Evaluation of Arterial and Freeway Interaction for Determining the Feasibility of Traffic Diversion

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Abstract: Traffic congestion is a common phenomenon in our daily lives that greatly costs society. A better understanding of the interaction between freeways and arterial streets may help traffic engineers and researchers improve the operation of existing facilities and deploy feasible traffic diversion plans to improve the usage of existing road capacity within a traffic network. This paper proposes a novel two-step approach to evaluate the interaction between freeways and arterial streets by comparing their performances. The first step is to identify freeway and arterial travel time pattern similarities via template matching techniques commonly used in computer vision. The interaction is quantified in the second step by using conditional probability theory. The result of the two-step process allows analysts to determine whether traffic diversion is possible or likely between freeways and parallel arterials. The city of Bellevue, Washington was selected as a case study site because of the availability of traffic sensor data. The results demonstrate that the analysis approach allows traffic analysts to more comprehensively observe the interaction between freeway and arterial performance by using existing data collection facilities. The quantitative interaction results provide a better understanding of diversion potential and are useful in incident response, individual route planning, and integrated corridor management. This approach can be applied to any city's freeway-arterial network if reliable sources of travel time data are available. **DOI: 10.1061/(ASCE)TE.1943-5436.0000235.**

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Introduction

Freeway and arterial street congestion is a daily phenomenon in most people's lives. Congestion results in many costs, such as increased fuel consumption and time wasted when vehicles are idling in traffic. Because constructing additional roads is not often a feasible solution, maximizing the utilization of existing roadway facilities is a relatively low-cost option for reducing congestion. To achieve this goal, integrated freeway-arterial corridor management was developed to maximize the throughput of transportation facilities. Practically, the corridor control scheme is implemented by diverting traffic in real-time using the Advance Traveler Information System (ATIS). Under nonrecurrent congestion, traffic diversion may benefit the traffic network (Chu et al. 2004). However, the impact of diverting traffic from the congested roadway to the noncongested roadway has more uncertainties under recurrent congestion conditions. The diversion may lead to traffic breakdown if the wrong diversion scheme is implemented. The factors resulting in traffic breakdown are difficult to investigate, and therefore, the complicating factors can be simplified by understanding their interactions. The knowledge of the interaction between freeways and arterials can answer the following questions: when the freeway is congested, to what extent will the arterial be congested concurrently? Vice versa, is diversion to the freeway possible when the arterial is congested? The answers can be helpful to determine the feasibility of traffic diversion and to improve the system performance.

The interaction between freeways and arterials can be understood by comparing their performance. However, because of the different characteristics of freeways and arterials, previous research has often analyzed them separately. For arterial performance, several papers have been published by Smaglik et al. (2007) and Tantiyanugulchai and Bertini (2003). For freeway performance, some efforts have been made by Brilon and Geistefeldt (2007), Jeng et al. (2007), and Varaiya (2007). Although Ritchie et al. (2005) proposed an anonymous vehicle tracking method to measure arterial and freeway performance, the performance measurements were conducted separately without further comparisons. In terms of the investigation of arterial and freeway interaction, the report by Rao et al. (1996) is the research that relates the most to this paper. These writers developed an approach to evaluating the spare capacity on arterial streets to determine the feasibility of freeway traffic diversion to mitigate recurring and nonrecurring congestion. However, their research only focused on the capacity

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analysis for arterials and did not discuss freeway-arterial interaction. Moreover, the analysis results were outdated and may not reflect modern travel behavior.

Therefore, an efficient approach is needed to quantitatively and qualitatively investigate the interaction between arterial streets and freeways. Through interaction analysis, spare capacity on either freeways or arterials can be determined and used to maximize the network throughput. However, the traditional method to investigate network throughput is based on expensive travel surveys and extensive data collection efforts. This study proposes a two-step approach to evaluate and quantify the interaction between freeway and arterial by using existing sensor data. The city of Bellevue, Washington was selected as the case study site.

Data Collection and Management

Study Site Description

The city of Bellevue in Washington was selected as the case study site because it has a unique geography that is covered with a complex freeway-arterial network. In addition, the existing inductive loop detectors on both arterials and freeways in the city are capable of collecting the traffic parameters required for this research. As shown in Fig. 1, three freeways, State Route 520 (SR-520), Interstate 90 (I-90), and Interstate 405 (I-405), surround the city, and several arterials connect these freeways and serve local traffic. SR-520 and I-90 are the two primary backbones that serve cross-Lake Washington traffic between Bellevue and downtown Seattle in the west. While I-90 and SR-520 provide for east-west travel, I-405 provides a north-south corridor. Some major arterials may be used as alternate routes for freeways during peak hours. For example, during the afternoon peak hours, a large number of commuters from the northeast (e.g., city of Redmond and Microsoft campus) travel through the city network to the west and south. Hence, this network contains sophisticated interaction that draws our attention. The interchange types of the primary afternoon peak traffic flow pattern are illustrated in Fig. 1. The interchange types contain direct access and indirect access. Direct access indicates that the interchange provides on-ramps and off-ramps. The no direct access type indicates that the arterials and freeways are not directly connected by an interchange. As shown in Fig. 1, neither I-405 nor SR-520 is connected with 116th Avenue NE by an interchange. The only exception is that I-405 northbound (NB) has an off-ramp connected to 116th Avenue.

Study Route

Study Freeway Routes

Fig. 1 shows the following three freeway routes:

1. The SR-520 segment runs from west of Bellevue Way to east of 148th Avenue.
2. The I-90 study segment also runs from west of Bellevue Way to east of 148th Avenue.
3. The study segment of I-405 runs from north of SR-520 to south of I-90.

Study Arterial Routes

Analyzing all arterials enclosed by the freeways would be a tedious task that may not reflect the interaction between freeways and the major arterials. Therefore, only major arterials were included this

