.03 |
| 20 | 5 | 53 | 59 | 68.30 | 56.24 | 55.43 |
| 21 | 5 | 55 | 126 | 86.34 | n/a | 56.78 |
| 22 | 5 | 59 | 74 | 65.06 | 68.04 | n/a |

For the test dataset, the overall shape of the IPC was compared with the three polynomial models. Each incident was discretized into 100 points, and at each point the actual queue length was compared to the estimated queue length. Table 4 shows the sum of square errors (SSE) and adjusted $R^2$ values for different models. The equations for SSE and $R^2$ are as follows:

$$SSE_j = \sum_{i=0}^{i=100} (q_{ir} - q_{ij})^2 \tag{1}$$

$$SST_j = \sum_{i=0}^{i=100} (q_{ir} - q_{mean})^2 \tag{2}$$

$$\text{R-Square}_j = 1- \left(\frac{n-1}{n-p}\right)\frac{\text{SSE}_j}{\text{SST}_j} \tag{3}$$

where

$q_{ir}$ is actual queue length at duration point $i$
$q_{ij}$ is estimated queue length at duration point $i$ and for a polynomial model $j$=2,3,4
$q_{mean}$ is mean value of all the queue lengths
$n$ is number of data points
$p$ is number of parameters to estimate

**Table 4. Model SSE and R square values**

| | Adjusted R square | | | Sum of square errors | | |
|---|---|---|---|---|---|---|
| **ID** | **2nd Degree** | **3rd Degree** | **4th Degree** | **SSE2** | **SSE3** | **SSE4** |
| 1 | 0.723 | 0.564 | 0.371 | 27 | 33 | 64 |
| 2 | -0.945 | 0.768 | -0.107 | 21 | 10 | 648 |
| 3 | 0.875 | 0.751 | 0.269 | 8 | 36 | 101 |
| 4 | 0.899 | 0.927 | 0.903 | 4 | 6 | 8 |
| 5 | 0.556 | 0.546 | 0.303 | 73 | 91 | 120 |
| 6 | 0.704 | 0.915 | -0.158 | 102 | 64 | 25093 |
| 7 | 0.54 | 0.679 | 0.693 | 138 | 167 | 163 |
| 8 | 0.724 | 0.583 | 0.57 | 285 | 148 | 543 |
| 9 | 0.179 | 0.17 | -0.056 | 147 | 148 | 72884 |
| 10 | 0.699 | 0.812 | -0.129 | 67 | 31 | 5826 |
| 11 | 0.962 | 0.96 | -0.311 | 7 | 7 | 2319 |
| 12 | 0.762 | 0.952 | 0.949 | 7 | 2 | 3 |
| 13 | 0.482 | 0.667 | 0.741 | 40 | 30 | 38 |
| 14 | 0.459 | 0.674 | 0.683 | 16 | 39 | 35 |
| 15 | 0.671 | 0.784 | 0.788 | 86 | 63 | 97 |
| 16 | 0.649 | 0.624 | 0.699 | 8 | 9 | 20 |
| 17 | 0.921 | 0.916 | 0.953 | 1 | 1 | 1 |
| 18 | 0.935 | 0.929 | 0.954 | 42 | 44 | 34 |
| 19 | 0.688 | 0.892 | 0.915 | 14 | 6 | 5 |
| 20 | 0.455 | 0.953 | 0.975 | 30 | 7 | 3 |
| 21 | 0.053 | -0.237 | -0.144 | 323 | 5165 | 860 |
| 22 | 0.946 | 0.969 | 0.917 | 12 | 6 | 13 |
| Mean | 0.588 | 0.718 | 0.49 | 66 | 278 | 4949 |
| 95% C.I | 0.1741 | 0.1204 | 0.1888 | 88 | 1093 | 16100 |

The results from the test dataset show that a third-order polynomial provided the best fit when compared to the second- and fourth-order polynomials. A criterion for evaluating the performance of the polynomial models is the adjusted $R^2$ value, which measures the proportion of the data that can be explained by the model. Figure 5 shows the $R^2$ values of several incidents modeled by a second-, third-, and fourth-order polynomial. Figure 5 shows that the third-order polynomial results in the best $R^2$ over the entire test dataset. Table 4 shows that the average adjusted $R^2$ of the third-degree model is better than the second- and fourth-degree models. In the category of sum of square errors, the overall average value for second-degree model is better than the others. However, if the outliers are removed, then the third-degree model is better. The third-order polynomial is able to reproduce the total delay estimates (or areas under the queue length/time curves) to within ±10%, with an average difference of 1.4 % from the true value. In comparison, the average difference for the second order is 5.3% and for the fourth order is 6.5%.

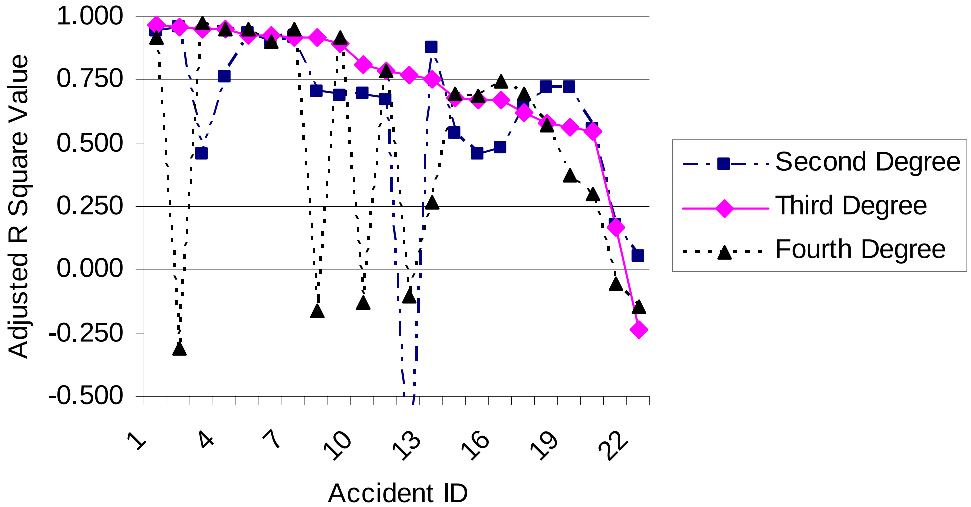


**Figure 5. Polynomial model fit**

## Master Incident Progression Curve

The master IPC is derived from the entire dataset of incident reports. In other words, the master IPC contains incidents of all severity types, traffic conditions (volume/capacity ratio), and numbers of vehicles involved. This master IPC is the basis upon which other more specific IPCs are derived.

Two approaches were initially considered for developing master IPCs. The first approach was to perform regression on the entire database of incidents. In this case, every data point from each incident would be used for curve fitting. This approach was quickly eliminated because the resulting curve would be very complex and not look like a real incident. Another approach was to try to capture the central tendency of all the incidents.

