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# Traffic Pattern Groups Based on Hourly Traffic Variations in Urban Areas

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Urban traffic monitoring programs commonly utilize short-duration counts, including counts less than 24 hours in duration. For certain applications, it is necessary to estimate daily traffic volume from these counts. This requires the application of hourly factors derived from traffic pattern groups (TPGs) that comprise count sites with similar hourly traffic patterns and that also share features that generate these patterns. This article applies a hybrid approach to developing TPGs based on hourly traffic variations. The hybrid approach integrates the results of a statistical cluster procedure with pragmatic knowledge about the underlying variables that account for statistical similarities. The analysis shows that roadway functional class (e.g., local, collector, and arterial classifications), traffic volume, and land use characteristics (e.g., residential, commercial, and industrial uses) help explain hourly variations and are thus appropriate variables to distinguish the TPGs used in the factoring process. Application of the approach using data collected in Winnipeg, Manitoba, Canada, results in the identification of six TPGs that exhibit hourly traffic patterns generated by unique combinations of values of the three explanatory variables investigated. More broadly, the results illustrate how urban jurisdictions can better leverage readily available partial-day traffic counts to meet the growing demand for traffic information.

## Introduction

Urban traffic monitoring programs provide traffic volume statistics to support a broad spectrum of transportation engineering functions pertaining to the planning, design, operation, and management of urban road infrastructure. According to the *Traffic Monitoring Guide*, traffic volume data are fundamental for, *inter alia*, forecasting future travel demand, designing highway geometry, timing traffic signals, scheduling maintenance, analyzing safety performance, and managing environmental impacts.[1] Traffic monitoring programs utilize continuous counts to provide temporal coverage supplemented by short-duration counts that provide spatial coverage. To account for expected, recurrent temporal variations in traffic volume (by month, day of the week, and hour) and to avoid temporal bias when annual volume statistics are calculated from short-duration counts, these short-duration counts are normally adjusted by applying temporal factors derived from continuous counts. This factoring process relies on the development of traffic pattern groups (TPGs), which typically consist of continuous counts that exhibit similar temporal traffic patterns and also share features (e.g., land use characteristics) that generate the temporal patterns observed. Thus, a short-duration count conducted at a location with certain features may be reasonably associated with a specific TPG and the raw traffic count adjusted accordingly.

The development and use of TPGs is common practice in traffic monitoring programs, particularly in rural areas where ample guidance is readily available for developing TPGs based on monthly and day-of-week traffic variations (e.g., the *Traffic Monitoring Guide*).[1,2] In contrast, traffic conditions in urban areas create challenges for the development of TPGs that are not normally present in rural areas. Two examples of these challenges are a) the presence of interrupted traffic flow conditions, which inhibits the implementation of some conventional traffic detection technologies (particularly those used for vehicle classification), and b) the relative density of access points to the urban street network, which makes it difficult to assume homogeneity of traffic conditions along road segments. Moreover, the common use of partial-day counts in urban traffic monitoring programs necessitates the development of hourly TPGs to translate these counts into daily volume estimates.[3] As the demand for more and better traffic data in urban areas continues to grow, there is a need to improve urban traffic monitoring practices and make better use of available data.[3,4] The development of hourly TPGs for urban areas helps meet this need.

This article applies a hybrid approach to developing TPGs based on hourly traffic variations in urban areas. The article has three main objectives, which correspond to the subsequent sections of this article. First, the article presents background information on current practices used to establish TPGs and the need for a new approach to address the challenges of monitoring traffic in urban areas. Second, it describes a proposed hybrid approach and explains how the three components of the approach are used to develop hourly TPGs. Third, it provides the results of the TPG development process and discusses relevant limitations.

The article describes the application of the approach in the context of traffic data collected in Winnipeg, Manitoba; therefore, certain analytical details are specific to this geographic context. The application focuses on hourly variations of motorized traffic and makes no distinctions based on vehicle classification. The TPG development is consistent with the concepts and recommendations of the *Traffic Monitoring Guide*.

## Background

The *Traffic Monitoring Guide* recommends three approaches for establishing temporal TPGs: a) the traditional approach, b) a cluster analysis, and c) an approach based solely on functional classifications of a highway system (this third approach will not be discussed further here).[1]

The traditional approach is subjective in nature and relies on an analyst's knowledge of the road system, interpretation of historical traffic volume patterns, and the explanatory factors that generate these patterns.[2] Normally, these factors include land use characteristics (e.g., the presence of recreational destinations) and roadway functional class. In particular, land use is known to directly influence both the temporal and spatial distribution of trips in urban areas. For example, the typical double-peaking hourly distribution present on certain urban routes reflects the demand for trips to and from places of employment in the early morning and late afternoon, though these patterns may only be evident on weekdays.[5,6] Other trip purposes, such as education, shopping, and recreation may generate different temporal patterns.[7] The major advantages of this approach are that it is relatively simple and the factoring process can be pragmatically explained. A lack of statistical validity is its major disadvantage. This leads to inaccuracies in the factoring procedure and the calculation of annual statistics, which ultimately have repercussions on transportation decision-making.[1,8,9]

A cluster analysis uses a statistical procedure that clusters or groups data objects together based on the degree of similarity between them. Cluster analyses have a well-documented record of application within the field of traffic monitoring.[2,6,9–13] In the development of hourly TPGs, the data object is a vector of hourly traffic ratios for a particular count site. At each generation of the cluster procedure, the data objects that are most similar are grouped to form a new data object. This process repeats until all data objects form a single cluster.[14]

The statistical validity of the resulting TPGs is the main advantage of this approach. In addition, the statistical analysis may reveal traffic patterns that would not otherwise be evident.[1] However, because only statistics are used in the development of TPGs, it is sometimes difficult to pragmatically explain the groups and have confidence when assigning short-duration counts to the groups. Recent research emphasizes the application of practical experience and geographic analysis tools to help explain the statistical results and their relationship to land use variables and roadway functional class, particularly when interpreting truck traffic patterns.[2,6,15–17] There is also little guidance in the available traffic monitoring literature concerning the determination of an optimal number of clusters.[1] Selecting too many clusters makes understanding the meaning behind the clusters unwieldy. Having too few clusters introduces greater error into the factoring procedure because of a lack of statistical homogeneity within the clusters.

Given the relative advantages and disadvantages of the two foregoing approaches, the *Traffic Monitoring Guide* indicates that there may be a need to integrate aspects of the two approaches. This need is particularly recognized when identifying patterns in truck traffic data. However, no specific guidance on how to integrate the approaches is provided, nor is this guidance readily available in the literature. This lack of guidance, jurisdiction-specific differences in the type of traffic monitoring equipment deployed, varying data collection procedures and priorities, and the complexity of urban transportation networks and users contribute to inconsistency in how urban jurisdictions develop TPGs.[18] This article offers guidance on integrating existing recommended practices for developing TPGs, with the aim of improving the quality and consistency of traffic data in urban areas.

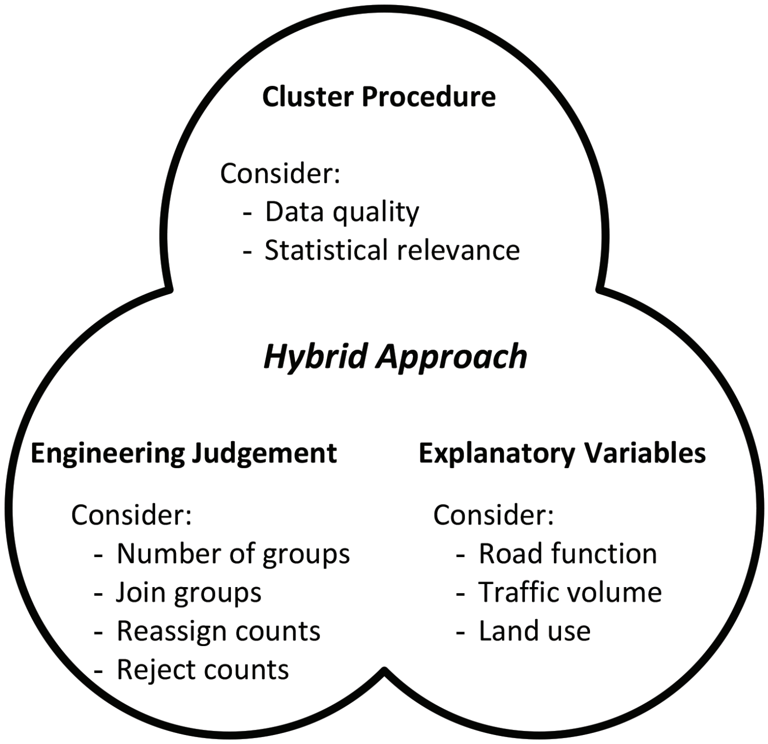
## Development of Hourly Traffic Pattern Groups

This section describes the development of TPGs based on hourly traffic variations in urban areas. The following subsections describe TPG development, beginning with a general description of the hybrid approach and the source data used in this application and then outlining each of the three components of the hybrid approach with reference to specific application results.

### *The Hybrid Approach*

This article applies the hybrid approach initially proposed by Reimer and Regehr for identifying and explaining truck traffic patterns.[17] We adapt this approach to suit the present context, which is the formation of (total) TPGs based on hourly traffic variations in urban areas. The hybrid approach adapted for this context (Figure 1) includes three components: a) a statistical analysis that identifies predominant hourly traffic patterns evident in available data, b) identification of variables that explain the patterns and distinctions between them, and c) application of engineering judgement in the subjective decisions required to produce the TPGs. The analyst integrates these components to develop and refine the groups, providing results that reflect statistical similarity as well as pragmatic understanding. As portrayed in the figure, the approach is not strictly formulaic, but rather emphasizes iteration between the three components where findings from each component inform subsequent analysis and ultimately help the analyst refine the groupings. Nevertheless, the approach requires methodical consideration of a number of factors within each of the three components, as will be discussed.

Figure 1. Hybrid Approach to the Development of Traffic Pattern Groups




Source: From Reimer, M. and J.D. Regehr, "A Hybrid Approach for Clustering Vehicle Classification Data to Support Regional Implementation of the Mechanistic-Empirical Pavement Design Guide," in *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2339 (2013): 113, Figure 1. Copyright, National Academy of Sciences, Washington, DC, 2013. Reproduced with permission from the Transportation Research Board.

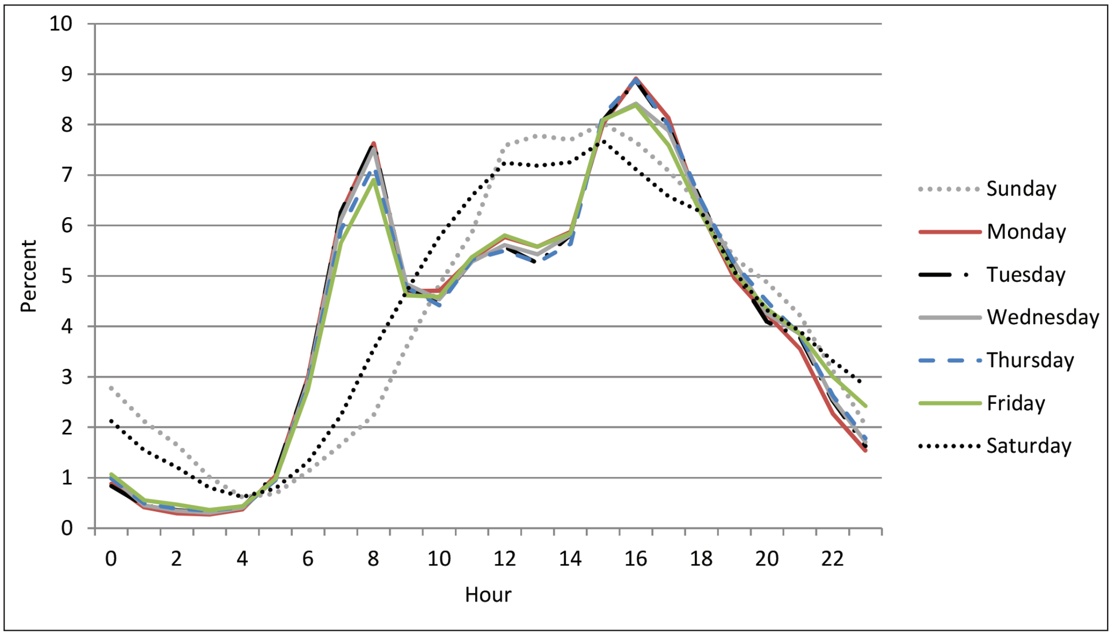
### *Source Data and Analytical Scope*

The application of the approach uses data obtained from the City of Winnipeg's traffic monitoring program. Winnipeg does not have continuous monitoring equipment; this precludes the use of monthly or seasonal factors in the development of TPGs. However, full-day hourly traffic variations are available from short-duration pneumatic tube counts, which in Winnipeg typically range from 48 hours (normally from Tuesday to Thursday) to one week in duration. Counts are seldom conducted on weekends, and the traffic volume cannot be disaggregated by vehicle class. After screening for data quality and removing partial-day counts, the database used for analysis comprised 1,152 counts taken at 897 different sites between 2007 and 2011, inclusive. Hernandez provides additional details about the data cleaning process.[18]

In addition to the multiday short-duration counts that provide the source data for the application of the hybrid approach, the City of Winnipeg conducts numerous short-duration counts that are less than 24 hours in duration. Because a full-day hourly distribution is unavailable for these counts, appropriate hourly factors must be applied to them to estimate a 24-hour volume; the TPGs provide these hourly factors.