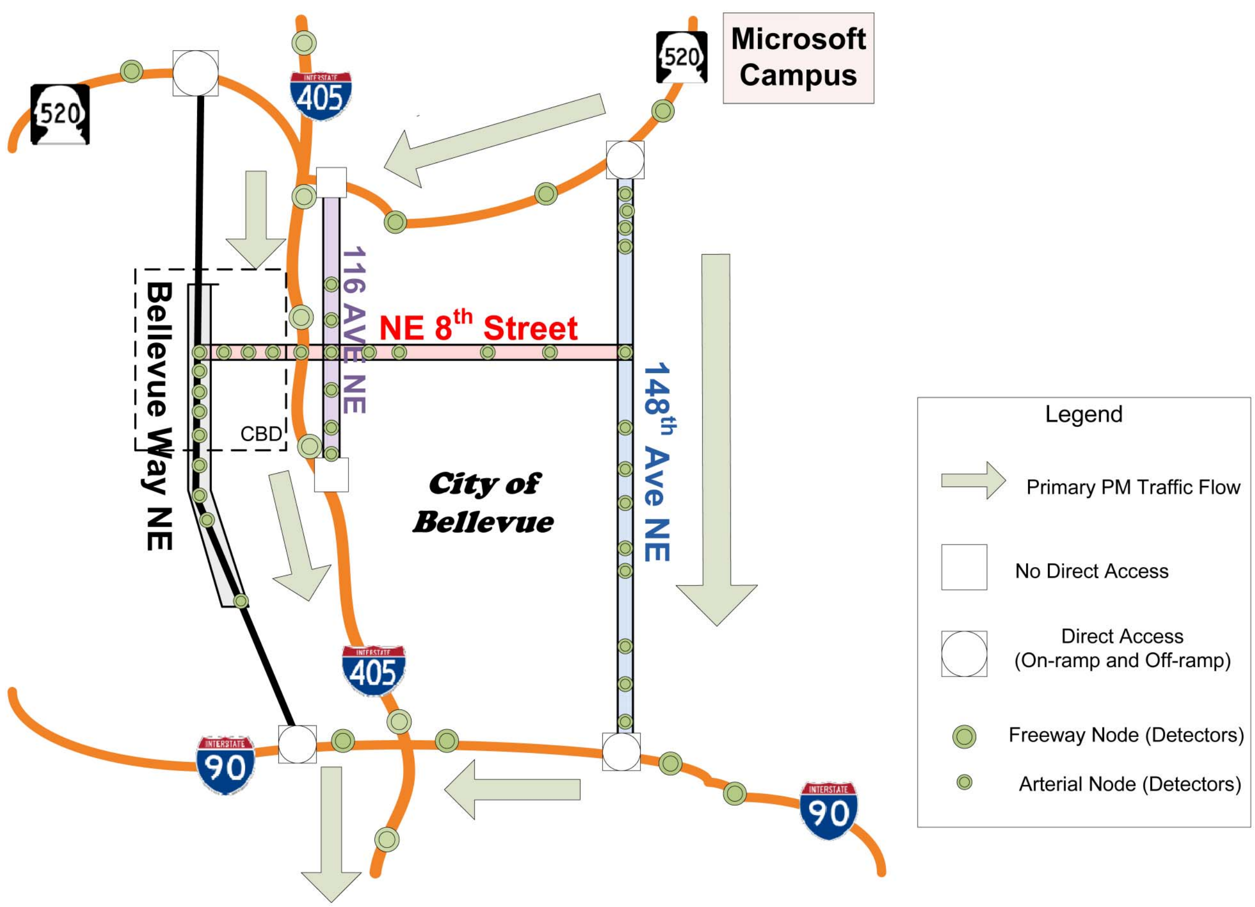

Fig. 1. Study site

study. The selection process used the Annual Average Weekday Traffic (AAWT) map provided by the city of Bellevue (2008) and also the accessibility of the three major freeways. All the study routes are illustrated in Fig. 1. Bellevue Way NE, 148th Avenue NE Street, and NE 8th Street (hereafter called Bellevue Way, 148th Avenue, and 8th Street, respectively) are the three major arterials. These three arterials had the highest AAWTs in 2007. Bellevue Way and 148th Street are two major north-south arterials that connect SR-520 and I-90. These two arterials are potential alternatives to I-405. 8th Street is the major arterial serving east-west traffic in the City. It not only intersects with I-405 but also connects the other two major arterials, 148th Avenue and Bellevue Way. In addition to these three major routes, 116th Avenue NE (hereafter called 116th Avenue) was also selected because it is close to and parallel with I-405.

Data Collection

Loop detectors have been widely used for traffic control and traffic data collection. Traffic volume, speed, and occupancy are the three parameters that loop detectors can provide in any lighting or weather conditions. The majority of the arterials and freeways in the study have functioning loop detectors. The data used in this study consist of freeway and arterial data that are explained as follows.

Arterial Inductance Loop Data

A Google-Map-based arterial traveler information (GATI) system (Wu and Wang 2009; Wu et al. 2007), developed by the Smart Transportation and Application Research Laboratory (STAR Lab) at the University of Washington, has been retrieving and archiving Bellevue's data every minute since January 1, 2007. These data sets include the volume and occupancy data used in later analyses. Details about the data format and database schema can be found in Wu et al. (2007). With the assistance of the GATI system, arterial data was easily retrieved and manipulated. The advance loop detectors are normally located at 100–130 ft (30.5–45.7 m) upstream from the stop bars. As illustrated in Fig. 1, 13 nodes on 148th Avenue, 10 nodes on 8th Street, nine nodes on Bellevue Way, and five nodes on 116th Avenue were used in this study. These nodes are the intersections with advance detectors installed at each approach.

Freeway Inductance Loop Data

Historical freeway loop detector data for study were retrieved from the Traffic Data Acquisition and Distribution (TDAD) website. TDAD was developed by the University of Washington. The TDAD database contains data from October 1998 to June 2007 (ITS UW 2008). The database contains measurements from all of the Washington State DOT's single-and dual-loop detectors, taken at 20-s intervals. The loop detectors in each loop station are capable of measuring the traffic parameters on every freeway lane. The measurements include volume, occupancy, and speed (from dual-loop detectors). As illustrated in Fig. 1, 14 dual-loop detectors were used to retrieve speed data in this study.

Data Collection Period

In this study, three months (April to June 2007) of loop data were collected from the study freeways and arterials. This period represents the spring quarter of travel behavior when all the schools are in session. Only weekday (Monday to Friday) data were used to analyze weekday traffic pattern and investigate freeway-arterial interaction. This sample size proved sufficient to verify the feasibility of the evaluation methodology proposed in this study. No major incidents, events, or inclement weather conditions affected the data consistency during the study period.

Data Quality Control

To assure the accuracy of the analysis results, a data quality control procedure was implemented to check the data quality for all the loop data collected during the study period. No loop detectors were omitted because of poor data quality. For the freeway loop data, LoopGrapher, a data visualization tool developed by the STAR Lab, was used to examine the loop quality. This tool can automatically plot months of data in all dimensions (e.g., volume and speed), comparing the data spatially and temporally. Arterial loop data, usually having higher fluctuations than freeway loop data, were preprocessed before being stored in the server. The preprocess procedure includes a volume and occupancy smoothing process, outlier removal, and prediction (Liang 2006). Furthermore, the GATI system was used to verify the data visually and quantitatively to ensure the absence of missing data and abnormal fluctuations. Other random errors, such as abrupt surges in volume data, can be handled by the proposed approach, which will be explained further in the Methodology section.