There are three common measures of central tendency: the mean, the median, and the mode. The mean is sensitive to extreme values so that major incidents would unduly influence the result. The mode can be problematic if the data is not uni-modal. Therefore, the median value was used. Each individual incident produced an incident progression curve similar to the one shown in Figure 6. In order to join multiple curves to form one curve, the curves were divided into equal increments. For each increment, the median values of incident duration and queue length were calculated. For example, if three incidents with durations of 40, 60, and 80 minutes are considered, then the corresponding increment size would be 4, 6, and 8 minutes. The median value of the duration and queue lengths is then computed. The result of this method produced a single progression curve that looks like an actual curve from a single incident.

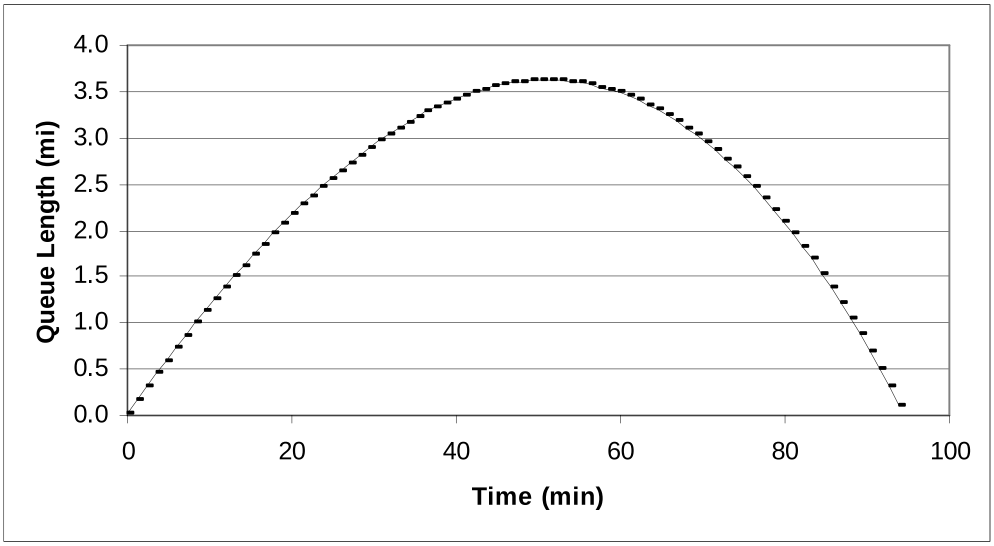


**Figure 6. Master IPC**

A static or dynamic threshold can be used to separate secondary accidents from primary accidents. An accident falling within the bounds of the threshold means that the accident occurred within the queue of the primary accident and within the duration of the primary accident. Two types of thresholds were compared in this research: static and dynamic. Each type of threshold is a function of both time and distance. For the master IPC, the static thresholds were 3.62 miles of maximum queue length and 43 minutes. The dynamic threshold is described by the following third-order polynomial equation:

$$Q = a_3 t^3 + a_2 t^2 + a_1 t + a_0 \tag{4}$$

where

$Q$ is the queue length of the primary accident in miles
$t$ is the time after the occurrence of the primary accident in minutes

The coefficients are shown in Table 5. The total duration is 94 minutes.

**Table 5. IPC polynomial coefficients for the master IPC**

| $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|
| 0.013873 | 0.12652 | -0.00094363 | -0.000007826 |

**Multiple Incident Progression Curves**

In contrast to traffic data, an accident database does not contain information about the maximum queue of an accident or the accident duration. However, accident database fields such as severity and number of vehicles can be used to develop different IPCs. If the volume (actual or historical) and the characteristics of the freeway segments are available, then additional IPCs can be developed using the volume/capacity (v/c) ratio. To estimate the v/c ratio, we need to estimate the capacity and convert the traffic volume into passenger car equivalent traffic volume. The procedure for estimating the v/c ratio is explained in the following.

To estimate capacity, the *Highway Capacity Manual* (2000) recommends determining the free flow speed (FFS) and then calculating the capacity based on the FFS. For example, if the FFS is 62 mph, then, using Table 6 (taken from the *Highway Capacity Manual*), the capacity is estimated as 2,320 passenger cars/hour/lane. Estimating the FFS for every freeway segment is very time consuming, so the FFS is estimated by adjusting the base free flow speed (BFFS). The BFFS for urban freeways is assumed as 70 mph. The formula for estimating the FFS is as follows:

$$FFS = BFFS - f_{LW} - f_{LC} - f_{N} - f_{ID} \tag{5}$$

where

$f_{LW}$ is adjustment for lane width in mph
$f_{LC}$ is adjustment for lateral clearance in mph
$f_{N}$ is adjustment for number of lanes in mph
$f_{ID}$ is adjustment for interchange density in mph

It is assumed that the all the lanes are 12 feet wide with more than 6 feet of clearance on the right shoulder; thus the adjustments for lane width and lateral clearance ($f_{LW}$ and $f_{LC}$) are zero. Further, it is assumed that there is an interchange per mile; therefore, the adjustment for interchange density ($f_{ID}$) was equal to 2.5 mph. Depending on the number of lanes in one direction, the $f_{N}$ varied from zero to 4.5 mph.

**Table 6. Relationship between FFS and freeway capacity**

| Free flow speed (mph) | Capacity (passenger car/ hour /lane) |
|---|---|
| 75 | 2,400 |
| 70 | 2,400 |
| 65 | 2,350 |
| 60 | 2,300 |
| 55 | 2,250 |

The parameters that affect the traffic flow rate are the peak hour factor (PHF); number of lanes; type of driver population; proportion of trucks, buses and recreation vehicles; and type of terrain. These parameters are first estimated to compute the analysis flow rate, $v_p$, which is the “v” in the v/c ratio. The equations for estimating the $v_p$ are as follows:

$$v_p = \frac{V}{PHF * N * f_{HV} * f_{P}} \tag{6}$$

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \qquad (7)$$

where

$v_p$ is analysis flow rate
$V$ is hourly volume (vehicles/hour)
$N$ is number of lanes
$f_{HV}$ is heavy vehicle factor
$f_p$ is driver population factor
$P_T$ is proportion of trucks and buses in the traffic
$E_T$ is passenger car equivalent for trucks or buses
$P_R$ is proportion of recreation vehicles in the traffic
$E_R$ is passenger car equivalent for recreation vehicles

For this dataset, the PHF is considered 0.95 because both freeways are in an urban setting. The driver population factor ($f_p$) is assumed to be one, since most of the traffic is assumed to be commuters or people familiar with the roadways they travel. The proportion of recreational drivers ($P_R$) is assumed to be zero. Based on data collected during morning and evening peak periods, it was found that the proportion of trucks and buses combined was below 0.05, so $P_T$ was assumed to be 0.05. The grade is considered to be below 2%, and the passenger car equivalent for trucks, $E_T$, is taken to be 1.5.