To avoid using hourly factors reflecting non-recurrent hourly variations that may occur on Mondays and Fridays (for example, on long weekends), some jurisdictions only use counts conducted on Tuesday, Wednesday, and Thursday to develop hourly factors.[1] An investigation of average hourly variations by day of the week in Winnipeg (Figure 2), however, reveals that for the 89 counts comprising a full week of traffic data, hourly distributions on Mondays and Fridays closely resemble those observed on other weekdays. Therefore, the development of the hourly TPGs includes data from all weekdays (but not weekends).

Figure 2. Average Hourly Variation by Day of the Week (n = 89 counts)



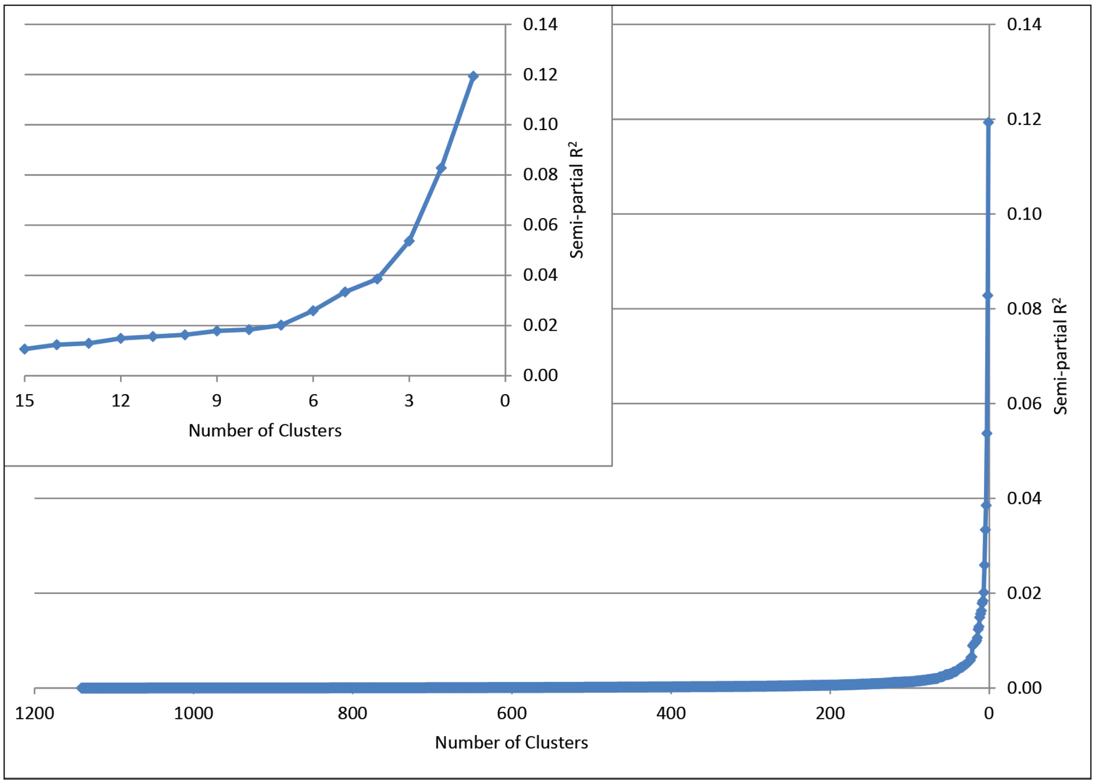

### *Cluster Procedure*

The cluster procedure applies Ward's minimum variance method. This method evaluates all possible unions between two data objects, selects the union of the two objects with the lowest sum of the squared deviations about the group mean, and averages the two objects to form a new data object.[14] The vector of average hourly traffic ratios for weekdays at each count location are the data objects used as inputs to the cluster procedure. This vector, at location *j*, is given as

$$P_j = (x_{oj},\ldots,x_{ij},\ldots x_{23j}), \quad (1)$$

where $x_{ij}$ is the ratio of the average hourly traffic volume for each hour *i* to the average weekday traffic volume at location *j*. The clustering repeats until all data objects combine into one cluster. The statistical variance within each cluster increases at each generation of the cluster procedure, reflecting the loss of homogeneity caused by grouping objects that are progressively less similar. The plot in Figure 3 of the semipartial $R^2$ statistic at each generation reveals this loss of homogeneity for the data used in this analysis, as the procedure moves from 1,152 objects to one object.

Figure 3. Semipartial $R^2$ Statistic at Each Generation of the Cluster Procedure




*Integration of Engineering Judgment and the Search for Explanatory Variables*

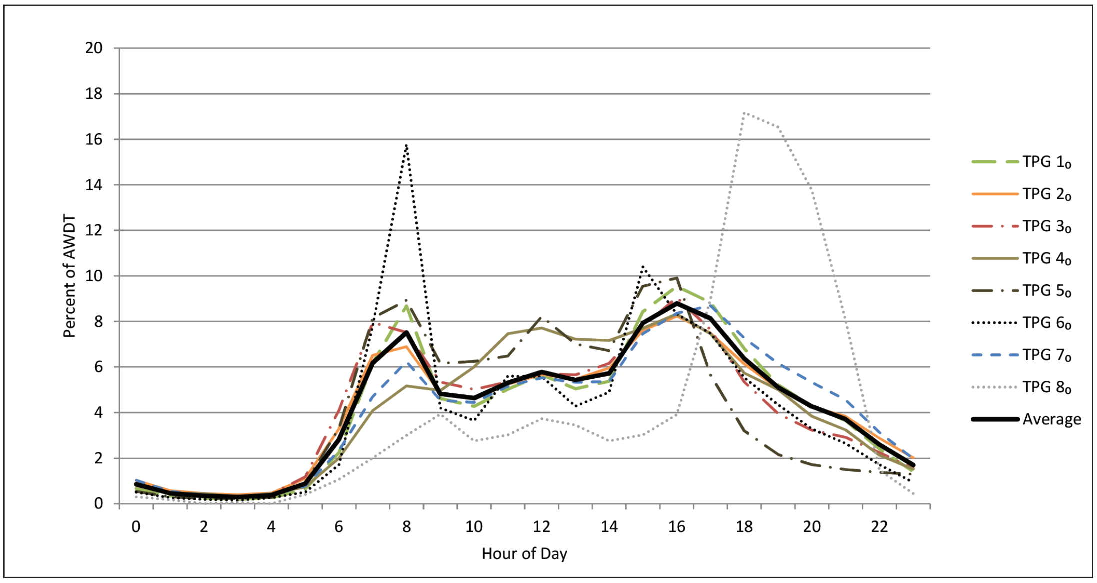
There is no generally accepted statistical method to determine an optimal number of clusters.[1] The objective is to select a number high enough to ensure acceptable statistical accuracy, but low enough to enable an analyst to describe the distinctions between the groups based solely on explanatory, nonstatistical variables. Ultimately, the initial selection is at least partially based on judgment. For the present application, the rate of loss of homogeneity within the cluster analysis, shown in Figure 3, suggests that there is relatively little change in the semipartial $R^2$ statistic until the number of clusters is less than eight. Therefore, the cluster procedure provides an initial set of eight TPGs; subsequent steps will refine this number and the composition of the groups.

Figure 4 shows the average weekday hourly variations for the eight clusters defined by the cluster procedure (the subscript zero denotes the initial state of the clusters), as well as the general average of all the counts used in the analysis. The general average has one peak at 8:00 a.m. (7.5 percent of average weekday daily traffic [AWDT]) and another peak at 4:00 p.m. (8.8 percent of AWDT). The figure reveals that average hourly factors for TPGs $1_0$, $2_0$, $3_0$, and $7_0$ fall within plus or minus one standard deviation of the general average. Ninety percent (1,041 of 1,152) of the counts are in TPGs $1_0$ (286 counts), $2_0$ (213 counts), $3_0$ (222 counts), and $7_0$ (320 counts). The remaining TPGs have the following distinctive characteristics:

- TPG $4_0$ (45 counts) does not exhibit a morning peak.
- TPG $5_0$ (31 counts) exhibits a small peak during midday and a rapid decrease following the afternoon peak hour.
- TPG $6_0$ (33 counts) exhibits a very high morning peak (16 percent of AWDT).

- TPG $8_0$ (2 counts) exhibits a very high afternoon peak (17 percent of AWDT). These two counts occurred on local roads that provide access to venues that generate unusual late afternoon traffic peaks associated with special recreational events. The *Traffic Monitoring Guide* recommends that TPGs consist of at least six sites; therefore, since TPG $8_0$ fails to satisfy this recommendation, it was excluded from further analysis.

Figure 4. Average Hourly Weekday Traffic Variations for Initial TPGs




The cluster procedure initially identifies seven distinct hourly patterns from the available data; however, there remains a need to associate these patterns with one or more explanatory variables. This is necessary because the temporal factoring of a short-duration count (less than 24 hours in duration) relies on the application of factors from a TPG characterized by an hourly traffic distribution similar to what would be expected at the short-duration count site, should a full day (or more) be observed. The assignment of appropriate factors, therefore, requires consideration of variables that can explain the observed hourly patterns identified by the cluster analysis and the distinctions between them. We hypothesize that three variables—roadway functional class, traffic volume, and land use characteristics—will help explain the hourly patterns evident from the data. The following paragraphs outline the investigation of this hypothesis.

*Roadway functional class:* The roadway functional class analysis uses a geographic information system to attribute the 897 count sites to 856 unique road segments. Each road segment falls into one of seven functional classes: major arterials, minor arterials, collectors, local roads, provincial trunk highways (primary highways under provincial jurisdiction but functioning principally as urban roadways), provincial roads (secondary highways under provincial jurisdiction but functioning principally as urban roadways), and "other" (ramps and transit facilities). The analysis reveals the following:

- About 70 percent (152 of 221) of the arterial road segments (major and minor) fall into TPGs $2_0$ and $3_0$.
- Nearly three-quarters (174 of 235) of collector segments fall into TPGs $1_0$ and $7_0$.
- Nearly three-quarters (275 of 380) of local road segments fall into TPGs $1_0$ and $7_0$.
- Nearly 80 percent (14 of 18) of road segments under provincial jurisdiction (primary and secondary routes) fall into TPG $3_0$. All (11 of 11) road segments on primary provincial routes fall into TPG $3_0$.

- Two road segments belong to the “other” functional class.
- Segments assigned to TPG $4_0$ belong to a mix of functional classifications, including minor arterials, collectors, and local roads.
- All segments assigned to TPGs $5_0$ and $6_0$ are functionally classified as local or collector roads.