Performance Measure: Travel Time

Travel time is one of the accepted measures of effectiveness (MOEs) common to both arterials (Zhang 1997; Liu 2008) and freeways (van Lint et al. 2008; Rumin et al. 2006; Margiotta et al. 2006). In this study, 5-min aggregation was chosen because this aggregation level is not sensitive to noise and still able to reflect traffic fluctuations in a timely manner. The freeway and arterial travel times will be calculated at this aggregation level.

Freeway Travel Time Calculation

Freeway travel time (FTT) is calculated based on an instantaneous model (Rumin et al. 2006). The travel time for study route i in sampling interval t, $\mathrm{FTT}(i,t)$, is calculated as the sum of the link travel times for each freeway segment. The link travel time is calculated as the link length, $l(j)$, divided by the average of the speeds retrieved from the dual-loop detectors in the upstream and downstream, respectively:

$$\mathrm{FTT}(i,t) = \sum_{j=1}^{n} \frac{2l(j)}{v(j_u,t) + v(j_d,t)} \tag{1}$$

where $v(j_u,t)$ and $v(j_d,t)$ = 5-min average speeds crossing over all lanes measured at the upstream j_u and downstream j_d dual-loop detectors at sampling interval t; j = link number; and n = number of links on a study route. Fig. 2 shows an example of the time-of-day FTT for June 5, 2007 (Tuesday) and also presents the weekday travel pattern for study freeways. As previously mentioned, a large number of commuters travel south and west through the city during afternoon peak hours, which results in noticeable congestion. In the following analysis, SR-520 westbound (WB), I-405 southbound (SB), and I-90 (WB) are considered as a group and the reverse directions considered as a second group to present a more understandable comparison.

Arterial Travel Time Calculation

The arterial travel time (ATT) calculation is handled in a manner similar to the FTT calculation. However, the link speed estimation includes the addition of control and queuing delay caused by signalized intersections. In this study, the arterial is divided into several links by the intersections. Links are defined as the segments between intersections. Hence, the ATT for route i in sampling interval t is calculated as the sum of the link travel times:

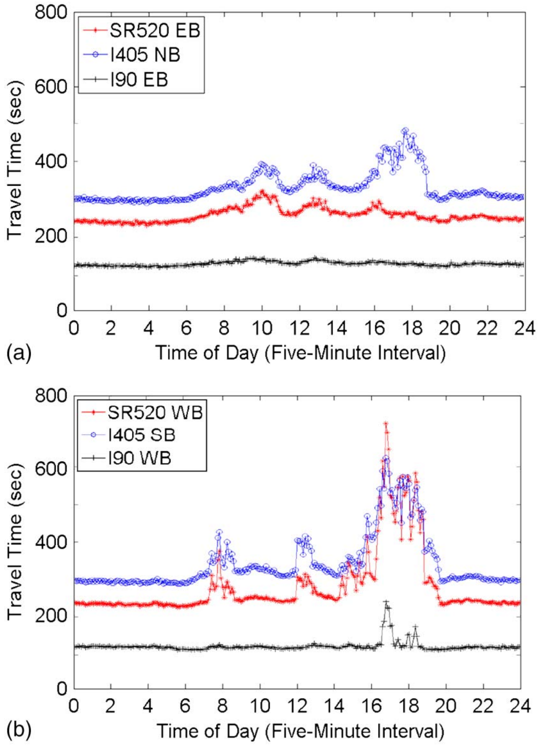

Fig. 2. Example results of freeway travel time calculation (Tuesday, June 5, 2007)

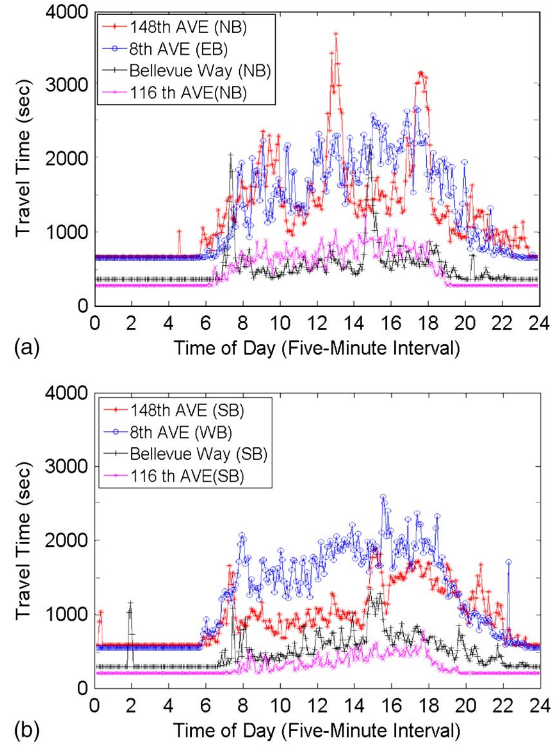

Fig. 3. Example results of arterial travel time calculation (Tuesday, June 5, 2007)

$$\mathrm{ATT}(i,t) = \sum_{j=1}^{n} \frac{l(j)}{v(j,t)} \qquad (2)$$

where l = length for link j; n = number of links on an arterial route; $v(j,t)$ = average travel speed crossing over all lanes for link j at sampling interval t. The calculated link speed should include the effects of control delay and queue delay. Several models, such as the Bureau of Public Roads (BPR)-based model and Iowa model, were proposed by previous research papers (Zhang 1999; Tsekeris and Skabardonis 2004). In this research, the theoretical speed model is used (Kutz 2004) to simplify the calculation process. Therefore, the link travel speed, v, is calculated by the equations as follows:

$$v = \frac{q}{d} \qquad (3)$$

$$d = \frac{o}{100\,\bar{L}} \qquad (4)$$

where q = traffic volume; d = density calculated from the detector occupancy measurement, o; $\bar{L}$ = average effective vehicle length of the traffic stream that crossed over the advance loop detectors during the sampling interval t. The length of an advance loop detector is 6 ft (1.9 m) and the assumed average vehicle length is 14 ft (4.27 m). With few trucks traveling on the arterials, an average effective vehicle length of 20 ft was assumed [$\bar{L} = 6 + 14$ ft $= 20$ ft (6.1 m)]. When the occupancy is lower than 5%, the maximum speed of the day is used. The calculated travel time may not reflect true travel times because the advance loop, a point detector, cannot accurately represent an entire link. However, the accuracy of the travel times will not significantly affect the interaction results because this research focuses only on the comparison of general trends of freeway and arterial performance. Details can be found the in the Methodology section.

Fig. 3 shows an example of the calculated travel times for the study arterials. In contrast to the FTTs, the study arterials have multiple peak periods. Overall, the arterial performance suffers from the afternoon peak congestion (approximately $3 \sim 7$ p.m.) more than other periods.