Table 7 shows a sample of the parameters chosen for IPC development. The complete set is provided in the appendix. The first two columns show the time and mile marker of the accident. The time is represented in minutes; 0 stands for midnight and 360 stands for 6 a.m. The mile marker is based on the MoDOT continuous log point. The columns "Maximum queue" and "Duration" contain the observed values of maximum queue length and actual duration of the particular accident. When the accident queue information is incomplete, e.g., the last traffic report still reports a queue length, the total duration is estimated and those values are presented in the column "Estimated duration."

**Table 7. Sample of data used to develop multiple IPC curves**

| Time (min.) | Mile marker (mi) | Max. queue (mi) | Duration (min.) | Estimated duration (min.) | Severity | # of vehicles | Segment ID | v/c ratio |
|---|---|---|---|---|---|---|---|---|
| 495 | 20.07 | 2.38 | 57 | 58.30 | 2 | 5 | 21 | 0.355 |
| 525 | 24.68 | 3.55 | 154 | 171.42 | 2 | 2 | 12 | 0.358 |
| 751 | 20.07 | 3.53 | 57 | 60.17 | 2 | 4 | 21 | 0.359 |
| 546 | 6.94 | 6.54 | 127 | 127.00 | 2 | 3 | 12 | 0.362 |
| 810 | 19.64 | 4.9 | 120 | 135.07 | 1 | 4 | 21 | 0.363 |
| 800 | 20.07 | 3.53 | 55 | 74.60 | 2 | 2 | 21 | 0.363 |

The severity and number of vehicles involved in the incident are presented in the next two columns. The severity codes 1, 2, and 3 respectively represent property damage only (PDO), injury, and fatality. The last column contains the v/c value for each accident segment. Out of 123 accidents chosen, two were apparent outliers for which the polynomial did not estimate the duration correctly. These two outliers were in the first two rows of the dataset, and their v/c ratio values were deleted to make sure they would not be used in further processing. For example, one record had a duration of 10 hours.

*IPC According to v/c Ratio Only*

The effects of incidents differ according to the traffic conditions or the v/c ratio. If we review the effects of incidents from the entire database, a natural separation seems to occur at a v/c value of around 0.7. For values less than 0.7, there do not seem to be any discernable differences in the effects of incidents. Therefore, a two-category system was developed based on v/c conditions (see Tables 8 and 9 and Figure 7).

**Table 8. IPC parameters and static thresholds based on v/c ratio**

| Description | Criterion | Maximum queue (mi) | Time of max. queue (min.) | Time to normal (min.) |
|---|---|---|---|---|
| Light/medium | v/c < 0.7 | 3 (3.16) | 45 (45) | 80 (82) or 1 hr. 20 min. |
| Heavy | v/c > 0.7 | 5 (4.71) | 70 (67) | 120 (122) or 2 hr. |

**Table 9. IPC polynomial coefficients based on v/c ratio**

| Criterion | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|
| v/c < 0.7 | 0.014200143 | 0.129503498 | -0.000965882 | -8.01096E-06 |
| v/c > 0.7 | 0.021165402 | 0.193025784 | -0.001439653 | -1.19404E-05 |

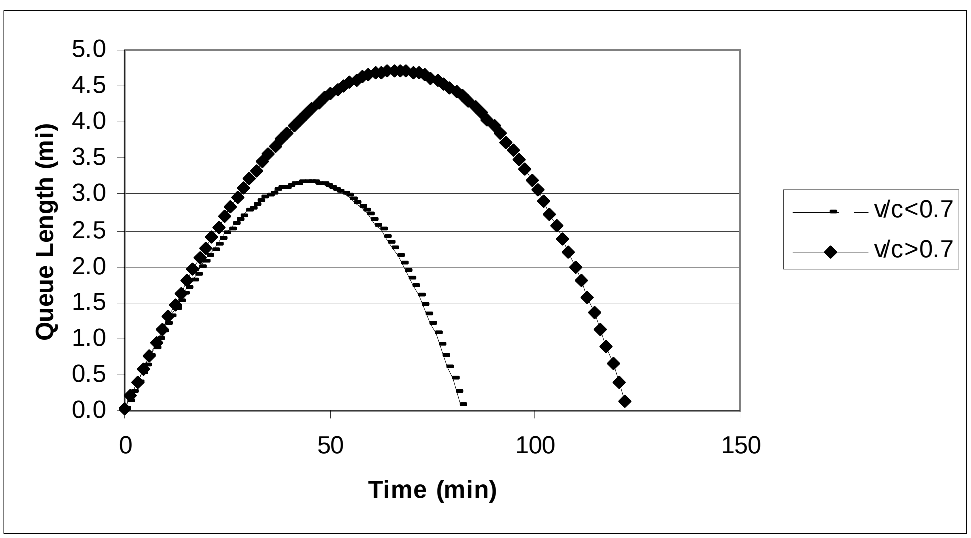


**Figure 7. IPC based on v/c**

*IPC According to Number of Vehicles Only*

In general, the number of vehicles involved in an incident is correlated to the severity of the incident, which is also correlated with the effects of the incident. Thus, the number of vehicles recorded in the accident database can be used as a variable to determine the appropriate IPC or threshold to be used in determining secondary accidents. See Tables 10 and 11 and Figure 8.

**Table 10. IPC parameters and static thresholds based on number of vehicles**

| **Description** | **Criterion** | **Maximum queue (mi)** | **Time of max. queue (min.)** | **Time to normal (min.)** |
|---|---|---|---|---|
| Single | Vehicles = 1 | 3 (3.36) | 45 (43) | 90 (89) or 1 hr. 30 min. |
| Double | Vehicles = 2 | 3.5 (3.56) | 50 (50) | 90 (91) or 1 hr. 30 min. |
| Multiple | Vehicles > 2 | 4 (3.73) | 50 (52) | 95 (95) or 1 hr. 35 min. |

**Table 11. IPC polynomial coefficients based on number of vehicles**

| **Criterion** | **$a_0$** | **$a_1$** | **$a_2$** | **$a_3$** |
|---|---|---|---|---|
| Vehicles = 1 | 0.015098886 | 0.137699922 | -0.001027014 | -8.51798E-06 |
| Vehicles = 2 | 0.015997629 | 0.145896346 | -0.001088146 | -9.025E-06 |
| Vehicles > 2 | 0.016761561 | 0.152863307 | -0.001140108 | -9.45597E-06 |