*Traffic volume:* An analysis of the distribution of counts comprising the seven initial TPGs by AWDT at the count sites confirms the findings of the roadway functional class analysis. This is expected, since in Winnipeg traffic volume is one variable used in the functional classification system.[19] Specifically, the analysis reveals the following:

- About 90 percent (252 of 286) of TPG 10 counts have an AWDT at the count site lower than 10,000, and 70 percent (201 of 286) have an AWDT at the count site lower than 5,000.
- About 90 percent (205 of 234) of counts at sites with an AWDT higher than 20,000 fall into TPGs $2_0$ and $3_0$.
- TPG $4_0$ contains count sites with an AWDT ranging from less than 5,000 to more than 20,000.
- Nearly 95 percent (29 of 31) of counts in TPG $5_0$ have an AWDT at the count site lower than 5,000.
- All (33 of 33) TPG $6_0$ counts have an AWDT at the count site lower than 5,000.
- About 90 percent (288 of 320) of TPG $7_0$ counts have an AWDT at the count site lower than 10,000, and nearly 80 percent (251 of 320) have an AWDT at the count site lower than 5,000.

*Land use:* Urban land use characteristics influence the demand for travel and the volume and nature of traffic—including hourly variations—occurring on the road system. The land use analysis uses a geographic buffering technique to investigate the relationship between land use characteristics (as defined by different types of land zones) and the seven initial TPGs. Each land zone falls into one of six land use categories: residential, commercial, industrial, agriculture, park, and “other.” The buffer analysis identifies road segments that touch each buffered land zone (a total of 15,719 land zones in Winnipeg), using a buffer width of 25 m. If a land zone touches one or more road segments categorized within the same initial TPG, the land use zone is linked to that TPG. For example, Figure 5 shows an illustrative schematic of the buffer analysis for one park zone (depicted with the dashed line and highlighted in gray) in a residential neighborhood. In this example, assuming counts taken on Segments 12 and 22 are attributed to TPG $1_0$, the analysis would link the park zone with TPG $1_0$, since the park’s buffer area touches only TPG $1_0$ segments. If the park’s buffer area touched multiple segments attributed to different TPGs, no linkage would be made. In this way, 2,722 land use zones were uniquely linked to an initial TPG.

Figure 5. Illustrative Schematic of a Buffer Analysis for One Park Land Zone

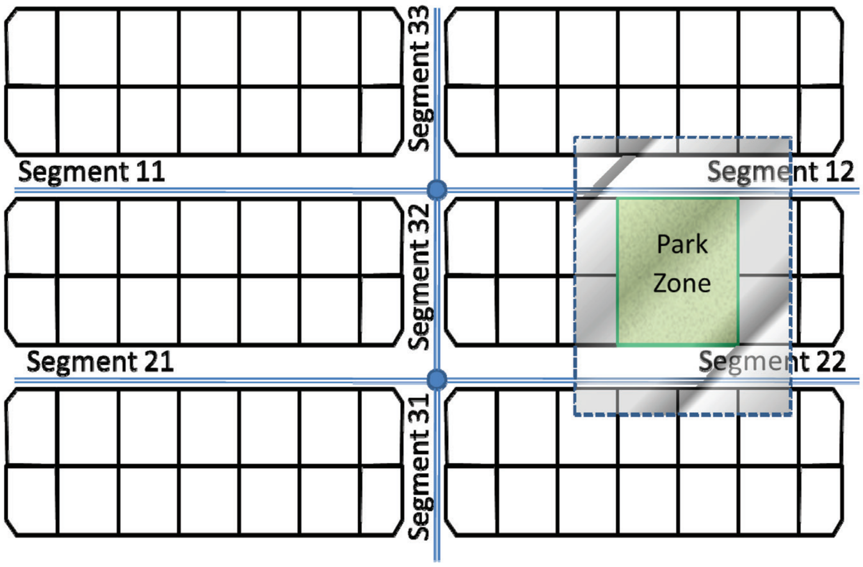
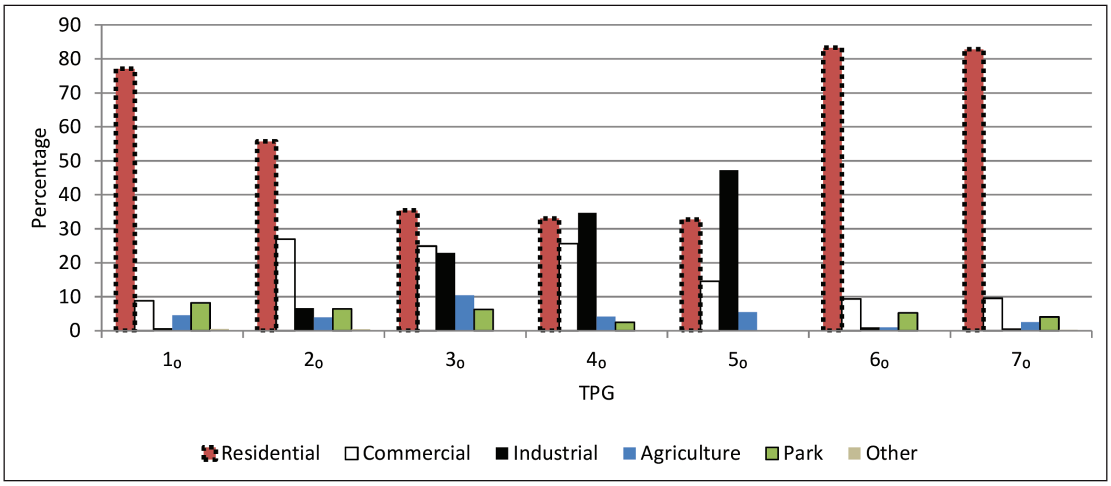



Figure 6 shows the distribution of these linkages and reveals that TPGs $1_0$, $6_0$, and $7_0$ locations are strongly associated with residential land use. Of the zones linked to these TPGs, the proportion of residential zones ranges from 77 percent to 83 percent. TPG $2_0$ is linked with residential and commercial land uses; 56 percent of the zones related to TPG 20 are residential zones and 27 percent are commercial zones. TPG $5_0$ exhibits the highest proportion (47 percent) of industrial land zones, and TPGs $3_0$ and $4_0$ exhibit mixed land use distributions.

Figure 6. Distribution of Initial Hourly TPGs by Land Use




The foregoing results support the hypothesis that roadway functional class, traffic volume, and land use characteristics are variables that can help explain the hourly traffic distributions evident from the cluster procedure—though a definitive causal link may not always be present. These results have led to a number of refinements to the initial TPGs. These refinements aim to clarify characteristics of the TPGs by considering whether groups should be joined or rejected, whether a count site should be moved from one group to another, and whether a count site should be removed from a group. The adjustments facilitate clear distinctions between the characteristics of the groups and ease the task of assigning short-duration counts (less than 24 hours in duration) to the groups once they are created. The refinements rely on both the analytical results and engineering judgement. The following refinements were made (the refined groups are denoted without the subscript zero):

- TPGs $1_0$ and $7_0$ are merged into TPG 1 because the count sites comprising these groups are predominantly located on collector and local roads with low AWDTs and are strongly influenced by residential land use. The groups were merged despite TPG $1_0$ exhibiting higher morning and afternoon peaks than TPG $7_0$, as revealed by the cluster procedure.
- All count sites in TPG $2_0$ located on collector and local roads are reassigned to TPG 1, since there is no clear reason to distinguish them from the TPG 1 locations.
- All count sites in TPG $3_0$ located on collector and local roads are rejected, because no variables that explain hourly temporal variations were found to characterize them.
- All counts in TPG $4_0$ that are not strongly associated with commercial zones are rejected from this group. Commercial land use appears to induce an hourly traffic pattern without a morning peak.
- All counts in TPG $5_0$ that are not strongly associated with industrial zones are rejected from this group.
- All counts in TPG $6_0$ that are not strongly associated with educational facilities (schools or colleges) on residential roads are rejected from this group. A more detailed geographic analysis of land use revealed the presence of schools in close proximity to TPG $6_0$ counts and helps explain the high morning peaks observed at these locations.

## Application Results and Limitations

This section presents the results of the TPG development process by providing a) a qualitative description of the final TPGs developed using the hybrid approach and b) the hourly factors for each TPG. In addition, this section discusses the limitations of applying these factors.

As described in the foregoing section, the application of the hybrid approach results in six hourly TPGs for the City of Winnipeg. Table 1 provides a description of each TPG in terms of the three explanatory variables investigated in the development of the groups. For example, TPG 1 sites exhibit morning and afternoon traffic peaks and are located on local or collector roads with low traffic volume (AWDT less than 10,000) in residential zones. It is imperative to uniquely distinguish between the TPGs in this way using readily available variables (such as roadway functional class, traffic volume, and land use). In practice, the assignment of short-duration counts to an appropriate TPG relies on the ability to categorize a short-duration count site using these variables without having a full day of observed traffic data at that site.

Table 1. Characterization of Hourly Traffic Pattern Groups, City of Winnipeg

| Group | General Shape of TPG Hourly Traffic Variation | Predominant Roadway Functional Class | Predominant Traffic Volume* | Predominant Land Use |
|---|---|---|---|---|
| TPG 1 | Morning and afternoon peaks | Local, collector | Low | Strongly residential |
| TPG 2 | Morning and afternoon peaks | Arterials | High | Residential, commercial |
| TPG 3 | Early morning and afternoon peaks | Arterials, primary provincial routes | High | Mixed |
| TPG 4 | Plateau between noon and 4:00 p.m. | Not on major arterials | Moderate | Commercial, industrial |
| TPG 5 | High morning and afternoon peaks | Local, collector | Low | Industrial |
| TPG 6 | Very high morning peak | Local | Low | Strongly residential (schools in vicinity) |

*Low volume: average weekday daily traffic (AWDT) < 10,000; high volume: AWDT > 20,000.

Together, the six TPGs encompass the most logical and common combinations of values for the three explanatory variables evident in the available source data. However, certain combinations are not reflected in the six TPGs in the interest of promoting homogeneity within the groups while limiting the total number of groups. This leads to the possibility of an analyst encountering a situation in which a count site cannot be clearly assigned to one of the six TPGs. For example, it is not straightforward to assign a count conducted on a local road near a park to one of the six TPGs, as currently defined. Faced with such a situation, the analyst may choose to:

- assign the count to the TPG that best represents the expected hourly traffic variation at the count site, regardless of the fact that "park" is not listed as the predominant land use for any of the TPGs;
- factor the count using a single nearby site or other similar site for which sufficient hourly data are available; or
- proactively conduct multiple-day counts on roads in park zones with the intent of developing a new TPG.

In addition to the qualitative descriptions provided in Table 1, each TPG is characterized by the average proportion of daily traffic volume occurring in each hour of the day. Table 2 shows these factors for the six TPGs, and the absolute precision interval of these proportions, for a significance level of 0.05. Assuming the random selection of count locations, the *Traffic Monitoring Guide* recommends the use of the absolute precision interval, $D_a$, to define the upper and lower confidence limits of the hourly factors.[1] The absolute precision interval is given by

$$D_a = t_{(1-d/2,\, n-1)}\, s/(n)^{0.5}, \quad (2)$$

where $s$ is the standard deviation, $t$ is the value of the student's t-distribution with a $1-d/2$ level of confidence and $n-1$ degrees of freedom, $d$ is the significance level, and $n$ is the number of locations. For a significance level of 0.05, there is a 95 percent probability that a similarly calculated confidence interval for some future sample would contain the true average hourly factor.