Alternative Travel Time Collection Sources

The proposed two-step approach relies on bountiful travel time data. For cities without loop detectors, other travel time collection methods can also be used, such as license plate matching and probe vehicle techniques (Turner et al. 1998). Recently, several emerging technologies have been developed that may increase the accuracy and feasibility of travel time collection on freeways and arterials. Wasson et al. (2008) developed the Bluetooth-based travel time collection system, which serves as a low-cost solution to travel time collection and may make the proposed approach more applicable to other cities. The vehicle signature-based method (Ndoye et al. 2008) can use the existing loop detectors to estimate more reliable travel time on arterials. Wireless magnetic sensors (Kwong et al. 2009) demonstrated capability of providing reliable travel time data and showed the potential to replace existing loop detectors. With the assistance of these technologies, travel time collection becomes more feasible and the application of the proposed methodology can be extended to other areas.

Methodology

After the travel times for the study period are calculated, measuring the interaction between their performances helps identify the driver behaviors on the freeway-arterial network. A two-step analysis approach is proposed. The first step is to evaluate the travel time similarity between freeways and arterials by using a pattern matching technique. The second step, conditional probability analysis, further quantifies their interactions. The methodology can be also applied to freeway-freeway or arterial-arterial interaction analyses, but this is out of the scope of this research.

Travel Time Pattern Analysis

Although the travel time for each day can be plotted as shown in Figs. 2 and 3, analyzing these traffic time plots can be labor-intensive, and drawing meaningful conclusions can be difficult. Hence, the travel time map is used to visually express the travel time pattern. In Figs. 4(a) and 4(b), the travel maps for SR-520 (WB) and 148th Avenue (SB) are taken as examples because they are known for being congested during afternoon peak hours. The x-axis is the time of day (24 h) and y-axis is the weekday (65 weekdays, from April to June). The colors demonstrate different levels of travel times. Fig. 4(a) shows that this portion of SR-520 (WB) regularly suffers from congestion during the morning (7–10 a.m.) and afternoon peak hours (3 ~ 7 p.m.). On the other hand, Fig. 4(b) shows that 148th Avenue had higher travel times from approximately 2:30 to 3:30 p.m.. Following a travel time drop, another peak hour period started at approximately 5 p.m. and ended at approximately 7 p.m.

The proposed travel time map provides an efficient way to visually inspect the traffic time pattern, but it is not sufficient for quantifying the similarity or correlation of travel time patterns. Therefore, correlation analysis is required to assist in identifying the interaction between freeways and arterials. However, the traditional correlation analysis is only used to analyze one-dimensional data, such as comparing the daily travel time pattern between two routes. To compare their long-term performance, a correlation-based template matching method is adopted in this paper. Hereafter, the travel time map should be regarded as an image and any portion of the image as a template.

Template matching techniques are commonly used in the field of computer vision to recognize human faces and track vehicles (Nallaperumal et al. 2006; Choi et al. 2006; Jain 1995; Gonzalez et al. 2004). Several methods have been proposed, such as measuring the correlation, sum of the squared errors, and sum of the absolute errors between two images to measure their similarity (Jain et al. 1995; Gonzalez et al. 2004). Among these methods,

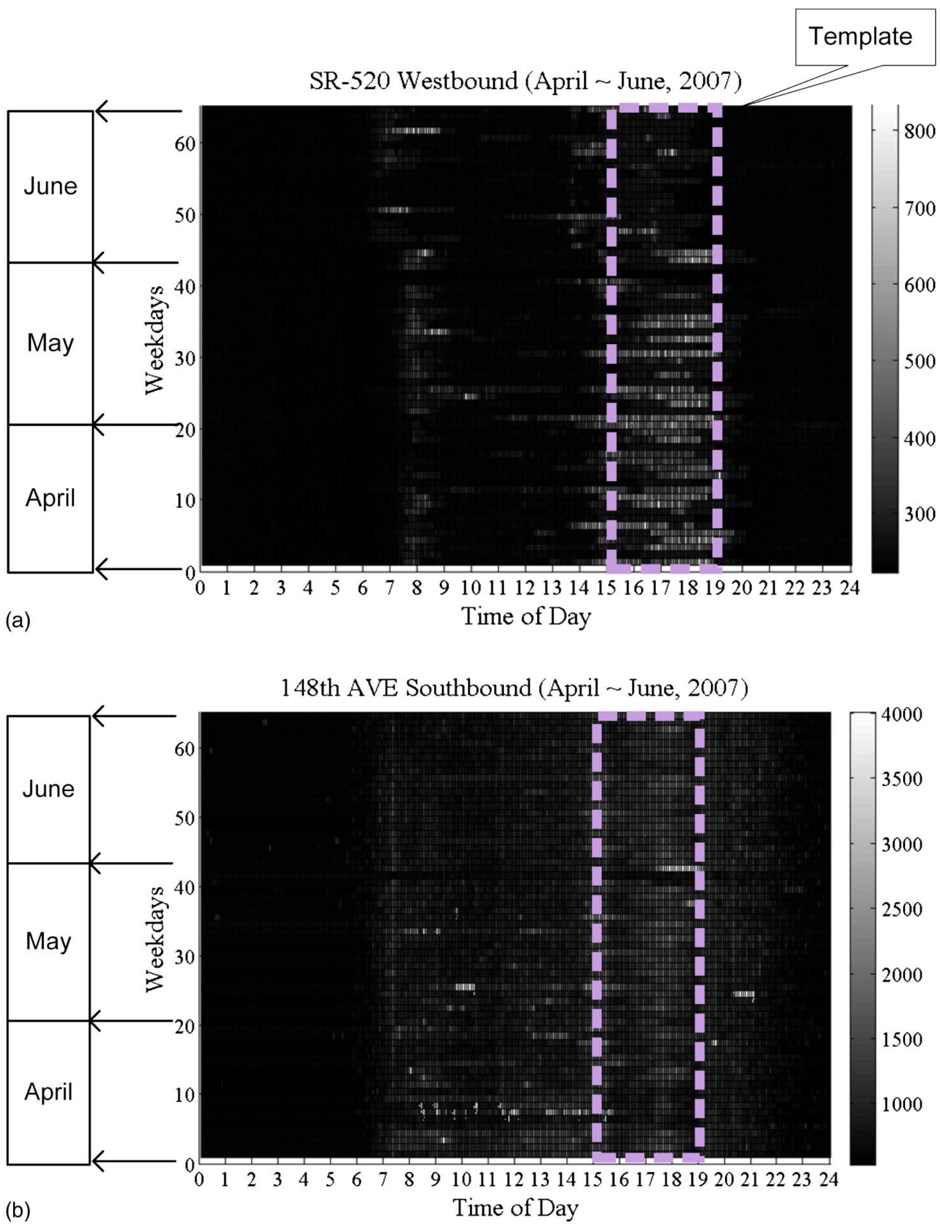

Fig. 4. Travel time map examples for (a) freeway SR-520 (WB); (b) arterial 148th Avenue (SB) (April to June, 2007)