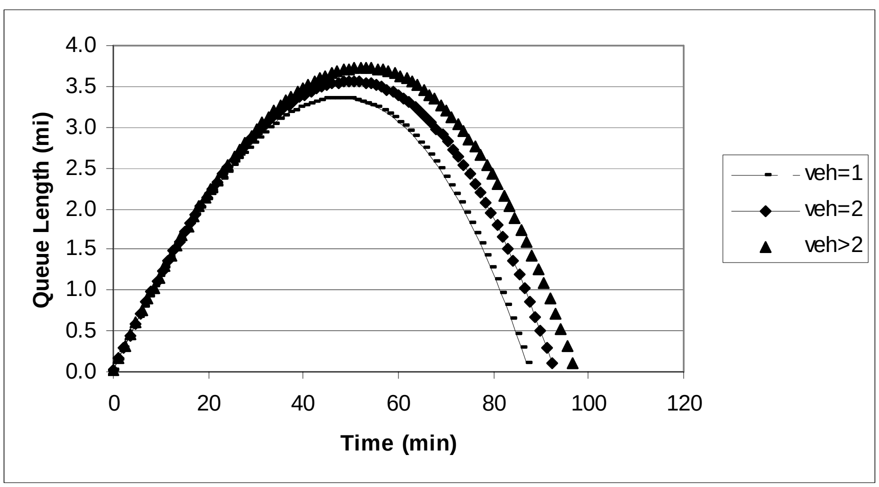


**Figure 8. IPC based on number of vehicles involved in the incident**

*According to Severity and v/c ratio*

The effects of incidents can be differentiated by severity and traffic conditions (measured using v/c ratio). Due to the small sample size of fatal accidents, only PDO and injury categories were used. For each level of severity, three different IPCs were developed based on the v/c ratio. The injury accidents intuitively show larger effects than PDO accidents. See Tables 12 and 13 and Figures 9 and 10.

**Table 12. IPC parameters and static thresholds based on severity and v/c ratio**

| Description | Criteria | Maximum queue (mi) | Time of max. queue (min.) | Time to normal (min.) |
|---|---|---|---|---|
| Light | PDO, v/c < 0.4 | 3 (3.02) | 40 (42) | 80 (78) or 1 hr. 20 min. |
| Medium | PDO, 0.4 < v/c < 0.7 | 3.5 (4.48) | 50 (48) | 90 (90) or 1 hr. 30 min. |
| Heavy | PDO, v/c > 0.7 | 4.5 (4.57) | 65 (64) | 120 (118) or 2 hr. |
| Light | INJ, v/c < 0.4 | 3 (3.157) | 45 (44) | 80 (82) or 1 hr. 20 min. |
| Medium | INJ, 0.4 < v/c < 0.7 | 3.75 (3.68)* | 50 (51) | 95 (95) or 1 hr. 35 min. |
| Heavy | INJ, v/c > 0.7 | 5 (4.912) | 70 (68) | 125 (127) or 2 hr. 5 min. |

**Table 13. IPC polynomial coefficients based on severity and v/c ratio**

| Criteria | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|
| PDO, v/c < 0.4 | 0.013571022 | 0.123766002 | -0.00092309 | -7.65604E-06 |
| PDO, 0.4 < v/c < 0.7 | 0.015638132 | 0.142617777 | -0.001063693 | -8.82219E-06 |
| PDO, v/c > 0.7 | 0.020536282 | 0.187288287 | -0.001396861 | -1.15855E-05 |
| INJ, v/c < 0.4 | 0.014186661 | 0.129380552 | -0.000964965 | -8.00335E-06 |
| INJ, 0.4 < v/c < 0.7 | 0.016523394 | 0.150691254 | -0.001123908 | -9.32161E-06 |
| INJ, v/c > 0.7 | 0.022073133 | 0.201304172 | -0.001501396 | -1.24525E-05 |

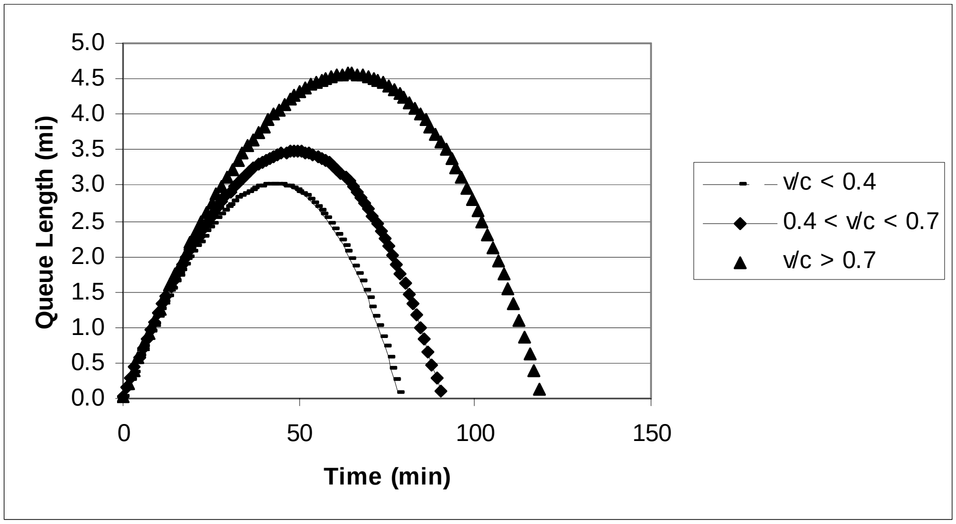


**Figure 9. IPC based on PDO accidents and v/c**

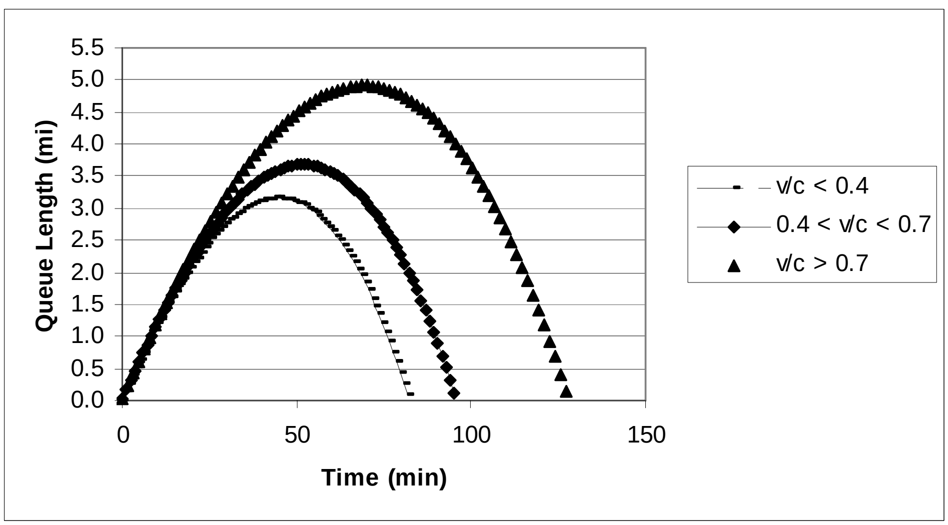


**Figure 10. IPC based on injury accidents and v/c**

## Using IPC to Derive the Number of Secondary Accidents

The process for extracting secondary accidents from the accident database is as follows. First, the accident database must be suitably formatted. The database is separated by route and by year (e.g., I-70, 2003), and each of the fields that describe each accident record is parsed and stored. The time and date fields are translated for computation so that they can be added and subtracted. The entire accident file is then converted into a doubly linked list so that the file can be collapsed into one record per accident. In other words, a file with one record per vehicle involved in an accident is consolidated into one record per accident.