## Table 2. Proportion of Daily Traffic and Absolute Precision of Hourly Factors for Each Traffic Pattern Group

| Number of Counts | Hour | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TPG | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ |
| 686 | TPG 1 | 0.009 | <0.001 | 0.004 | <0.001 | 0.003 | <0.001 | 0.003 | <0.001 | 0.003 | <0.001 | 0.007 | <0.001 |
| 131 | TPG 2 | 0.010 | 0.001 | 0.005 | <0.001 | 0.004 | <0.001 | 0.003 | <0.001 | 0.004 | <0.001 | 0.011 | 0.001 |
| 188 | TPG 3 | 0.008 | <0.001 | 0.004 | <0.001 | 0.003 | <0.001 | 0.003 | <0.001 | 0.004 | <0.001 | 0.012 | <0.001 |
| 20 | TPG 4 | 0.008 | 0.001 | 0.004 | 0.001 | 0.003 | 0.001 | 0.003 | 0.001 | 0.003 | 0.001 | 0.007 | 0.001 |
| 15 | TPG 5 | 0.007 | 0.003 | 0.003 | 0.001 | 0.002 | 0.001 | 0.002 | 0.001 | 0.004 | 0.002 | 0.010 | 0.003 |
| 26 | TPG 6 | 0.005 | 0.001 | 0.002 | 0.001 | 0.002 | 0.001 | 0.001 | <0.001 | 0.002 | 0.001 | 0.005 | 0.001 |

| Number of Counts | Hour | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TPG | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ |
| 686 | TPG 1 | 0.023 | 0.001 | 0.054 | 0.001 | 0.074 | 0.001 | 0.046 | 0.001 | 0.044 | 0.001 | 0.051 | 0.001 |
| 131 | TPG 2 | 0.033 | 0.001 | 0.064 | 0.002 | 0.069 | 0.001 | 0.051 | 0.001 | 0.048 | 0.001 | 0.054 | 0.001 |
| 188 | TPG 3 | 0.043 | 0.001 | 0.080 | 0.002 | 0.074 | 0.001 | 0.053 | 0.001 | 0.050 | 0.001 | 0.053 | 0.001 |
| 20 | TPG 4 | 0.020 | 0.003 | 0.041 | 0.005 | 0.049 | 0.004 | 0.050 | 0.003 | 0.056 | 0.002 | 0.068 | 0.003 |
| 15 | TPG 5 | 0.045 | 0.011 | 0.105 | 0.011 | 0.081 | 0.008 | 0.053 | 0.009 | 0.053 | 0.009 | 0.063 | 0.008 |
| 26 | TPG 6 | 0.014 | 0.002 | 0.066 | 0.012 | 0.165 | 0.015 | 0.040 | 0.005 | 0.033 | 0.003 | 0.056 | 0.005 |

| Number of Counts | Hour | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TPG | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ |
| 686 | TPG 1 | 0.056 | 0.001 | 0.052 | 0.001 | 0.054 | 0.001 | 0.079 | 0.001 | 0.089 | 0.001 | 0.088 | 0.001 |
| 131 | TPG 2 | 0.058 | 0.001 | 0.056 | 0.001 | 0.061 | 0.001 | 0.074 | 0.001 | 0.083 | 0.001 | 0.076 | 0.001 |
| 188 | TPG 3 | 0.056 | 0.001 | 0.056 | 0.001 | 0.061 | 0.001 | 0.077 | 0.001 | 0.090 | 0.001 | 0.077 | 0.001 |
| 20 | TPG 4 | 0.081 | 0.005 | 0.076 | 0.004 | 0.074 | 0.003 | 0.078 | 0.003 | 0.083 | 0.003 | 0.073 | 0.004 |
| 15 | TPG 5 | 0.076 | 0.007 | 0.067 | 0.008 | 0.067 | 0.007 | 0.098 | 0.011 | 0.108 | 0.010 | 0.060 | 0.010 |
| 26 | TPG 6 | 0.057 | 0.005 | 0.043 | 0.004 | 0.050 | 0.005 | 0.111 | 0.012 | 0.084 | 0.007 | 0.076 | 0.006 |

| Number of Counts | Hour | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TPG | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ | $x_i$ | $D_a$ |
| 686 | TPG 1 | 0.070 | 0.001 | 0.057 | 0.001 | 0.048 | 0.001 | 0.041 | 0.001 | 0.028 | 0.001 | 0.017 | 0.001 |
| 131 | TPG 2 | 0.062 | 0.001 | 0.049 | 0.001 | 0.042 | 0.001 | 0.038 | 0.001 | 0.027 | 0.001 | 0.019 | 0.001 |
| 188 | TPG 3 | 0.054 | 0.001 | 0.039 | 0.001 | 0.033 | 0.001 | 0.029 | 0.001 | 0.023 | 0.001 | 0.016 | 0.001 |
| 20 | TPG 4 | 0.060 | 0.004 | 0.053 | 0.007 | 0.042 | 0.004 | 0.032 | 0.003 | 0.021 | 0.002 | 0.015 | 0.003 |
| 15 | TPG 5 | 0.027 | 0.006 | 0.017 | 0.004 | 0.016 | 0.004 | 0.013 | 0.004 | 0.012 | 0.004 | 0.010 | 0.004 |
| 26 | TPG 6 | 0.057 | 0.005 | 0.044 | 0.005 | 0.035 | 0.005 | 0.027 | 0.004 | 0.017 | 0.002 | 0.009 | 0.001 |

Note: $x_i$ is the average hourly proportion developed from all counts in the TPG; $D_a$ denotes absolute precision interval.

The precision interval can also be expressed proportionally relative to the average, by dividing the absolute precision by the average hourly proportion. The *Traffic Monitoring Guide* recommends a relative precision for each factor of plus or minus 10 percent, except for factors derived from groups intended for specialty purposes (such as recreational traffic).[1] The hourly factors developed for Winnipeg that meet the precision recommendation of the *Traffic Monitoring Guide* (plus or minus 10 percent) include:

- all hourly factors for TPGs 1 and 3;
- all hourly factors for TPG 2 except for the hour from 3:00 a.m. to 4:00 a.m.;
- daytime and evening hourly factors for TPG 4 except for the hours from 7:00 a.m. to 8:00 a.m. and 7:00 p.m. to 8:00 p.m. (nighttime hours from 10:00 p.m. to 6:00 a.m. did not meet the recommended precision);
- peak hour and noon hour factors for TPG 5 (i.e., from 8:00 a.m. to 9:00 a.m., from 12:00 p.m. to 1:00 p.m., and from 4:00 p.m. to 5:00 p.m.); and
- daytime hourly factors for TPG 6 except for the hours from 7:00 a.m. to 8:00 a.m., 9:00 a.m. to 10:00 a.m., and 3:00 p.m. to 4:00 p.m. (evening and nighttime hours from 7:00 p.m. to 6:00 a.m. did not meet the recommended precision).

Failure to meet relative precision recommendations occurs for TPGs with fewer counts (e.g., TPG 5) and for hours with lower traffic volume. TPG 5 exhibits the lowest level of relative precision, with a maximum relative precision interval of approximately 60 percent during the early morning hours when the hourly traffic volume is less than 0.2 percent of the total daily volume. These results do not necessarily preclude the use of the factors, though analysts should be aware of the potential implications when applying them.

Beyond the limitations associated with the precision of the hourly factors, the applicability of the results is limited in two main ways. First, as stated earlier, the source data cannot be reliably disaggregated by vehicle class; therefore, the TPGs formulated using the available data are relevant only when considering total motorized traffic. Truck-specific factoring procedures necessitate the development of truck TPGs. Second, for certain applications, it may be desirable to estimate annual average daily traffic from a short-duration count (less than 24 hours). Additional factors that account for day-of-week and monthly traffic variations are needed to do this. The integrated components of the hybrid approach may be applicable in the development of such factors.

Direct comparison of these results to those that would have been obtained using either the traditional approach or a cluster analysis is challenging, since the hybrid approach integrates aspects of these two approaches and thus cannot be considered independent of them. Nevertheless, the application of the hybrid approach to develop TPGs as described in this article appears to offer two main advantages. The use of a cluster analysis enabled identification of predominant traffic patterns evident in data quickly and without bias. Given the size of the dataset included in the application described in this article (more than 1,100 counts), a solely qualitative assessment of these data—as might be attempted if applying the traditional approach on its own—could be cumbersome. Second, as described in the foregoing section, it was necessary to modify the initial results of the cluster analysis to ensure that they reflected patterns that could be intuitively understood by an analyst tasked with assigning short-duration counts to the groups. Reliance on solely statistical results that disregard this pragmatic knowledge could yield groups that lack a clear definition of the underlying variables generating the observed hourly traffic patterns.

## Conclusion

This article develops TPGs based on hourly variations in total traffic volume through the hybrid application of a cluster procedure, an investigation of the underlying variables that explain hourly patterns, and engineering judgment. This approach extends current practice for developing TPGs for monitoring traffic by integrating statistical and pragmatic considerations and recognizing the need to balance these through engineering judgment. The development of the TPGs reveals that roadway functional class (e.g., arterial, collector, and local classifications), traffic volume, and land use characteristics (e.g., residential, commercial, and industrial uses) influence observed hourly patterns and are thus appropriate variables to distinguish the TPGs used in the factoring process.

The article illustrates application of this approach by developing TPGs from traffic data collected in Winnipeg, Manitoba. The TPGs presented in the article are therefore specifically relevant for this geographic context, though the general patterns evident in the empirical data and the approach used to identify and explain them have broader relevance. In Winnipeg, six distinct hourly traffic patterns emerged:

- TPG 1 sites exhibit morning and afternoon traffic peaks. They are located on local and collector roads with low traffic volume in residential zones.
- TPG 2 sites exhibit morning and afternoon traffic peaks similar to but slightly lower than TPG 1. They are located on arterials with high traffic volume in residential or commercial zones.
- TPG 3 sites exhibit morning and afternoon traffic peaks; the morning peak occurs about one hour earlier than the morning peaks for TPGs 1 and 2. The sites are located on arterial roads and provincial routes with high traffic volume. A mix of land uses (residential, commercial, and industrial) influences the hourly patterns in this group.
- TPG 4 sites do not exhibit a morning peak. They are located on road segments with a mix of functional classes (minor arterials, collectors, local roads) and moderate traffic volume. The sites are heavily influenced by commercial zones.
- TPG 5 sites exhibit high morning and afternoon traffic peaks. They are located on local and collector roads with low traffic volume and are heavily influenced by industrial zones.
- TPG 6 sites exhibit a very high morning traffic peak. They are located on local roads with low traffic volume and are heavily influenced by schools in residential zones.

The majority of hourly factors developed for Winnipeg meet the recommended level of relative precision of plus or minus 10 percent. This is particularly true for TPGs 1, 2, and 3 (which comprise the highest number of counts), and during hours of the day with higher traffic volume (e.g., peak hours). Analysts should be aware of the potential implications of applying factors with high variability.

Increasing demand for reliable and meaningful traffic volume data about all road users challenges conventional traffic monitoring practices in urban areas. Enhancing the utility of short-duration counts through more robust factoring procedures is one example of an emerging best practice in urban traffic monitoring. The development of temporal TPGs based on hourly, day-of-week, or monthly variations in traffic volume facilitates this practice and enables estimation of daily volume (as is the case for the Winnipeg example discussed in this article), or even annualized average daily volume, from short-duration counts. Further refinements of these factoring procedures will involve disaggregation by vehicle class (e.g., trucks) and nonmotorized road users. Increasingly data-intensive and complex practices, however, necessitate careful interpretation and pragmatic understanding.

## Acknowledgment

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# Quantifying Safety and Economic Impacts of Texas Travel Information Centers

By Samer Dessouky, Hatim Sharif, Jose Weissmann, and John Joseph

The study summarized by this paper was to develop a methodology and gather sufficient data to quantify the increase in safety for travelers and the economic benefits due to travel information centers (TICs) on the Texas Department of Transportation roadway network. Visitor surveys conducted at the TICs suggest that TICs provide substantial economic benefits, and, when interpreted through a safety index, also suggest that TICs provide a significant increase in traveler safety. Analysis of crash data provides further evidence that TICs increase traveler safety, as the decrease in crash rates in traffic having access to TICs is significantly lower.

## Introduction

Travel information centers (TICs), or Welcome Centers, are typically located at entry points to states in the United States. They provide an opportunity for travelers to rest and relax, and to obtain various types of travel-related information, such as official state travel maps and guides and promotional literature featuring state attractions, recreational activities, and accommodations. TICs are also believed to reduce driver fatigue and other adverse physiological effects, in-vehicle driver distraction, and roadside and shoulder stops, and to provide a safe refuge and safety-related information under hazardous weather, visibility, and roadway conditions.[1]

Literature suggests that TICs and similar facilities reduce drivers' fatigue, a major cause of traffic accidents. According to the National Highway Traffic Safety Administration, traffic accidents result in an estimated 1,500 fatalities and 71,000 injuries in the United States every year.[2] A study of Ontario, Canada, roads in 2004 found that 18 percent of all fatal crashes and 26 percent of crashes causing injury were fatigue related.[3] Based on an operational definition of fatigue, the Australian Transport Council estimated that fatigue was a factor in 20–30 percent of fatal crashes.[4] It was reported that fatigue can be more effectively managed when drivers take breaks that coincide with periods of fatigue.[5] The National Sleep Foundation's poll found that 60 percent of adult drivers said they had driven a vehicle while feeling drowsy or fatigued.[6] A more alarming statistic from the poll is that more than one-third of those polled had actually fallen asleep while driving. This agrees with an earlier survey study by McCartt, et al. who reported that 47.1 percent of the truck drivers in New York had fallen asleep while driving.[7] Ohayon, et al. reported that working outside regular daytime hours was associated with shorter sleep duration, sleepiness, and driving collision risk.[8] They found that night driving disrupted sleep habits the most, resulting in excessive sleepiness and sleep attacks during driving.