two-dimensional (2D) correlation is regarded as one of the most suitable approaches to quantify the similarity between two patterns because it is not affected by the absolute difference of two patterns. In other words, this method is not sensitive to the outliers in the travel time estimation. Therefore, this method can effectively quantify the similarity of the freeway and arterial travel time fluctuations, even though some nonrecurrent congestion exists. The 2D correlation coefficient, ρ, is defined as follows (Lin 2002):

$$\rho = \frac{mn\sum_{i=1}^{m}\sum_{j=1}^{n}(A_{ij}\cdot F_{ij}) - \sum_{i=1}^{m}\sum_{j=1}^{n}A_{ij}\sum_{i=1}^{m}\sum_{j=1}^{n}F_{ij}}{\sqrt{[m\cdot n\sum_{i=1}^{m}\sum_{j=1}^{n}(A_{ij})^2 - (\sum_{i=1}^{m}\sum_{j=1}^{n}A_{ij})^2]\cdot[m\cdot n\sum_{i=1}^{m}\sum_{j=1}^{n}(F_{ij})^2 - (\sum_{i=1}^{m}\sum_{j=1}^{n}F_{ij})^2]}} \quad (5)$$

where A_{ij} = a cell (a travel time sample) of the template image cropped from the ATT map at time i and day j; F_{ij} = a cell of the template image cropped from an FTT map at time i and day j; m and n = dimensions of the template image. Each travel map had frequent fluctuations during afternoon peak hours. In this study, quarterly weekday traffic patterns during afternoon peak hours were evaluated and serve as an example case. Hence, the sampling time interval index, $i = 180$–228 (3–7 p.m.) and weekday index is $j = 1$–65 (65 weekdays during the study period). As illustrated in Figs. 4(a) and 4(b), the travel time templates are enclosed by dashed rectangles.

Each selected freeway template was matched with each selected arterial template. Table 1 shows the correlation coefficient for each freeway-arterial pair. For example, in Fig. 4, the correlation between the travel time templates extracted from the SR-520 (WB) and 148th (SB) cases is 0.33. For easy distinction, the cell with a higher correlation value is highlighted with a darker color. Owing to the complexity of the travel time patterns (especially for arterials), a correlation coefficient of 0.50 can be regarded as high, implying that arterial and freeway travel time patterns have significant similarity. A correlation coefficient of 0.30 is regarded as moderate, implying that the travel time patterns are similar.

As mentioned previously, commuters from Redmond and the Microsoft campus move westbound and southbound through the City of Bellevue traffic network during afternoon peak hours. Hence, it is not surprising that SR-520 (WB) and I-405 (SB) have high correlation values (0.50 and 0.53, respectively), and I-90 (WB) has a moderate correlation value (0.33) with Bellevue Way (SB). Meanwhile, these three freeways also correlate with 148th Avenue (SB) (0.33, 0.36, and 0.25, respectively). On the basis of the similarities of these travel time patterns, one can infer that commuters using SR-520 (WB) may choose either Bellevue Way (SB) or 148th Avenue (SB) as alternatives to I-405. However, 116th Avenue (NB), the street closest to and parallel with I-405, has fairly low correlation with any other freeways. This might be because the north and south ends of 116th Avenue do not have ramps connecting to SR-520 or I-405.

By selecting a range of the times of day (range in x-axis) depending on the peak hour spread and the period of interest (weekday range in y-axis), monthly or weekly travel time pattern analysis can be completed in the same manner. Moreover, this template matching method can be used to search the most similar template (travel time pattern) in the whole travel time image. It can also be used to examine the correlation of changes in travel patterns [for example, creating and comparing templates containing data on the change in travel time on SR-520 (WB) with Bellevue Way (SB)]. It is also relatively simple to perform time offset correlations (i.e., comparing conditions on SR-520 at 5:00 p.m. with conditions on Bellevue Way at 5:05 p.m.) Similar applications in image processing can be found in the work of Gonzalez et al. (2004).

Conditional Probability Analysis

Through travel time pattern analysis, one can realize the temporal correlation of every freeway-arterial combination. However, this analysis cannot provide two-way information, such as whether the freeway or arterial causes fluctuations in the other roadway. To quantify the two-way relationship (interaction) between freeway and arterial performance, a conditional probability analysis is proposed.

Conditional Probability Theory

The conditional probability theory (Hines 2003) was adopted to quantify the interaction between freeway and arterial performance. This can help analysts answer the questions: what is the freeway performance given the measured arterial performance? What is the arterial performance given the measured freeway performance? The conditional probability for performance comparison can be written as

$$P(X|Y) = \frac{P(X\cap Y)}{P(Y)} \quad \text{and } P(Y|X) = \frac{P(Y\cap X)}{P(X)} \quad (6)$$

Table 1. Correlation Coefficient Table (Afternoon Peak Hours)

Freeways and arterials	SR-520 (WB)	I-405 (SB)	I-90 (WB)	SR-520 (EB)	I-405 (NB)	I-90 (EB)
148th Avenue (SB)	0.33	0.36	0.25	0.24	0.19	0.19
8th Street (WB)	0.16	0.20	0.11	0.26	0.18	0.15
Bellevue Way (SB)	0.50	0.53	0.33	0.18	0.25	0.13
116th Avenue (SB)	0.17	0.20	0.10	0.31	0.25	0.16
148th Avenue (NB)	0.08	0.11	0.07	0.13	0.16	0.07
8th Street (EB)	0.26	0.30	0.17	0.34	0.32	0.21
Bellevue Way (NB)	0.08	0.09	0.02	0.09	0.04	0.07
116th Avenue (NB)	0.03	0.06	0.01	0.20	0.12	0.07

where X = freeway performance and Y = arterial performance. In this study, the performance is categorized into three levels: free-flow traffic (F), moderate traffic (M), and congested traffic (C). Hence, the performance for freeway X and arterial Y can be separated into the categories $X = \{\text{Freeway Performance}\} = \{\text{FC, FM, FF}\}$ and $Y = \{\text{Arterial Performance}\} = \{\text{AC, AM, AF}\}$ where FC = congested freeway traffic; FM = moderate freeway traffic; FF = free-flow freeway traffic; AC = congested arterial traffic; AM = moderate arterial traffic; and AF = free-flow arterial traffic.

Determining Performance Levels

To perform categorical data analysis using conditional probability theory, the travel time threshold values have to be determined in advance to distinguish different levels of performance in the data set. Table 2 shows the travel time threshold values calculated for different speeds on the arterials and freeways. For freeways, the average travel speeds of 60 and 40 mph were selected to distinguish the three performance levels (F, M, and C). For arterials, average travel speeds of 30 and 10 mph were selected for separating these three performance levels.