When the accident database is in a suitable format, applying the results from this report is straightforward and involves three steps:

- Step 1. The user selects an appropriate variable for differentiating the effects of an incident. Some common variables are severity, v/c, and the number of vehicles involved in an incident.
- Step 2. The user selects the IPCs corresponding to the selected variable. If none of the variables are available, then the user can select the master IPC, which includes all traffic conditions.
- Step 3. The user applies the IPCs to derive secondary accidents. In other words, the IPCs are used to filter out accidents that were not within the queue created by the primary accident. The use of the IPC or polynomial models can involve some programming.
- Step 3 (alternate). If a user is unable to use the dynamic IPCs, then simple static thresholds can still be used. This involves a query of the database of accidents that occur within a certain time and within a certain distance upstream of the primary accident. The tradeoff between the static threshold and dynamic IPC is the ease of implementation versus accuracy.

This procedure, shown in Figure 11, identifies the possible secondary accidents from an accident database.

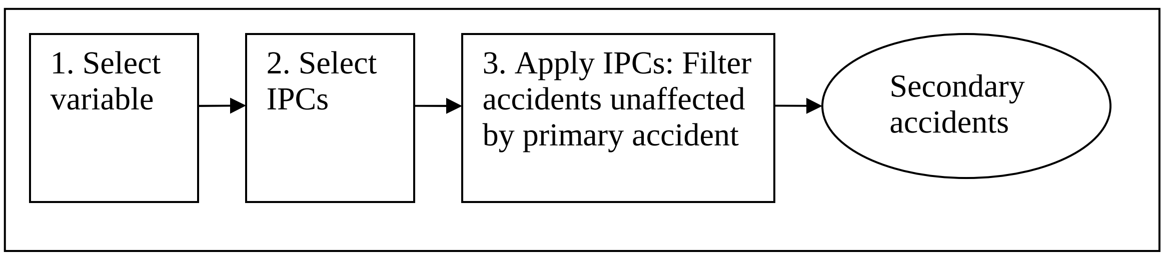


**Figure 11. IPC application flowchart**

## SAMPLE APPLICATION IN ST. LOUIS, MISSOURI

To illustrate the application of the dynamic threshold method, a year's worth of accident data from I-70 and I-270 in Missouri was used. Year 2003 data was used and contained 5,514 accidents. Out of these accidents, 397 were classified as secondary based on the dynamic threshold curve, and 390 were classified as secondary accidents based on the static threshold curve. The area under the static and dynamic threshold curves was 148.3 mile-minutes and 164.8 mile-minutes, respectively.

On the surface, these numbers imply that the use of static or dynamic thresholds produce similar results, since the area under the curves and the total number of secondary accidents classified were similar. In reality, however, the two thresholds yielded different results, which can be clearly seen in Figure 12 and Table 14. In Figure 12, the origin is the time and location at which the primary accident occurred, the y-axis represents the upstream displacement from the location of the primary accident, and the x-axis represents the time after the onset of the primary accident. The graph in Figure 12 shows a significant number of accidents that are not common to the application of both the static and dynamic thresholds. Table 14 shows that 125 accidents were classified as secondary by the dynamic threshold but not by the static. Conversely, 118 accidents were classified as secondary by the static threshold but not by the dynamic. The classification results thus actually differ by more than 30%.

This difference can be significant, since accident costs can differ significantly based on the severity of the accident. For example, the consequence of a fatal accident is much greater than a property damage only (PDO) accident. Table 14 also shows that the results are similar for daytime only versus all day.

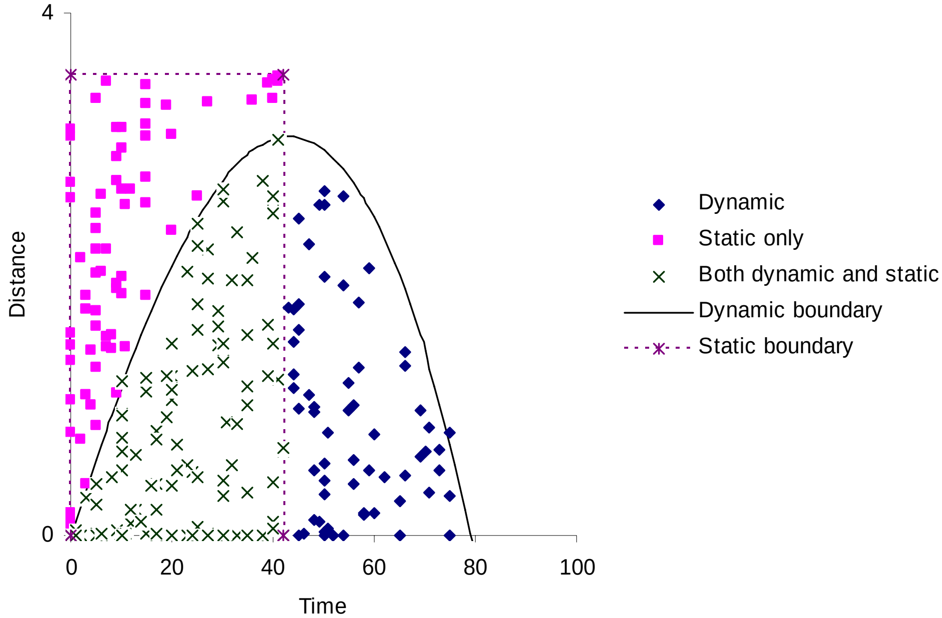


**Figure 12. Secondary accidents based on static and dynamic thresholds**

**Table 14. Comparison of dynamic versus static thresholds**

| Time Period | Number of secondary accidents | | | | |
|---|---|---|---|---|---|
| | **Dynamic only** | **Static only** | **Both** | **Total dynamic** | **Total static** |
| Daytime (5:30 a.m.–6:30 p.m.) | 106 | 98 | 215 | 321 | 313 |
| All day | 125 | 118 | 272 | 397 | 390 |

## CONCLUSIONS

This research improves upon the existing method for deriving secondary accidents by eliminating the assumption that the queue length is constant (as it is in static thresholds). The analysis of 5,514 freeway accidents shows that the static and dynamic methods can differ by over 30%.

To derive the dynamic threshold, 480 intranet incident reports were analyzed and 119 incident reports were used for calibrating the master incident progression curve. Some of these incident reports were incomplete; therefore they were modeled using a third-order polynomial. A chi-squared test showed that the frequency distributions of the complete and incomplete incident reports were not different. Various incident progression curves were developed using various accident and traffic flow parameters.

Agencies can utilize the existing curves to estimate the number of secondary accidents occurring in a given year. This information can help evaluate the safety performance of the agencies' incident management system or other transportation systems.