Availability of TICs also helps reduce shoulder parking. King reported that the lack of TIC-like facilities resulted in drivers of heavy vehicles parking on road shoulders and increasing the number of roadside accidents.[1] Smith, et al. reported that on routes where the supply of rest areas and TICs is limited, drivers of heavy vehicles tended to park on highway shoulders and ramps, creating a significant safety hazard.[9] A more recent study found that during nighttime hours, there was a significant increase in single-vehicle crashes related to shoulder parking beyond rest areas and TICs.[10]

Excess travel (i.e., driving a greater distance than necessary due to being lost or making wrong turns) is stressful, and leaves the anxious driver less focused on traffic and roadway conditions. However, crash data typically does not reveal whether the driver was engaged in excess travel at the moment of the crash, and thus the contribution of excess travel to crashes is difficult to quantify.

TICs also serve as safe refuge facilities during hazardous conditions, such as severe weather, icy roads, or low visibility. They can prevent the risks of continued driving or stopping on the roadside. During these situations and major road closures, travelers can stop at these centers and receive guidance on when and how to resume travel.

Researchers have studied the impacts of TICs on in-state tourism. Most of these studies have focused on two broad areas: visitor profiles and the impact of the information provided at TICs on travelers' behavior. Mason, Muha, and Fesenmaier studied the demographic characteristics of TIC users in different states.[11–13] Howard, Gitelson, and Stewart, et al. examined the differences between these users and other travelers who do not stop at the TICs.[14,15] The factors that led travelers to stop at these centers have been identified by Fesenmaier, Howard, Gitelson, and Gitelson and Perdue.[13,14,16] Gitelson and Perdue investigated how the travel information at the TICs helped influence travelers' current and future visits.[16] Other studies investigated the impact of information obtained on travelers' behavior, such as increases in spending and duration of stay in the TIC's state.[13,17–20]

Several researchers conducted surveys of visitors at TICs to study the reasons why the visitors stop there. Tierney and Haas reported that the use of restrooms is the most common reason for stopping.[21] Gitelson and Perdue reported that a substantial proportion of North Carolina TIC visitors stopped for restroom use and to pick up information.[16] Those visitors reported that they would use the information for decisions on both current and future trips. Fesenmaier and Vogt found that the majority of TIC visitors in Indiana stopped to use restrooms (62 percent), and approximately 25 percent of the respondents indicated they stopped to stretch/exercise/nap or to obtain sightseeing information.[17] About 10 percent of those surveyed indicated that they stopped specifically to obtain travel information. Results of many travel and tourism studies contend that obtaining travel information was one of the major reasons for stopping at TICs.[12,16,20,21]

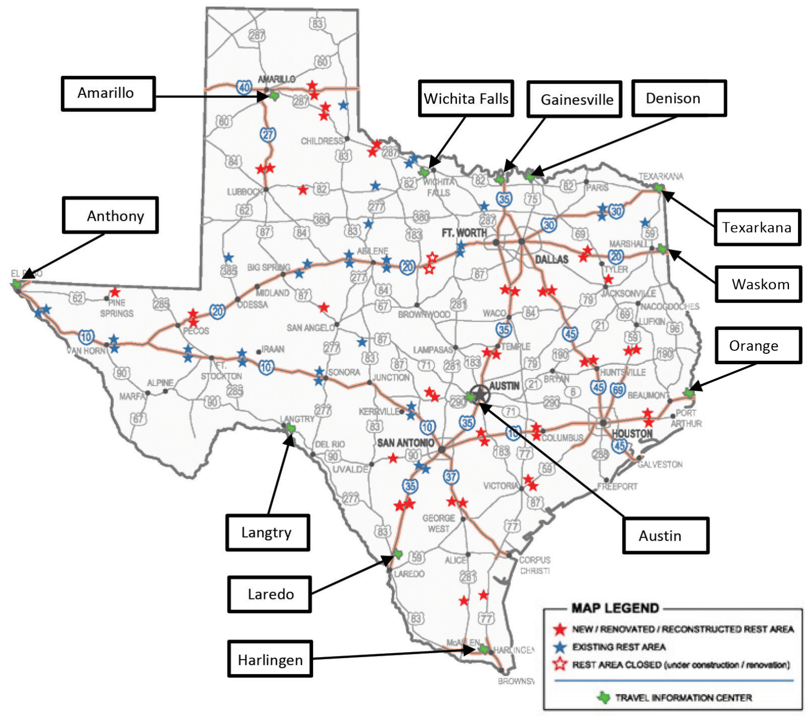
The impact of TICs on the travelers' behavior was also studied to evaluate the level of information use, the types of information obtained, and the effect of information on travel behavior.[16,20] Gitelson and Perdue indicated that substantial percentages of the individuals stopping at TICs cited receiving various types of trip-related information as reasons for stopping.[16] Most importantly, the respondents also indicated that they were likely to use the information they received for current and/or future trip decisions. Tierney and Haas reported that the impacts of information obtained at state TICs included a 25 percent increase in visitors' average daily expenditures.[21] The results also showed that the centers had a significant impact on travel decision making. Fesenmaier, et al. found that the information provided influenced the travel behavior of many of the TIC users.[20] A large proportion of those surveyed indicated that they were more likely to use the information obtained at TICs to plan future trips, suggesting that information was often collected and then stored for future use. Fesenmaier and Vogt reported that one-third of respondents spent additional money, 21 percent stayed longer than initially planned, and 29 percent visited places not originally planned as a result of the information obtained.[17]

The purpose of the study summarized in this paper was to quantify the safety and economic impacts of Texas TICs and present a methodology to measure these impacts. The methodology includes data collection from all Texas TICs located across the state and the development of in-person survey tools to assess TIC safety impacts on drivers. A statistical quantification of the measurable safety benefits using survey responses was conducted. In addition, detailed crash analysis on road segments potentially affected by three centers was implemented. Similarly, researchers used the results of surveys collected from TICs' visitors for the last two years to estimate the economic impacts of the TICs.

## Overview of the Survey

Texas has 12 TICs that serve travelers entering the state (Figure 1). The centers are staffed by professional travel counselors who help with driving directions and provide information on nearby facilities, attractions, events, and weather and road conditions. The centers also provide a place for travelers to rest and relax and, in many cases, serve as a refuge during inclement weather and dangerous road conditions. The information provided includes a map of Texas, a Texas travel guide, as well as other travel and tourism literature. The centers' staffs are activated as a state emergency resource and dispense information on a variety of subjects including emergency shelter information and emergency medical resources. The Orange County TIC is shown as an example of a TIC facility in Figure 2.

### Figure 1. Texas' Twelve Travel Information Centers and Rest Areas



An on-site safety survey was conducted at the 12 TICs to collect information from the visitors regarding their travel plans and the purpose for their stop. The survey was structured into two parts. The first included questions for all visitors on their trip before and after the stop, the reasons for stopping, and their preferences for stopping during their trip at TICs, rest areas, and other comparable facilities. The second includes follow-up questions, for returning visitors only, on the services they obtained at the centers that altered or assisted their travel plans. In each question, multiple answers were suggested to assist with a quick reply. More details on the survey questions can be found at Sharif, et al.[22] The total number of surveys for this study was 2,098, and the response rate for the follow-up section was 72 percent. The surveys were handed out to the visitors during their stops at the TIC facilities through the summer operating hours from 8:00 a.m. until 6:00 p.m. throughout the week. The 12 TICs were requested to perform the survey from March to August of 2014.

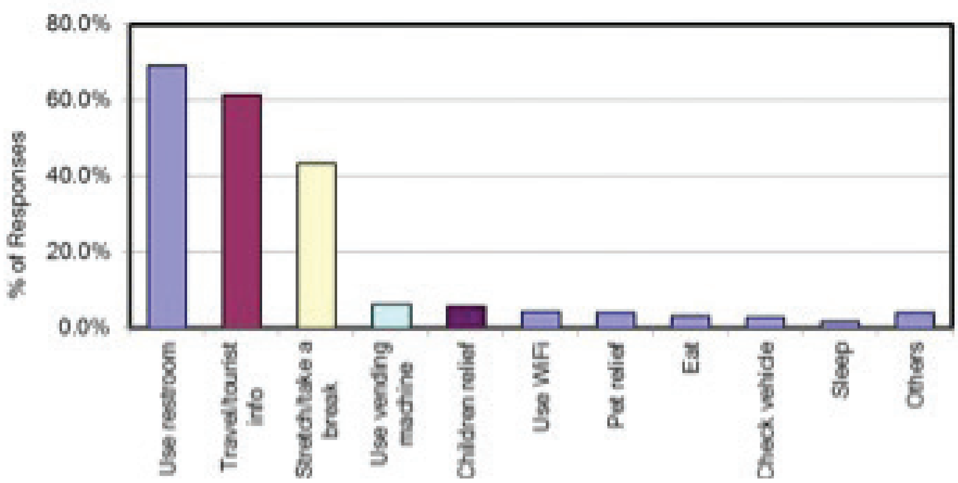
Figure 2. Aerial View of the Orange Travel Information Center

Results of the survey suggested that 32 percent of the visitors spent more than 4 hours driving prior to their stop and 38 percent expected to resume traveling for at least 4 hours more. The vast majority of the visitors crossing Texas borders expressed their interest in visiting major metropolitan areas (e.g., Houston-Galveston, San Antonio, and Dallas–Fort Worth). Visitors with less than a 1-hour trip were mostly local residents living in close proximity and taking advantage of the centers' amenities (maps, restroom, etc.). Visitors reported different reasons for stopping at TICs, as illustrated in Figure 3(a). Notably, 69, 61, and 43 percent of the responses were associated with using restrooms, obtaining travel information, and taking a short break, respectively. Other reasons for stopping, such as children and pet relief, sleeping, and eating, were not listed by the majority of visitors.

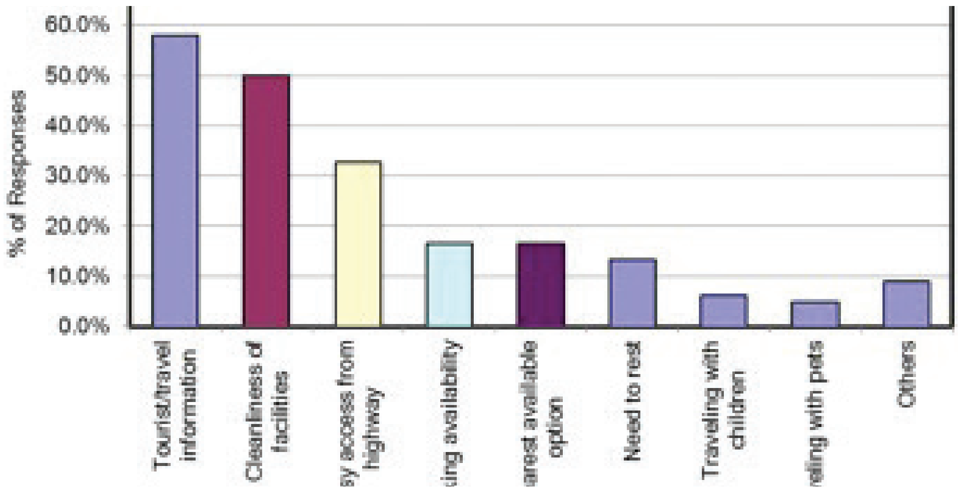
The survey was also designed to determine the extent to which the TIC might be preferred over commercial facilities (e.g., food chains and gas stations). Of the responses, 58, 50, and 33 percent reported that the availability of travel information, cleanliness of the facilities, and easy access from highways, respectively, were the major incentives for them to prefer TICs over other comparable facilities [Figure 3(b)]. Also, 69 and 53 percent of respondents suggested that TICs are their preferred stop for restrooms and short breaks over other facilities. However, more than 80 percent pointed out that stopping at TICs is not likely a preference for common interruption activities such as eating, long rest, and sleeping.