Accordingly, route length divided by the threshold speeds provided the travel time thresholds to determine three congestion levels. The estimated ATT thresholds need to consider the delays caused by the traffic signals. The approach used in this study is that the travel time threshold is determined by the travel time (link length divided by the speed limit) plus average control delays. The average intersection delays (control delays and queue delays) calculated in a Synchro 7 microsimulation model (Hush and Albeck 2006) were used. The parameter input, e.g., volume, in this model is based on the afternoon peak conditions. Average control delays are calculated by the built-in Highway Capacity Manual (HCM)-based method. The goal of calculating the thresholds is to separate the travel times into three congestion levels. Hence, another possible solution to avoid complicated calculation for the average control delays is to investigate the distribution of ATTs collected during the study period, and engineers can separate travel times into three congestion groups (F, M, and C) by using professional engineering judgment.

The route travel time distribution percentiles corresponding to the travel time thresholds are included in Table 2. The percentile indicates how much percentage of travel time samples is below the travel time threshold. Take SR-520 (WB) for example: 92% of travel times collected over the study period is below the threshold (372.6 s)

Conditional Probability Table

On the basis of the travel time thresholds, performance relationships can be investigated by using conditional probability theory. In other words, each cell (travel time sample) in Fig. 2 was categorized into three performance levels based on the predefined travel time thresholds. After converting all the cells, the conditional probability equation [Eq. (6)] is used to calculate the conditional probabilities for all the scenarios. Each combination of freeway and arterial performance levels will form a conditional probability table. To investigate all the freeway-arterial relationships, nine combination tables were constructed for analyzing afternoon peak hour period (3–7 p.m.). These tables include tables for $\{\text{FC, AC}\}$, $\{\text{FC, AM}\}$, $\{\text{FC, AF}\}$, $\{\text{FM, AC}\}$, $\{\text{FM, AM}\}$, $\{\text{FM, AF}\}$, $\{\text{FF, AC}\}$, $\{\text{FF, AM}\}$, and $\{\text{FF, AF}\}$.

Tables 3–5 show the conditional probability tables of $\{\text{FC, AC}\}$, $\{\text{FF, AF}\}$, and $\{\text{FM, AM}\}$ as examples. The cell with a higher probability value is darker in color. In Table 3, the greater probability indicates that there may be less opportunity for travelers to divert in the congested condition. In Table 4, the greater probability indicated that there may be greater opportunity for travelers to divert because of free-flow conditions. Table 5 shows an example of the moderate traffic condition, which can give more diversion potential than the other tables. Overall, these tables allow analysts to efficiently observe the interaction between the freeway and arterial performance.

Table 3 shows the conditional probability table for $\{\text{FC, AC}\}$ to provide information about how traffic can shift given a congested condition. Using 8th Street (WB) as an example, when the freeway is congested, the arterial is likely to be congested. In contrast, the freeway is less likely to be congested when the arterial is congested. One can find that although the freeway was not congested, drivers would be less likely to use the freeway given a congested arterial. This might be because trips on the arterial are not as easily diverted because of the shorter origin/destination (O/D) distance. Other arterial corridors [8th Street eastbound (EB), 116th Avenue (NB)] show a similar trend.

Table 4 shows the conditional probability table for $\{\text{FF, AF}\}$ to provide information about how traffic can shift given a free-flow condition. Arterial-freeway and freeway-arterial have fairly equal probabilities for SR-520 (EB) and I-405 (NB). This might be because they generally experience similar free-flow conditions in the afternoon. For the traffic from Redmond and the Microsoft campus [SR-520 (WB), I-405 (SB), and I-90 (WB)], if the arterials are experiencing free-flow conditions, these freeways are likely also experiencing free-flow conditions because of the high overall

Table 2. Travel Time Threshold Values for Determining the Performance Level

	Average travel speed	40 mph		60 mph			
Length (mi)	Freeway routes	Travel time threshold (s)	Percentile (%)	Travel time threshold (s)	Percentile (%)	Speed limit (mph)	
4.14	SR-520 (WB/EB)	372.6	92 (WB)/99(EB)	248	72 (WB)/37(EB)	60	
5.20	I-405 (SB/NB)	468.0	94 (SB)/99(NB)	312	65 (SB)/45(NB)	60	
2.20	I-90 (WB/EB)	198.0	98 (WB)/99(EB)	132	96 (WB)/78(EB)	60	
	Speed threshold	10 mph		30 mph			
Length (mi)	Arterial routes	Travel time threshold (s)	Percentile (%)	Travel time threshold (s)	Percentile (%)	Speed limit (mph)	Control delay (s)
3.55	148th Avenue (SB/NB)	1,619	94 (SB)/87(NB)	767	37 (SB)/27(NB)	35	341
2.72	8th Street (WB/EB)	1,425	55 (WB)/59(EB)	773	34 (WB)/40(EB)	30	446
1.98	Bellevue Way (SB/NB)	889	93 (SB)/97(NB)	414	38 (SB)/50(NB)	30	177
1.30	116th Avenue (SB/NB)	617	98 (SB)/67(NB)	305	60 (SB)/45(NB)	30	149

Table 3. Conditional Probability Table for Combination {FC, AC}

		SR-520 (WB)	I-405 (SB)	I-90 (WB)	SR-520 (EB)	I-405 (NB)	I-90 (EB)
148th Avenue (SB)	$P(AC\|FC)$	19.59%	24.49%	24.49%	4.08%	8.16%	6.12%
	$P(FC\|AC)$	24.49%	24.49%	6.12%	1.02%	2.04%	1.53%
8th Street (WB)	$P(AC\|FC)$	52.65%	57.14%	46.94%	73.47%	63.27%	51.02%
	$P(FC\|AC)$	9.08%	7.88%	1.62%	2.53%	2.18%	1.76%
Bellevue Way (SB)	$P(AC\|FC)$	26.94%	36.73%	14.29%	2.04%	12.24%	4.08%
	$P(FC\|AC)$	26.94%	29.39%	2.86%	0.41%	2.45%	0.82%
116th Avenue (SB)	$P(AC\|FC)$	4.90%	5.10%	6.12%	4.08%	0.00%	4.08%
	$P(FC\|AC)$	24.49%	20.41%	6.12%	4.08%	0.00%	4.08%
148th Avenue (NB)	$P(AC\|FC)$	16.73%	17.35%	8.16%	6.12%	12.24%	2.04%
	$P(FC\|AC)$	10.46%	8.67%	1.02%	0.77%	1.53%	0.26%
8th Street (EB)	$P(AC\|FC)$	54.69%	46.94%	53.06%	42.86%	53.06%	26.53%
	$P(FC\|AC)$	10.13%	6.95%	1.97%	1.59%	1.97%	0.98%
Bellevue Way (NB)	$P(AC\|FC)$	3.27%	3.57%	0.00%	2.04%	4.08%	2.04%
	$P(FC\|AC)$	8.16%	7.14%	0.00%	1.02%	2.04%	1.02%
116 th Avenue (NB)	$P(AC\|FC)$	32.24%	28.57%	26.53%	36.73%	57.14%	16.33%
	$P(FC\|AC)$	7.68%	5.44%	1.26%	1.75%	2.72%	0.78%