## REFERENCES


Bunch, J.A., J.J. Larkin, and K.E. Wunderlich. 1999. *ITS impacts assessment for Seattle MMDI evaluation: Modeling methodology and results*. FHWA DTFH61-95-C00040. Washington, DC: Federal Highway Administration.

Cambridge Systematics. 1990. *Incident Management*. Alexandria, VA: Trucking Research Institute.

Christiansen, I. and L. Hauer. 1996. Probing for Travel Time. *Traffic Technology International* August/September: 41–44.

Dailey, D. 1993. Travel Time Estimation Using Cross Correlation Techniques. *Transportation Research* 27B.2: 97–107.

Eisele, W. and L. Rilett. 2002. Estimating Corridor Travel Time Mean, Variance, and Covariance with Intelligent Transportation Systems Link Travel Time Data. Paper presented at the annual Transportation Research Board, Washington, DC.

Fenno, D. and M. Ogden. 1998. Freeway Service Patrols: A State of the Practice. *Transportation Research Record* 1634: 28–38.

Garib, A., A.E. Radwan, and H. Al-Deek. 1997. Estimating Magnitude and Duration of Incident Delays. *Journal of Transportation Engineering* 123.6: 459–466.

Giuliano, G. 1989. Incident Characteristics, Frequency, and Duration on a High Volume Urban Freeway. *Transportation Research* 23A.5: 387–396.

Karlaftis, M.G., S.P. Latoski, N.J. Richards, and K.C. Sinha. 1999. ITS Impacts on Safety and Traffic Management: An Investigation of Secondary Crash Causes. *ITS Journal* 5: 39–52.

Kreeger, K. and R. McConnell. 1996. Structural Range Image Target Matching for Automated Link Travel Time Computation. Paper presented at the Third Annual World Congress on Intelligent Transportation Systems, Orlando, FL.

Kuhne, R. 1991. Freeway Control Using a Dynamic Traffic Flow Model and Vehicle Reidentification Techniques. *Transportation Research Record* 1320: 251–259.

Lee C., B. Hellinga, and F. Saccomanno. 2003. Proactive Freeway Crash Prevention Using Real Time Traffic Control. *Canadian Journal of Civil Engineering* 30: 1034–1041.

Levinson, D., and P.K. Parthasarathi. 2001. An Economic Evaluation of Freeway Service Patrols. Paper presented at the IEEE/Intelligent Transportation Systems Conference. Oakland, CA.

Lindley, J. 1987. Urban Freeway Congestion: Quantification of the Problem and Effectiveness of Potential Solutions. *ITE Journal* 57.1: 27–32.

MacCarley, C. and B. Hemme. 2001. A Computer Vision Detection System for Network Model Validation. Paper presented at the annual Transportation Research Board. Washington, DC.

Moore, J.E., G. Giuliano, and S. Cho. 2004. Secondary Accident Rates on Los Angeles Freeways. *Journal of Transportation Engineering* 130.3: 280–285.

Morales, J. 1987. Analytical Procedures for Estimating Freeway Traffic Congestion. *ITE Journal* 57.1: 45–49.

Morris, M. and W. Lee. 1994. Survey of Efforts to Evaluate Freeway Service Patrols. Transportation Research Record, 1446, 77-85.

Raub, R.A. (1997). Secondary Crashes: An important component of Roadway Incident Management. *Transportation Quarterly* 51.3: 93–104.

Petty, K. 1997. Accurate Estimation of Travel Times from Single Loop Detectors. Paper presented at the annual Transportation Research Board. Washington, DC.

Petty, K., R.L. Bertini, A. Skabardonis, and P. Varaiya. 1997. *The Los Angeles Freeway Service Patrol (FSP) Evaluation: Study Methodology and Preliminary Findings*. http://repositories.cdlib.org/its/path/papers/UCB-ITS-PWP-97-17

Pierce, R., C. Sun, and J. Lemp. 2005. Incident Delay Modeling with the Use of Video Reidentification. Paper presented at the annual Transportation Research Board. Washington, DC.

Shah, V.P. and K. Wunderlich. 2001. *Detroit Freeway Corridor ITS Evaluation*. FHWA DTFH61-00-C-0001. Washington, DC: Federal Highway Administration.

Skabardonis, A., K. Petty, H. Noeimi, D. Rydzewski, and P. Varaiya. 1996. I-880 Field Experiment: Database Development and Incident Delay Estimation Procedures. Transportation Research Record 1554: 204–212.

Smith, B., L. Qin, and R. Venkatanarayana. 2003. Characterization of Freeway Capacity Reduction Resulting from Traffic Accidents. *Journal of Transportation Engineering* 129.4: 362–368.

Stamatiadis, C., N.H. Gartner, J. Winn, and R. Bond. 1998. Evaluation of the Massachusetts Motorist Assistance Program. *Transportation Research Record* 1634: 2–9.

Sullivan, E. 1997. New Model for Predicting Freeway Incidents and Incident Delays. *Journal of Transportation Engineering* 123.4: 267–275.

Farradyne, P.B. 2000. *Traffic Incident Management Handbook*. Washington, DC: Federal Highway Administration, Office of Travel Management.

Texas Transportation Institute (TTI). 2003. *2003 Urban Mobility Report*. College Station, TX: Texas Transportation Institute. http://mobility.tamu.edu/ums/

Turner, S., W. Eisele, R. Benz, and D. Holdener. 1998. *Travel Time Data Collection Handbook*. FHWA-PL-98-035. Washington, DC: Federal Highway Administration and Texas Transportation Institute.

Yokota, T, T. Inoue, Y. Kobayashi, and K. Takagi. 1996. Travel Time Measuring System Based on Platoon Matching: A Field Study. Paper presented at the ITS America Annual Meeting. Houston, TX.

Zeng, N. and J. Crisman. 1998. Vehicle Matching Using Color. Paper presented at the IEEE Conference on Intelligent Transportation Systems. Boston, MA.