Figure 3. Survey Responses for (a) Main Reasons for Stopping at TICs and (b) Preference Factors for Stopping over Comparable Facilities

**(a)**

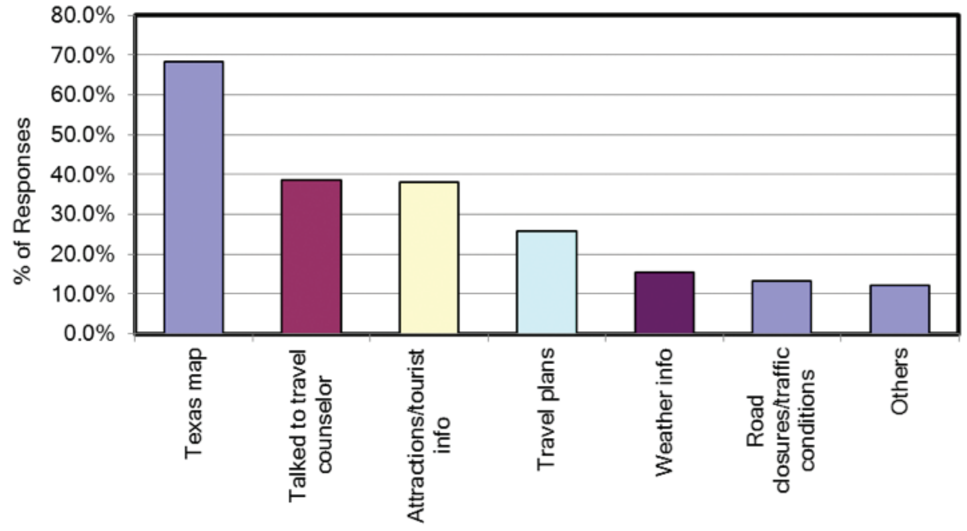



**(b)**




The second part of the survey targeted only those who had previously stopped and used the TICs' amenities. Responses suggested that 68 percent of the visitors picked up a copy of the state road map, while 38 percent established a conversation with the center counselors to obtain attraction and trip information. As shown in Figure 4, less than 15 percent reported that they attempted to obtain weather and road closure information. More than 80 percent of the responses to the follow-up section pointed out that the information and services they previously obtained from their stop had helped enhance their travel plans.

Figure 4. Information and Services Used by Return Visitors During Their Stop




## TICs' Impact On Travelers' Safety

The survey responses were used to determine the significance of the TICs in increasing travelers' safety. This was accomplished by identifying a safety weight for each response to safety-related survey questions. The procedure for identifying the weight factor is associated with the impact of the survey question on travelers' safety. For example, the safety impact on those who spent longer driving hours prior to stopping at a TIC is higher than on those who spent fewer hours. Also, using the restroom and taking a break are associated with a greater safety impact as compared to using Wi-Fi or vending machines. The weight factors are determined on a scale of 1 to 5, where 1 represents an insignificant impact and 5 represents a very significant impact on safety. The rationale for the weight factors is based on travelers' feedback and the literature review of previous safety studies.[23–25] Examples of weight factors associated with survey responses are shown in Table 1. It is worth noting that a validation on the logical weight factor assignment has not been conducted in this research and will be established in a subsequent study. The weight factors in Table 1 along with the number of survey responses were used to establish the safety index according to Equation 1 as follows:

$$\text{Safety Index} = \frac{\sum_{1}^{n} \textit{No. of Responses} \times \textit{Weight Factor}}{\textit{Total No. of Responses}}, \quad (1)$$

where $n$ refers to number of responses. The safety index ranged from 3.02 to 4.19 for all questions, with an average value of 3.66. Results suggested that the TICs have a significant impact on travelers' safety.

**Table 1. Identification of the Weight Factors for Survey Responses**

| Survey Response | Weight Factor |
|---|---|
| Driving more than 4 hours | 5 |
| Use restroom | 5 |
| Stretch/break | 5 |
| Weather/road information | 5 |
| Travel/tourist information | 4 |
| Check vehicle | 4 |
| Speak to counselor | 4 |
| Pick up state map | 3 |
| Parking availability | 3 |
| Long rest/sleep | 3 |
| Children relief | 2 |
| Pet relief | 2 |
| Driving less than 1 hour | 1 |
| Eat a meal | 1 |
| Use Wi-Fi | 1 |

### *TICs' Utility During Inclement Weather*

A safety assessment was conducted on the TICs' role during winter storm hurricane season events. During these events, emergency phone calls to the state Interactive Voice Response (IVR) from travelers are routed to all state TICs for a real-time update on road conditions, climate, hurricane routes, road closures, etc.

Figure 5 shows the call records of the IVR reported from September 2011 to May 2014. During this period, numerous winter storms affected Texas and the surrounding states. These storms were as follows: Groundhog Day blizzard (February 2011 North American winter storm), Southwest winter storm (December 19–21, 2011), North American storm (November 22–25, 2013), Cleon (December 5–11, 2013), Kronos (January 24–25, 2014), Leon (January 27–29, 2014), Slovenia (February 2–4, 2014), Pennsylvania (February 6, 2014), and Titan (March 2–5, 2014). Figure 5 suggests that during these storms, spikes in the IVR calls were evident as many users sought help or safety-related information. The average call volumes were 53,762 and 9,892 during winter storms, and 7,807 and 2,582 during non-winter storms, for the IVR and TICs, respectively. This suggests that the centers play a vital role in providing crucial information during hazardous road conditions.

Figure 5. Number of Calls Handled by the Automated IVR System Versus Calls Answered by Travel Information Center Staff during Hurricane Season from 2010 to 2014

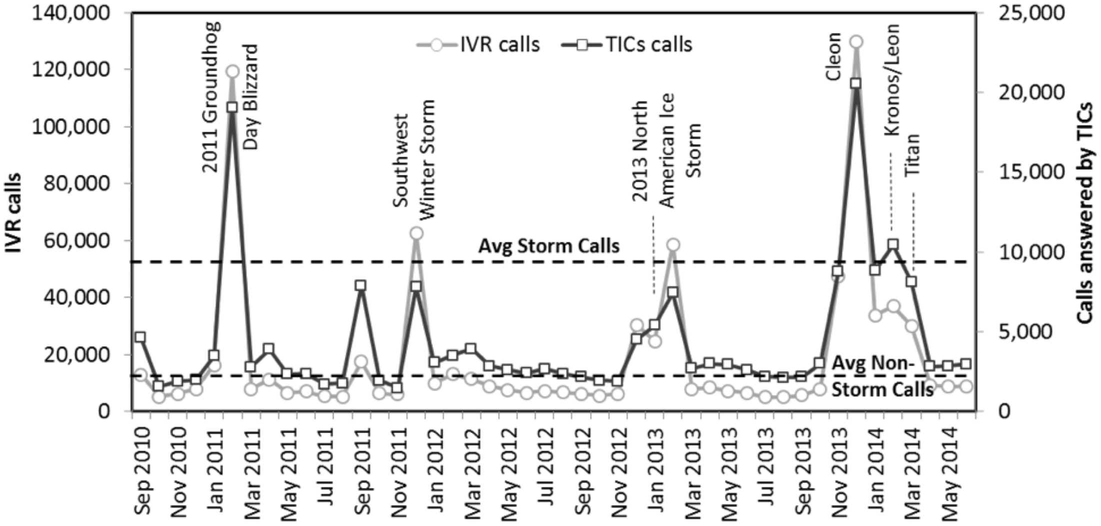
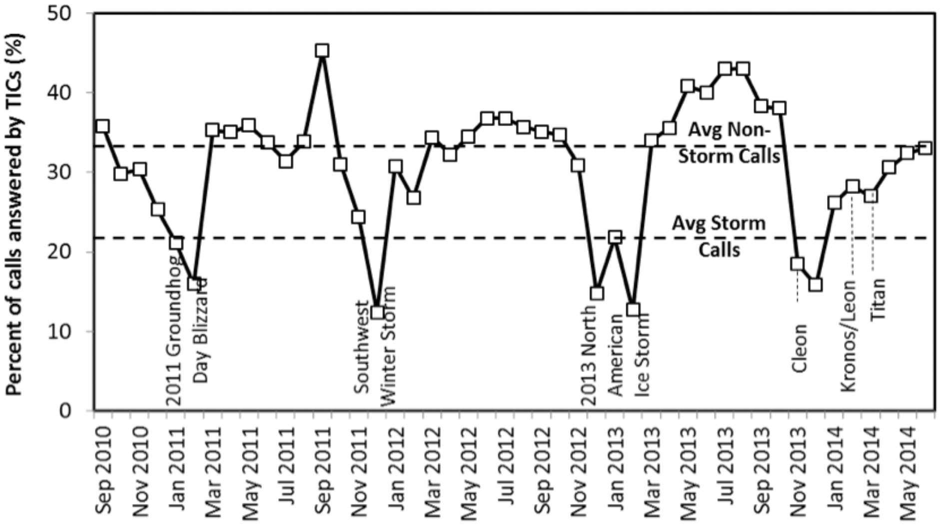



Figure 6 shows that the percentage of calls answered by TICs dropped during the winter storm seasons as compared to other non-hazardous conditions during the year. The average percentage of calls that the centers answered compared to the total IVR calls was 22 and 34 percent during winter and non-hazardous conditions, respectively. This could be attributed to the overflow of calls that the centers received and that increased the waiting time for staff members to answer. It could also be due to the sufficient road and climate information that the IVR provided, particularly during winter storms. Records also suggest that the percentage of calls transferred to the TICs is on the rise based on the winter storm call volumes in 2013 compared to 2014, proving that their role in providing guidance and assistance in hazardous conditions has increased among callers.

Records from the hurricane season in 2008—Dolly (July 24–27), Gustav (August 29–September 1), and Ike (September 10–18)—suggested that the diverted calls from the IVR to the TICs were 1,288, 652, and 13,973, respectively. These diverted calls accounted for nearly 88 percent of the total calls received by the IVR. These calls were classified by the IVR as "Road Conditions" inquiries. While assessing the safety impact of these calls is numerically unquantifiable, responding to the road condition inquiry calls is crucial for the safety of travelers during hazardous weather.

Figure 6. Percent of Calls Answered by Travel Information Centers during Hurricane Season from 2010 to 2014




## TICs' Impact on Crash Rates

Crash data were obtained from the Crash Records Information System, a statewide crash reporting database. The records contain information on crash events (e.g., latitude and longitude coordinates, time and direction of travel) that can be linked to the roadway alignment within close proximity of a specific TIC for the years 2011 through 2013. These records were used to estimate the crash rate, *R*, represented in terms of crashes per million vehicle miles traveled as follows:

$$R = (N \times 1{,}000{,}000)/(L \times V \times 365), \qquad (2)$$

where *N* is the number of crashes along the study roadway segment per year, *L* is the length of the roadway segment in miles, and *V* is the average daily traffic volume along the roadway. A statistical analysis was performed using a paired *t*-test and analysis of variance to determine the significance of the difference in mean crash rates in two opposing directions of a highway. The paired *t*-test procedure determines the significance of the differences between the average crash rates for the direction that benefits from the potential stopping of a driver to rest and relax at the TIC and the average crash rates of drivers in the opposite direction that may have been driving for an extended period of time. The *t*-test was used with the null hypothesis that there is no difference between the crash rates in the two opposing directions, at a significance level of $\alpha = 0.05$. The paired analysis assumes that for crash rate comparisons, factors such as roadway geometry, traffic volumes, and heavy vehicle percentages are similar for the opposing directions of roadway segments, and that these effects would then cancel out in the analysis. It is also assumed that the amount of traffic entering/exiting the TIC zones from other local road segments is very small and does not affect the statistical analysis presented later. More importantly, the analysis of crash rate is focused on the entrance roads where TICs are located. The crash rates at other road segments entering/exiting the state without TICs were not considered in the study.

The numbers of crashes for three TICs—Gainesville, Orange, and Amarillo—were statistically analyzed with segment lengths of 30, 67, and 52 miles, respectively. The Orange TIC is located along the eastern border with Louisiana along the eastbound lane of Interstate Highway (IH) 10. This center is the busiest in Texas and is located in an area affected by tropical storms and hurricanes. The Gainesville TIC is located along the northern border with Oklahoma along the southbound direction of IH 35. The Amarillo TIC is located in the northwest part of the state along the eastbound direction of IH 40. This center is nearly centered between the New Mexico state border at 80 miles west and the Oklahoma state border 100 miles east on IH 40. The locations of the three TICs are shown in Figure 1.