Table 4. Conditional Probability Table for Combination {FF, AF}

	Freeway route	SR-520 (WB)	I-405 (SB)	I-90 (WB)	SR-520 (EB)	I-405 (NB)	I-90 (EB)
148th Avenue (SB)	$P(AF\|FF)$	45.03%	47.38%	38.48%	50.26%	47.85%	38.98%
	$P(FF\|AF)$	88.18%	82.91%	99.40%	50.26%	57.82%	82.82%
8th Street (WB)	$P(AF\|FF)$	38.60%	40.14%	34.63%	39.12%	36.66%	34.65%
	$P(FF\|AF)$	82.47%	76.62%	97.59%	42.67%	48.33%	80.33%
Bellevue Way (SB)	$P(AF\|FF)$	46.29%	49.37%	39.80%	46.85%	45.04%	39.98%
	$P(FF\|AF)$	87.02%	82.94%	98.69%	44.98%	52.24%	81.55%
116th AVE (SB)	$P(AF\|FF)$	61.96%	62.68%	60.30%	61.05%	62.56%	60.02%
	$P(FF\|AF)$	74.67%	67.50%	95.87%	37.57%	46.52%	78.49%
148th Avenue (NB)	$P(AF\|FF)$	28.35%	28.72%	27.65%	30.53%	30.40%	28.33%
	$P(FF\|AF)$	74.04%	67.01%	95.24%	40.70%	48.98%	80.27%
8th Street (EB)	$P(AF\|FF)$	44.90%	46.99%	40.92%	48.47%	48.56%	41.42%
	$P(FF\|AF)$	81.16%	75.90%	97.57%	44.74%	54.16%	81.24%
Bellevue Way (NB)	$P(AF\|FF)$	50.89%	51.36%	49.08%	47.70%	49.89%	49.26%
	$P(FF\|AF)$	74.74%	67.41%	95.09%	35.78%	45.22%	78.51%
116 th Avenue (NB)	$P(AF\|FF)$	46.20%	47.13%	44.83%	51.62%	50.74%	44.98%
	$P(FF\|AF)$	74.88%	68.26%	95.85%	42.72%	50.74%	79.10%

Table 5. Conditional Probability Table for Combination {FM, AM}

		SR-520 (WB)	I-405 (SB)	I-90 (WB)	SR-520 (EB)	I-405 (NB)	I-90 (EB)
148th Avenue (SB)	$P(AM\|FM)$	72.06%	71.00%	67.35%	62.86%	64.72%	62.32%
	$P(FM\|AM)$	25.32%	36.46%	3.64%	67.95%	61.22%	21.90%
8th Street (WB)	$P(AM\|FM)$	20.88%	21.91%	22.45%	23.47%	22.92%	22.45%
	$P(FM\|AM)$	19.39%	29.74%	3.21%	67.06%	57.29%	20.85%
Bellevue Way (SB)	$P(AM\|FM)$	61.38%	63.48%	58.16%	56.48%	56.73%	55.42%
	$P(FM\|AM)$	22.80%	34.46%	3.32%	64.55%	56.73%	20.58%
116th Avenue (SB)	$P(AM\|FM)$	42.54%	42.96%	38.78%	39.03%	40.29%	39.25%
	$P(FM\|AM)$	22.12%	32.65%	3.10%	62.45%	56.41%	20.41%
148th Avenue (NB)	$P(AM\|FM)$	62.32%	61.22%	51.02%	60.87%	60.47%	62.64%
	$P(FM\|AM)$	20.77%	29.83%	2.62%	62.43%	54.26%	20.88%
8th Street (EB)	$P(AM\|FM)$	21.51%	19.87%	26.53%	20.31%	19.59%	21.66%
	$P(FM\|AM)$	23.30%	31.46%	4.42%	67.69%	57.14%	23.47%
Bellevue Way (NB)	$P(AM\|FM)$	48.04%	48.66%	44.90%	45.41%	46.36%	46.78%
	$P(FM\|AM)$	20.82%	30.82%	2.99%	60.54%	54.08%	20.27%
116 th Avenue (NB)	$P(AM\|FM)$	24.65%	23.63%	28.57%	23.93%	24.49%	24.02%
	$P(FM\|AM)$	21.36%	29.93%	3.81%	63.81%	57.14%	20.82%

$P(\text{FF}|\text{AF})$s. However, one cannot determine the arterial condition given freeways experiencing free-flow conditions because of the low overall $P(\text{AF}|\text{FF})$. I-90 (EB)'s free-flow probability displays a curiously strong relationship with arterial free-flow status, shown by the darker color. In contrast, arterial free-flow status is weakly related to I-90's free-flow status, as shown by the lighter color. It is not surprising that 99% of the collected travel times collected from I-90 (EB) were in the noncongestion condition, as shown in Table 2. SR-520 (EB) and I-405 (NB) columns have almost equal probabilities, $P(\text{FF}|\text{AF})$ and $P(\text{AF}|\text{FF})$; therefore, they have equal diversion potential from freeway to arterial and arterial to freeway.

For some drivers, shifting to the freeway with moderate traffic condition can still improve travel time (the average speed threshold for "moderate" is 40 mph, which is still faster than most of the arterials). It is therefore important to examine the freeway-arterial interaction when traffic is moderate. The conditional probability for $\{\text{FM}, \text{AM}\}$ shown in Table 5 can be a suitable source of such information. In the moderate traffic condition, arterials have little interaction with SR-520 (WB), I-405 (SB), I-90 (WB), and I-90 (EB) based on low values of $P(\text{FM}|\text{AM})$. Fairly high $P(\text{AM}|\text{FM})$ values for I-90 (WB) indicate that moderate congestion on freeway is more predicable when the freeway has moderate congestion. However, to draw better conclusions, other tables, such as $\{\text{FC}, \text{AM}\}$ and $\{\text{FM}, \text{AC}\}$, should be considered. Cases of moderate traffic are not emphasized in this study but are important for more detailed analysis in future applications.

Similar to the travel time pattern analysis, this method is not sensitive to the accuracy of the travel time estimation as long as the performance levels are properly defined, based on traffic characteristics or each route's travel time distribution.