**APPENDIX**

**Table A.1. Data used for developing multiple master curves**

| Time (min.) | Mile marker (mi) | Max. queue (mi) | Duration (mi) | Estimated duration (min.) | Severity | # of vehicles | Segment ID | v/c ratio |
|---|---|---|---|---|---|---|---|---|
| 840 | 39.66 | 10.94 | 138 | 633.61 | 1 | 2 | 12 | -- |
| 608 | 17.99 | 8.57 | 103 | -9.87 | 2 | 2 | 22 | -- |
| 400 | 2.88 | 2.68 | 113 | 134.58 | 2 | 3 | 22 | 0.068 |
| 400 | 3.87 | 1.98 | 57 | 146.76 | 1 | 2 | 22 | 0.092 |
| 1392 | 31.14 | 2.42 | 46 | 58.22 | 2 | 2 | 12 | 0.141 |
| 322 | 14.17 | 1.75 | 48 | 48.00 | 2 | 1 | 21 | 0.273 |
| 444 | 29.49 | 1.53 | 93 | 93.00 | 2 | 3 | 12 | 0.273 |
| 435 | 23.31 | 2.18 | 77 | 77.00 | 1 | 3 | 12 | 0.319 |
| 619 | 23.62 | 1.96 | 213 | 213.00 | 3 | 3 | 21 | 0.322 |
| 495 | 20.07 | 2.38 | 57 | 58.30 | 2 | 5 | 21 | 0.355 |
| 525 | 24.68 | 3.55 | 154 | 171.42 | 2 | 2 | 12 | 0.358 |
| 751 | 20.07 | 3.53 | 57 | 60.17 | 2 | 4 | 21 | 0.359 |
| 546 | 6.94 | 6.54 | 127 | 127.00 | 2 | 3 | 12 | 0.362 |
| 810 | 19.64 | 4.9 | 120 | 135.07 | 1 | 4 | 21 | 0.363 |
| 800 | 20.07 | 3.53 | 55 | 74.60 | 2 | 2 | 21 | 0.363 |
| 330 | 235.16 | 3.66 | 74 | 113.64 | 2 | 1 | 11 | 0.367 |
| 780 | 234.45 | 1.75 | 68 | 87.58 | 2 | 2 | 11 | 0.408 |
| 480 | 14.86 | 4.44 | 59 | 81.29 | 2 | 1 | 22 | 0.410 |
| 984 | 20.82 | 0.75 | 55 | 55.00 | 2 | 1 | 21 | 0.432 |
| 790 | 223.69 | 1.59 | 49 | 58.13 | 1 | 4 | 11 | 0.436 |
| 680 | 13.59 | 3.67 | 38 | 38.00 | 2 | 1 | 21 | 0.453 |
| 585 | 11.17 | 4.23 | 292 | 348.63 | 2 | 2 | 12 | 0.453 |
| 815 | 11.67 | 1.75 | 53 | 53.00 | 2 | 2 | 21 | 0.459 |
| 900 | 24.01 | 6.02 | 143 | 163.49 | 2 | 1 | 22 | 0.462 |
| 855 | 32.07 | 2.24 | 43 | 44.89 | 2 | 1 | 22 | 0.466 |
| 759 | 17.69 | 1.15 | 41 | 46.11 | 2 | 5 | 21 | 0.468 |
| 768 | 17.69 | 1.15 | 54 | 61.38 | 2 | 2 | 21 | 0.468 |
| 725 | 17.69 | 1.15 | 69 | 78.14 | 2 | 3 | 21 | 0.468 |
| 564 | 17.69 | 0.5 | 31 | 31.00 | 2 | 2 | 21 | 0.468 |
| 437 | 26.26 | 3.77 | 107 | 169.53 | 2 | 3 | 21 | 0.476 |
| 915 | 241.83 | 3.03 | 122 | 154.83 | 2 | 4 | 11 | 0.479 |
| 830 | 16.54 | 0.5 | 45 | 45.00 | 2 | 4 | 21 | 0.481 |
| 785 | 17.69 | 4.1 | 139 | 139.00 | 2 | 6 | 21 | 0.483 |
| 932 | 25.26 | 2.77 | 145 | 183.77 | 2 | 3 | 21 | 0.483 |
| 1075 | 232.72 | 1.22 | 39 | 39.00 | 2 | 2 | 11 | 0.486 |
| 829 | 225.15 | 2.25 | 70 | 70.00 | 1 | 1 | 11 | 0.497 |
| 412 | 19.14 | 5.95 | 118 | 118.00 | 2 | 3 | 22 | 0.507 |
| 380 | 5.04 | 3.06 | 83 | 100.38 | 2 | 2 | 22 | 0.511 |
| 380 | 245.7 | 2.8 | 62 | 113.42 | 2 | 4 | 11 | 0.514 |
| 1039 | 13.59 | 1.92 | 59 | 65.17 | 1 | 2 | 21 | 0.517 |
| 863 | 8.41 | 4.11 | 84 | 87.33 | 2 | 2 | 12 | 0.518 |
| 1032 | 9.42 | 1.34 | 68 | 68.00 | 2 | 3 | 22 | 0.521 |
| 505 | 17.69 | 1.15 | 76 | 76.00 | 2 | 3 | 21 | 0.528 |
| 1011 | 241.06 | 5.46 | 100 | 101.38 | 1 | 2 | 11 | 0.534 |
| 978 | 12.42 | 5.39 | 72 | 99.17 | 2 | 4 | 21 | 0.534 |
| 956 | 31.14 | 3.18 | 49 | 49.00 | 1 | 2 | 12 | 0.544 |
| 990 | 234.45 | 2.95 | 79 | 82.29 | 1 | 2 | 11 | 0.548 |
| 413 | 4.3 | 0.85 | 49 | 49.00 | 2 | 2 | 12 | 0.548 |
| 998 | 29.49 | 4.81 | 73 | 85.56 | 2 | 2 | 12 | 0.554 |
| 985 | 29.49 | 2.99 | 72 | 93.56 | 2 | 3 | 12 | 0.554 |
| 446 | 17.69 | 5.27 | 67 | 93.19 | 2 | 3 | 21 | 0.554 |