Table 2 summarizes the number of crashes included in the analysis for the years 2011 to 2013. The data suggest that the directions where TICs are located are associated with a reduced crash rate compared to the opposite directions.

## Table 2. Number of Crashes at Study Segments 2011 to 2013

| | Gainesville TIC | | Orange TIC | | Amarillo TIC | |
|---|---|---|---|---|---|---|
| Year | Northbound | Southbound* | Eastbound | Westbound* | Eastbound* | Westbound |
| 2011 | 120 | 89 | 455 | 419 | 35 | 37 |
| 2012 | 121 | 93 | 574 | 509 | 27 | 40 |
| 2013 | 131 | 110 | 545 | 448 | 32 | 54 |
| **Total** | **372** | **292** | **1,574** | **1,376** | **94** | **131** |

*Direction where TIC is located

Table 3 summarizes the statistical results for the means of the crash rates in the study road segments. For the Gainesville center, the mean crash rates for the northbound and southbound directions are different, with the northbound crash rate mean being higher than the southbound crash rate mean. The statistical significance of this difference in mean crash rates for northbound and southbound was evaluated using a paired *t*-test comparison. The calculated *t* value is 1.95, corresponding to a *p*-value of 0.05, supporting the statement that the crash rate averages for the Gainesville study route are different. It also supports that there is a crash rate reduction that is possibly associated with the presence of the Gainesville TIC, which fosters rest stops for drivers driving southbound into Texas. It is noted that crash rates are possibly affected by factors such as weather and work zones that the paired comparison may be unable to filter out of the analysis. Therefore, the analysis considered lumping crash rates temporally so that aggregation may filter out some of these factors.

Similarly, for the Orange center, the mean crash rates for the eastbound and westbound directions are different, with the westbound crash rate mean being higher than the eastbound crash rate mean. The paired *t*-test results in a *t* value of 2.11, corresponding to a *p*-value of 0.036, supporting the statement that the crash rate averages for the Orange TIC study route are different. It also supports that the crash rate reduction is possibly associated with the presence of the Orange center, which fosters rest stops and other support for those driving westbound into Texas.

For the Amarillo TIC, the calculated *t* value is 1.01, corresponding to a *p*-value of 0.31, thus not supporting the statement that the crash rate averages for the Amarillo study route are different in the east and west directions. However, a closer examination of Table 2 shows a reduction of the number of crashes for the eastern direction as compared with the western direction, possibly showing an effect of the Amarillo TIC on the number of crashes for drivers heading in the eastern direction. It is worth mentioning that the nature of the Amarillo TIC is unique in that it is located in an urban area where visitors have other amenities and commercial facilities to choose from. It is thus possible that visitors are coming from both directions of I-40.

Table 3. Crash Rate Statistics at Three TIC Study Segments from 2011 to 2013

| | Crash Rate | Mean | Standard Deviation | Min | Max | *t*-Value | *p*-Value |
|---|---|---|---|---|---|---|---|
| **Gainesville** | Southbound* | 0.57 | 0.65 | 0 | 4.28 | 1.95 | 0.054 |
| | Northbound | 0.75 | 0.60 | 0 | 3.00 | | |
| **Orange** | Eastbound | 1.416 | 2.745 | 0 | 22.07 | 2.11 | 0.036 |
| | Westbound* | 1.155 | 1.661 | 0 | 12.00 | | |
| **Amarillo** | Eastbound* | 0.705 | 1.413 | 0 | 8.50 | 1.01 | 0.31 |
| | Westbound | 0.556 | 0.800 | 0 | 6.08 | | |

*Direction where TIC is located

## Economic Benefits Of TICS

To evaluate the economic benefits of the 12 TICs, the Texas Department of Transportation (TxDOT) developed a methodology based on an on-site survey tool for the collection and analysis of travelers' behavior. The economic survey was conducted in years 2013 and 2014 to seek travelers' information on their travels. The survey includes questions related to number of trips to Texas, trip duration, purpose of travel, and origin and final destination.

The economic benefits are quantified by estimating the likelihood of TIC counselors and travel brochures to extend the travelers stay. The extension of the stay is associated with an increase in travel spending per party. Therefore, once these parties are counted, one can quantify the estimated spending. Using the estimated daily spending per person and the average travel party size, one can estimate the daily travel spending per party.

The surveys were collected from each TIC in proportion to its visitation. If no visitors came in during the set window, no survey would be collected until the next time window. The daily person spending figure was calculated based on Shifflet.[26,27]

The economic impact is calculated based on two types of survey responses. For visitors who will extend their trip longer than originally planned, their total trip spending will be increased by pro-rating, based on their daily spending and the number of additional days they suggest in the survey response. For visitors who will visit more attractions/points of interest in Texas on this trip than originally planned (without spending additional time), their spending figure will be increased by a factor of a half day. Finally, for the visitor who will not make changes to their trip but will use the information for future trips, the TIC is assumed to have caused no increase in spending. More details on the methodology used to calculate the economic impact are described by Sharif et al.[22] Results from the economic survey listed in Table 4 were used to calculate the TICs' economic impact.

Table 4. Key Variables Determined from Survey Responses

| | FY 2013 | FY 2014 |
|---|---|---|
| Daily per-person spending* | $102 | $115 |
| Number of travel parties receiving a counseling session at TIC | 638,472 | 687,607 |
| Average travel party size | 2.4 | 2.41 |
| % of respondents extending trip longer than originally planned | 13.9% | 15.5% |
| % of respondents visiting more attractions/points of interest than originally planned (without spending additional time) | 59.9% | 60.9% |

**Sources*: D.K. Shifflet & Associates Ltd., "Texas Visitor Profile," McLean, VA, 2012; D.K. Shifflet & Associates Ltd., "Texas Visitor Profile," McLean, VA, 2013.

Using the number of collected surveys, the total number of travel parties can be estimated per year. The percentage who decided to extend their stay can be used to estimate the number of parties along with the number of days they planned to stay based on survey responses. Using an arithmetical summation of the total number of extended days and the estimated daily spending per party, one can estimate the total direct visitor spending. Table 5 presents the expected figures of traveler spending and tax revenues from the survey responses. Excluding the operational and facility (maintenance) costs, results suggest that TICs have a considerable impact in promoting tourism spending. In addition to the calculations of direct visitor spending based on the methodology above, it was estimated that every $100,000 in direct visitor spending supports one job and contributes to state and local tax revenue.[22]

These estimated economic benefits can be considered conservative, as they do not take into account the additional unquantified economic benefits of comfort and convenience, safety impact, and reduced excess travel. For instance, the safety benefit results from reducing crashes, property damage, injuries, and lost time will have an unquantified economic benefit. Moreover, TICs provide additional unquantified economic benefits by reducing excess travel time. They achieve this reduction by providing directional information that takes into account both the most efficient route and any delays or detours resulting from highway conditions along that route.

### Table 5. Summary of Economic Impact and Expenditures Generated by TICs

| Travel Information Center Economic Benefits | FY 2013 ($ million) | FY 2014 ($ million) |
|---|---|---|
| **Direct visitor spending generated by centers** | 82.8 | 109.9 |
| **State and local tax revenue generated by centers** | 4.6 | 6.2 |
| **Travel Information Center operating and facility costs** | 6.4 | 5.7 |

## Summary and Conclusion

TICs in Texas serve a broad range of travelers, including vacation/recreational travelers, commuters, and motorcyclists. The majority of travelers stop at TICs to obtain travel and tourism information, use the restroom, or simply take a break to rest and stretch. The safety survey responses suggested that the overwhelmingly most common reasons for stopping at a TIC were to use the restroom and to stretch/walk/take a break. The primary reasons for selecting TICs rather than a nearby commercial facility were the availability of travel information, quick access from the highway, and clean rest rooms.

TICs offer numerous safety benefits for travelers such as reduction of driver fatigue and other wellness issues, transmission of critical information on safety and hazardous road and weather conditions, reduction of driver or passenger discomfort and distraction, reduction of highway shoulder stops, and reduction of excess travel. Three highway segments were selected to study the effect of a TIC's existence on crash reduction. Analysis of crash data revealed statistically significant reductions in crash rates, possibly due to the existence of two TICs (Orange and Gainesville), as well as a significant crash count reduction for the Amarillo TIC, based on analysis of the directions of travel that benefit from the incentive to stop and rest. The results agree with previous studies on the safety benefits of TICs and similar facilities. For example, Carson, et al., who analyzed crash data around two TICs in Texas, found that the existence of these TICs reduced crashes by about 7 percent and 15 percent.[28] Acknowledging that most safety benefits of the centers cannot be directly quantified, a safety index was proposed to estimate how the center users perceive the impact of the usage of TICs on the safety of their travel experience. Results suggested that TICs have significant impact on the safety of the travelers as evidenced by the computed values of the proposed safety index.

The economic benefits of TICs include comfort and convenience, promotion of in-state tourism, reduction of excess travel to get services, savings on vehicle operation and maintenance, benefits to specific business enterprises, and reduction of traffic diversion into communities. Only tourism benefits were evaluated in this study. The results of the economic analysis showed that all TIC facilities might be considered economically viable. The total state and local tax revenues generated by TICs through tourism enhancement for 2013 and 2014 were $4.5 and $6.2 million, respectively. Other economic benefits of TICs, such as reduction of excess travel to access similar services if the centers did not exist and comfort and convenience benefits, were not assessed. Benefit-cost analysis was not formally performed in this study. However, based on previous TxDOT studies and estimates from this study, the benefit-cost ratio of Texas TICs may well be greater than 10:1.

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# Empirical *Before-After* Comparison of the Operational Performance of Diverging and Conventional Diamond Interchanges

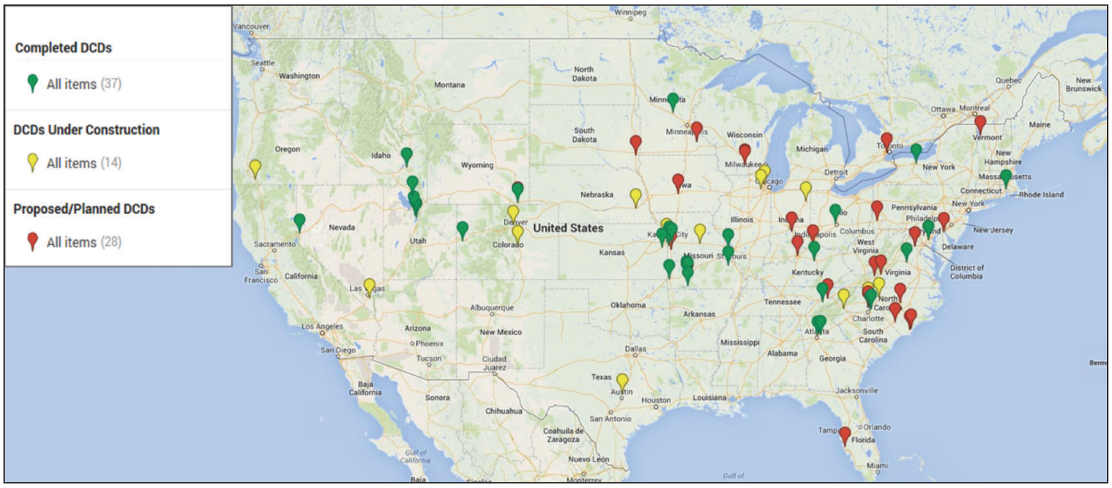
By Chunho Yeom, Joseph E. Hummer, Ph.D., P.E., Bastian J. Schroeder, Ph.D., P.E., Christopher Cunningham, P.E., Christopher Vaughan, P.E., and Nagui M. Rouphail, Ph.D.