Application and Findings

The proposed two-step approach consists of travel time pattern analysis and conditional probability analysis. These analysis results have to be interpreted concurrently or misleading conclusions will be drawn. The travel time pattern analysis provides useful temporal correlation information, but it lacks two-way interaction information for different performance levels. The conditional probability analysis provides an overview of two-way interaction between freeways and arterials, but it does not consider the impact of the time-dependent factor. For example, if the arterial street and freeway have the same congestion duration but have different beginning and ending times, the conditional probability may still be high, but one cannot conclude concurrent interaction between freeways and arterials. Therefore, the conclusion of freeway-arterial interaction should be based on the results of both analyses.

Table 6 provides a summary of analysis result interpretation. The feasibility of traffic diversion can be reinvestigated based on the analysis results (Tables 1 and 3–5).

1. Bellevue Way (SB) has been regarded as a potential detour for I-405 (SB). Compared with other routes, Bellevue Way (SB) has relatively high correlation with SR-520 (WB), I-405 (SB), and I-90 (WB) (0.50, 0.53, and 0.33, respectively) in Table 1. Table 3 shows weak two-way relationships between all the freeways and Bellevue Way (SB) because of the low conditional probabilities for either freeway-to-arterial or arterial-to-freeway. Low conditional probabilities give the traffic engineer a hint that the congested traffic can be diverted from either freeway-to-arterial and vice versa.
2. 8th Street (EB) has been regarded as an alternative route for SR-520 (EB). Compared with the pair of Bellevue Way (SB) and I-405 (SB), this freeway-arterial pair has different interactions. Table 1 shows that 8th Street (EB) has slightly high correlation with freeways, especially with SR-520 (EB) (0.34). Unlike case of the Bellevue Way (SB), when the freeway [SR-520 (EB)] is congested, the arterial [8th Street (EB)] is likely to be concurrently congested (42.86%), but the opposite has much less probability (1.59%). This might be because the capacity of SR-520 (EB) is not fully utilized during the afternoon peak hours. When congestion occurs on the arterial, traffic can be diverted from 8th Street (EB) to SR-520 (EB). In contrast, the freeway traffic is not recommended to be diverted to the arterial because of high correlation and high $P(\text{AC}|\text{FC})$.
3. 148th Avenue (SB) has also been considered another detour for I-405 (SB), especially for the traffic from the Microsoft campus. Compared with Bellevue Way (SB), 148th Avenue has relatively low correlation with SR-520 (WB), I-405 (SB), and I-90 (WB) (0.33, 0.36, and 0.25, respectively) in Table 1. Meanwhile, 148th Avenue (SB) and I-405 (SB) have low conditional probabilities [both $P(\text{AC}|\text{FC})$ and $P(\text{FC}|\text{AC})$ are 24.49%]. Although 148th Avenue (SB) has a very similar freeway-arterial interaction pattern to Bellevue Way (SB), its low correlation may not encourage traffic diversion during afternoon peak hours.
4. Geographically, 116th Avenue (SB) seems to be an alterative route for I-405 (SB). Because of its low interaction (low correlation and conditional probabilities) with all the study freeways shown in Tables 3 and 5, 116th Avenue (SB) is not a recommended alternative route for I-405 (SB). As mentioned previously, there is no ramp connecting to SR-520 in the north of I-405. This also explains the reason for the low interaction.

Based on the application results of the two-step approach, the findings of diversion opportunities for afternoon peak hours are:

1. I-405 (SB) can be a feasible alternative route for Bellevue Way (SB).
2. Compared to Bellevue Way (SB), 148th Avenue (SB) has a similar interaction with other freeways, but the interaction is weaker. Weaker interaction may not justify traffic diversion during peak hours.
3. When 8th Street (EB) is congested, SR-520 (EB) can be a suitable alternative route, but the opposite is not recommended.
4. 116th Avenue is not a suitable alternative route for I-405 because of the geometric constraints and low interaction shown in the analysis results.

Expert Validation

To verify the applicability of the proposed approach, an expert validation procedure was desired. Hence, the proposed approach and

Table 6. Summary of Analysis Result Interpretation (Congestion Cases)

		Correlation	
		High	Low
Conditional probability	High	Congestion happens concurrently on the freeway and the arterial. Traffic diversion is not recommended.	The freeway and arterial traffic patterns are different. Traffic diversion is not recommended because of the unpredictability of the traffic pattern.
	Low	Although high correlation exists, the possibility of congestion is lower. Traffic diversion is feasible.	

its results were presented to an expert panel on March 12, 2009. The expert panel consisted of traffic engineers, urban planners and information technology (IT) staff from the city of Bellevue. The main purpose of this validation process was to verify whether the research findings agree with their years of experience and observations. The panel agreed with the results, noting that they truly reflecting travelers' behaviors in the city, and further recommended that the approach should be incorporated with their online ATIS to facilitate their decision-making process.

Conclusions and Recommendations

Although understanding the interaction between freeway and arterial street performance is helpful for realizing traffic flow behavior within a network, few methods focus on investigating arterial and freeway interactions. Traditional travel pattern analysis is commonly implemented by using expensive time-consuming travel surveys. This paper proposes a novel two-step approach to evaluating the interaction between freeways and arterials by evaluating their performance using existing sensor data. Once travel time information is obtained, the first step is used to analyze travel time patterns to understand the similarities between the arterials and the freeways. In the second step, the conditional probability analyses quantify the interaction between arterials and freeways.

This two-step analysis can effectively recognize the interactions and is inherently insensitive to travel time estimation. Freeway-arterial interaction information can provide traffic engineers with a potential solution to optimize the city network by identifying the feasibility of traffic diversion between freeways and arterials. This type of diversion analysis can be used for drivers to make individual travel decisions, or for traffic management agencies to encourage diversion in specific situations. Moreover, combining the information provided by Tables 3–5 can provide critical information for building the extension of real-time ATIS applications.

To provide precise results and meaningful conclusions, one should be aware of the following criteria:

1. The two steps are equally important. Analysts would make erroneous conclusions if only one step of the analysis is used.
2. The correlation is based on travel time. The segment length used in the analysis should be able to reflect the fluctuation of travel time. The freeway segments outside the study area should not be included.
3. The template length in the travel pattern analysis should be determined by the length of the peak hour period. Noncongested interval samples will result in high correlation value because these intervals match easily. However, this problem will be identified in the conditional probability analysis.

Although the proposed approach adopted the city of Bellevue as a case study site, it is applicable for most cities with freeway-arterial networks if travel time data is available. In terms of future research, even though the proposed approach is not sensitive to travel time calculation errors, sensitivity analyses can be conducted to investigate impacts of travel time errors on analysis results. Moreover, it will be desirable to investigate the applicability of the proposed approach to more complicated traffic networks and under frequent nonrecurrent congestion (e.g., inclement weather and major incidents).

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