| Time (min.) | Mile marker (mi) | Max. queue (mi) | Duration (mi) | Estimated duration (min.) | Severity | # of vehicles | Segment ID | v/c ratio |
|---|---|---|---|---|---|---|---|---|
| 465 | 20.06 | 1.13 | 79 | 79.00 | 2 | 3 | 12 | 0.554 |
| 939 | 23.26 | 4.12 | 135 | 135.00 | 1 | 2 | 22 | 0.566 |
| 775 | 16.49 | 3.68 | 135 | 164.81 | 2 | 4 | 12 | 0.566 |
| 1005 | 233.06 | 0.36 | 46 | 58.60 | 1 | 1 | 11 | 0.567 |
| 1010 | 14.74 | 2.32 | 88 | 88.00 | 2 | 2 | 21 | 0.569 |
| 525 | 20.94 | 5.33 | 78 | 107.45 | 2 | 2 | 22 | 0.570 |
| 492 | 20.94 | 5.33 | 75 | 93.41 | 2 | 3 | 22 | 0.570 |
| 447 | 16.04 | 2.85 | 41 | 51.02 | 2 | 2 | 22 | 0.570 |
| 530 | 11.17 | 2.44 | 72 | 83.22 | 2 | 2 | 12 | 0.574 |
| 388 | 5.85 | 3.95 | 65 | 78.00 | 1 | 3 | 21 | 0.576 |
| 435 | 18.93 | 2.44 | 102 | 142.98 | 2 | 2 | 12 | 0.579 |
| 520 | 10.59 | 1.86 | 62 | 105.01 | 2 | 4 | 12 | 0.580 |
| 1015 | 6.07 | 1.03 | 71 | 91.22 | 1 | 2 | 22 | 0.580 |
| 504 | 243.24 | 2.84 | 58 | 66.46 | 1 | 3 | 11 | 0.583 |
| 490 | 230.52 | 2.22 | 20 | 22.77 | 1 | 4 | 11 | 0.586 |
| 1050 | 25.76 | 3.67 | 52 | 70.17 | 2 | 2 | 22 | 0.591 |
| 1047 | 25.76 | 4.82 | 37 | 42.73 | 1 | 3 | 22 | 0.591 |
| 1025 | 25.76 | 4.82 | 55 | 68.10 | 1 | 2 | 22 | 0.591 |
| 435 | 241.83 | 3.03 | 82 | 113.33 | 2 | 2 | 11 | 0.603 |
| 896 | 26.26 | 5.44 | 105 | 123.87 | 2 | 2 | 21 | 0.605 |
| 954 | 23.62 | 2.8 | 60 | 60.00 | 2 | 2 | 21 | 0.606 |
| 930 | 23.62 | 2.8 | 92 | 114.73 | 2 | 2 | 21 | 0.606 |
| 465 | 22.09 | 7.23 | 74 | 87.62 | 1 | 2 | 22 | 0.608 |
| 1000 | 33.78 | 3.95 | 82 | 85.04 | 1 | 2 | 22 | 0.608 |
| 1000 | 33.78 | 3.95 | 40 | 48.69 | 1 | 4 | 22 | 0.608 |
| 1040 | 18.59 | 5.78 | 93 | 93.08 | 1 | 3 | 12 | 0.631 |
| 506 | 12.42 | 0.75 | 5 | 5.84 | 1 | 4 | 21 | 0.637 |
| 958 | 25.76 | 3.67 | 63 | 79.17 | 1 | 4 | 22 | 0.640 |
| 1060 | 20.07 | 2.38 | 34 | 35.68 | 1 | 2 | 21 | 0.645 |
| 962 | 32.07 | 2.24 | 64 | 64.00 | 2 | 2 | 22 | 0.657 |
| 482 | 19.14 | 3.1 | 66 | 66.00 | 1 | 2 | 22 | 0.658 |
| 1032 | 32.07 | 8.81 | 53 | 80.25 | 1 | 4 | 22 | 0.666 |
| 507 | 17.99 | 2.38 | 44 | 44.00 | 1 | 3 | 22 | 0.667 |
| 414 | 12.06 | 6.67 | 106 | 119.57 | 2 | 1 | 22 | 0.681 |
| 430 | 234.45 | 1.75 | 61 | 84.60 | 2 | 2 | 11 | 0.692 |
| 1060 | 17.69 | 2.95 | 59 | 59.00 | 2 | 3 | 21 | 0.701 |
| 1048 | 22.09 | 4.1 | 58 | 58.00 | 1 | 2 | 22 | 0.706 |
| 1079 | 22.09 | 2.95 | 52 | 59.84 | 1 | 2 | 22 | 0.706 |
| 1042 | 22.09 | 6.48 | 96 | 118.63 | 2 | 5 | 22 | 0.706 |
| 936 | 23.31 | 8.46 | 52 | 97.97 | 2 | 2 | 12 | 0.708 |
| 480 | 12.42 | 5.39 | 54 | 58.58 | 2 | 4 | 21 | 0.715 |
| 1007 | 22.09 | 6.05 | 74 | 92.84 | 1 | 3 | 22 | 0.725 |
| 960 | 24.68 | 2.48 | 60 | 60.00 | 2 | 2 | 12 | 0.735 |
| 971 | 16.54 | 4.87 | 78 | 130.94 | 2 | 2 | 21 | 0.738 |
| 1020 | 11.17 | 2.76 | 75 | 85.52 | 1 | 3 | 12 | 0.751 |
| 412 | 233.06 | 1.56 | 108 | 108.00 | 2 | 3 | 11 | 0.762 |
| 908 | 27.21 | 8.07 | 187 | 187.00 | 1 | 2 | 22 | 0.774 |
| 446 | 17.99 | 2.38 | 69 | 69.00 | 1 | 2 | 22 | 0.775 |
| 456 | 17.99 | 4.8 | 65 | 75.66 | 1 | 2 | 22 | 0.775 |
| 466 | 17.99 | 3.13 | 58 | 70.24 | 1 | 3 | 22 | 0.775 |
| 450 | 230.52 | 6.92 | 101 | 133.19 | 1 | 3 | 11 | 0.791 |
| 455 | 230.52 | 5.42 | 57 | 69.71 | 1 | 2 | 11 | 0.791 |
| 446 | 7.03 | 7.03 | 108 | 108.00 | 2 | 3 | 21 | 0.793 |
| 479 | 7.35 | 3.74 | 74 | 74.00 | 1 | 2 | 21 | 0.793 |
| 430 | 228.34 | 3.24 | 42 | 51.91 | 1 | 2 | 11 | 0.812 |
| 398 | 7.35 | 7.35 | 172 | 172.00 | 1 | 4 | 21 | 0.822 |

| Time (min.) | Mile marker (mi) | Max. queue (mi) | Duration (mi) | Estimated duration (min.) | Severity | # of vehicles | Segment ID | v/c ratio |
|---|---|---|---|---|---|---|---|---|
| 390 | 7.03 | 7.03 | 48 | 59.33 | 1 | 2 | 21 | 0.822 |
| 995 | 27.21 | 5.12 | 133 | 185.43 | 2 | 1 | 22 | 0.824 |
| 412 | 226.97 | 4.07 | 60 | 90.66 | 1 | 3 | 11 | 0.828 |
| 1000 | 26.26 | 5.44 | 126 | 126.00 | 2 | 3 | 21 | 0.830 |
| 982 | 26.26 | 3.77 | 101 | 109.73 | 2 | 3 | 21 | 0.830 |
| 395 | 9.32 | 3.35 | 117 | 117.00 | 1 | 2 | 22 | 0.831 |
| 420 | 9.42 | 5.55 | 81 | 98.43 | 1 | 2 | 22 | 0.831 |
| 387 | 9.42 | 7.44 | 109 | 138.28 | 2 | 2 | 22 | 0.831 |
| 390 | 9.42 | 4.03 | 109 | 138.46 | 1 | 2 | 22 | 0.831 |
| 437 | 9.42 | 4.36 | 106 | 123.09 | 2 | 5 | 22 | 0.844 |
| 964 | 28.1 | 7.28 | 115 | 144.33 | 1 | 5 | 21 | 0.854 |
| 428 | 8.08 | 4.21 | 61 | 102.72 | 1 | 2 | 22 | 0.858 |
| 1025 | 16.49 | 3.68 | 61 | 61.00 | 2 | 2 | 12 | 0.890 |
| 1070 | 27.96 | 4.65 | 46 | 66.41 | 2 | 3 | 12 | 0.932 |
| 1020 | 20.06 | 2.66 | 27 | 30.41 | 1 | 3 | 12 | 0.933 |
| 910 | 27.96 | 1.46 | 65 | 65.00 | 1 | 2 | 12 | 0.936 |