A diverging diamond interchange (DDI), also known as a double crossover diamond interchange, is an unconventional interchange design. The DDI design is able to accommodate heavy left-turn demand more efficiently than conventional diamond interchanges by switching directions of travel for the arterial through movements. The first DDI in the United States opened in 2009, with approximately 37 currently in operation and hundreds more under construction or in the planning phases. This paper presents an empirical analysis of *before* and *after* field data collected at two sites under FHWA project DTFH61-10-C-00029, *Field Evaluation of Double Crossover Diamond Interchanges*. Operational performance data assessed in this paper include traffic volume, saturation flow rate, queue length, delay, and travel time. The study focused on the *before* and *after* evaluation of two conventional diamond interchanges at Front Street and I-435 in Kansas City, MO, USA, and at Winton Road and I-590 in Rochester, NY, USA. The field data analysis reveals that DDIs generally operate more efficiently than their conventional diamond interchange counterparts. The Kansas City site had considerable savings in queue lengths and delays for all directional movements, while the Rochester site's queue lengths and delays indicated somewhat mixed results, showing improvements in a specific directional movement like left turns from the arterial, but exhibiting deterioration in other, less notable movements.

## Introduction

A diverging diamond interchange (DDI) is an unconventional interchange design that is considered a potential improvement strategy for failing conventional diamond interchanges. By switching directions of travel for the arterial through movements, the DDI is able to handle locations with heavy left-turn demand more efficiently, as left turns onto the freeway are free-flowing at the interchange ramp terminal.[1] The first DDI interchange was built in France in the 1970s. The Missouri Department of Transportation (MoDOT) constructed the first DDI in the United States in June 2009 in Springfield, MO, USA.[2,3] Since then, as many as 37 DDIs have been operating nationwide, an additional 14 or more are currently being constructed, and hundreds more are being planned for the near future. The locations of DDIs in the United States currently in operation, under construction, or in the planning stages are depicted in Figure 1.

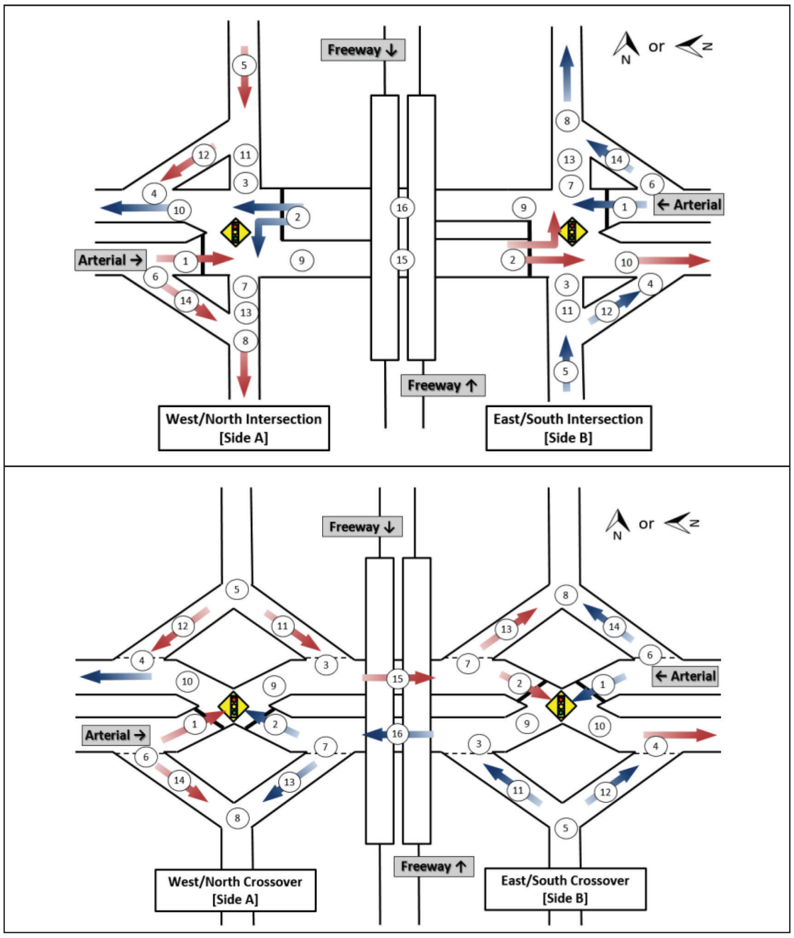
### Figure 1. DDIs as of Early 2014 Operating, Under Construction, or Planned in the U.S.




*Source:* Institute for Transportation Research and Education. *Highway Systems Group-Research*. Available: http://www.itre.ncsu.edu/HWY/research.html. (Accessed on Dec. 4, 2014.)

DDIs are commonly implemented to reduce delays, especially for sites with heavy left-turning movements to or from the freeway. At DDIs, traffic crosses over for both inbound movements to the interchange, allowing drivers to use the opposing side of the road between the two interchange signals, as Figure 2 shows, in a comparison of the two interchange forms. Therefore, vehicles that are turning left from the arterial to the freeway no longer require one or more additional signal phases, reducing the number of signal phases from three (or four) to two critical phases at each ramp terminal and potentially decreasing delays for left and through movements. Reduced delays at DDIs may also be attributed to the elimination of the left turn phase dedicated to the freeway onramp present in conventional diamond interchanges—a phase that often causes significant queuing between the ramp terminals. This additional signal phase often causes spillback and blocking of the through lanes at the upstream intersection where heavy left-turn volumes are present.

Figure 2. Movements in a Conventional Diamond Interchange (top) and a DDI (bottom)




Based on the literature, it was hypothesized by the research team that field data collected at DDIs should indicate decreased delays and queue lengths for most, if not all, of the approaches at the interchange. The expected improvements should, at a minimum, decrease delays and queues for left-turn vehicles onto the freeway, since this movement often represents one of many benefits that are expected from DDIs. This paper will examine the effectiveness of the operations at a DDI in comparison to the conventional diamond interchange.

This paper uses data collected during Federal Highway Administration (FHWA) Project DTFH61-10-C-00029, *Field Evaluation of Double Crossover Diamond Interchanges*. In the course of this project, researchers collected a variety of operational field data at seven "early" DDIs, but were only able to collect *before* data at two of these locations. This paper focuses on field data for the two sites where data *before* and *after* DDI construction were available: Front Street and I-435 in Kansas City, MO, and Winton Road and I-590 in Rochester, NY, USA. Table 1 provides a timeline of the data collection efforts at each site, along with general characteristics of the two DDIs.[4] Note that at each site, *before* and *after* data collection was completed only when the interchange operated as a conventional diamond with no construction and after the DDI was fully operational for at least 6 months.

## Table 1. Event Date and Site Characteristics of Kansas City and Rochester DDIs

| Sites | | | Front Street | Winton Road |
|---|---|---|---|---|
| Event date | | | Before study: Mar. 2011<br>DDI open: Dec. 2011<br>After study: Aug. 2012 | Before study: May 2011<br>DDI open: Sept. 2012<br>After study: May 2013 |
| Site Characteristics | Crossroad classification | | Arterial | Arterial |
| | Orientation of arterial | | E/W | N/S |
| | Crossroad posted speed (mph) | | 35 | 45 |
| | # of lanes | between crossovers | 4 | 5 |
| | | at crossovers | 2x2 / 2x2 | 2x2 / 2x2 |
| | Approximate crossover angles (deg.) | | 40 / 41 | 40 / 40 |
| | Crossroad average annual daily traffic volumes | | 14,700 | 17,700 |
| | Underpass or overpass | | Underpass | Underpass |
| | Spacing between crossovers (feet) | | 660 | 520 |
| | Spacing to adjacent signalized frontage road (feet)[1] | west/north | 1,800 | 3,060 |
| | | east/south | 420 | 520 |
| | Signal timing | coordinated | Yes | Yes |
| | | weekday cycle length AM/PM (seconds) | 70/45 | 100/120 |
| | | detection type | Video | Inductive loop |
| | Freeway off-ramp control[2] | right turn | S/F | S / S |
| | | left turn | S/Y | S / S |
| | Pedestrian/bicycle accommodation | | Yes | Yes |
| | Pedestrian/bicycle location | | Inside | Outside |
| | Adjacent land uses[3] | | C / V | O / V |

[1] Measured from centerline to centerline
[2] M=Merge, S=Signal, F=Free-flow (lane add), Y=Yield
[3] A=Agricultural, C=Commercial, I=Institutional, O=Office, R=Residential, V=Vacant

In the *before* condition, the diamond interchange at Front Street and I-435 experienced operational problems due to high traffic volumes—especially from trucks turning left onto the freeway, which frequently spilled back and blocked adjacent through lanes. Since this interchange experienced a high percentage of left turns to and from the freeway, the DDI design was thought to be a suitable solution.[5] By implementing this design, MoDOT was able to limit costs, as the DDI was retrofitted into the existing right of way under the freeway bridge. Also, because the lane configurations and cross section did not differ significantly from a conventional diamond, the Kansas City site provided a valid comparison in the *before* and *after* periods.

The Rochester interchange at Winton Road and I-590 experienced a significant amount of congestion from heavy left-turn movements in the *before* condition, specifically from I-590 onto Winton Road in the morning and vice versa in the afternoon. Long queues, unbalanced lane utilization, and high delays with frequent stops were commonly observed during the peak hours with the conventional diamond design. The New York State Department of Transportation (NYSDOT) had implemented many treatments aiming to reduce the delay, even implementing a twice-per-cycle left-turn maneuver during the peak traffic period. With the objective of decreasing delays and increasing traffic progression, NYSDOT decided to implement a DDI at that location. Details on the *before* and *after* designs at both sites are provided in the FHWA project report.[4]

The research objective of this paper is to examine how well two selected DDIs operate in comparison to their previous conventional diamond interchange counterparts. This work represents the first fully documented comparison of a conventional diamond converted to a DDI using strictly empirical data; all previous studies used simulation as a basis for comparison.[6–9]

The scope of the results presented in this paper was limited in several ways. First, the study compared and analyzed field data obtained from only two sites: the DDI installations in Kansas City, MO, and Rochester, NY. These were the only sites included in the large FHWA study for which reliable *before* data were available.[10] Second, the analysis was limited to volumes, saturation flow rates, queues, delay, and travel times collected in each *before* and *after* period. Data collection was performed for 1 to 2 days for each category of data. The FHWA project team also collected and analyzed data related to safety, signal timing, and a microscopic simulation program, which are available elsewhere.[11,12]

## Literature Review

The *Highway Capacity Manual* (HCM) provides an interchange analysis methodology in Chapter 22.[13] This methodology does not include unconventional interchanges like DDIs; however, since DDIs have similar origin-destination patterns to a diamond interchange, they could be analyzed by applying the control delay concept from the HCM as a measure of effectiveness (MOE). Chapter 17 of the HCM describes level of service (LOS) criteria for urban street segments based on the travel speed as a percentage of the base free-flow speed (FFS), a concept that could also be used to analyze travel time data through the two crossovers at each of the DDIs.

Chlewicki first published the DDI concept in the United States and presented the efficiency of the interchange using Synchro with three MOEs: total delay, stop delay, and total stops.[6] In the paper, the author stated that the conventional diamond interchange had at least twice the amount of delay and stops compared to a DDI servicing the same volumes.

Bared, et al. experimented with symmetrical two-lane and three-lane DDIs using microsimulation.[7] They tested DDIs under various volume conditions in terms of throughput, delay, stop time, number of stops, and maximum queue length. After comparing the results with a conventional diamond, they concluded that the DDI performed better under higher volume conditions, emphasizing that the biggest performance difference between the DDI and the conventional diamond interchange resulted from the left-turn movement capacity—the DDI provided twice as much capacity as the conventional diamond for this movement. They observed similar performance between the diverging and conventional diamond interchanges at low to moderate volumes.

Siromaskul and Speth also used microsimulation to compare three types of interchanges: a tight diamond, a single point urban interchange, and a DDI.[8] They presented several measures of effectiveness, such as lane mileage of the interchange, lane configurations, and VISSIM network performance results. They concluded that the DDI had an advantage in handling heavy turning volumes at a low cost, due to fewer lane miles required compared to the other alternatives.

The DDI at I-44 and Missouri Highway 13 in Springfield, MO, has been assessed with respect to traffic operations, safety, and public perception.[9] Field data, including traffic volume, percentage of trucks, and travel times, were collected and used to develop and calibrate traffic simulation models in VISSIM. MoDOT concluded that the DDI would operate well, especially for left-turn movements. The average intersection delays were calculated from simulation, using 2010 and 2035 volumes. The model predicted a 4.8 percent and a 6.5 percent decrease in total delays compared to a diamond interchange for all movements during those two analysis periods, respectively.

From the literature review for DDIs, it is clear that the DDI may have operational advantages over conventional diamonds in certain circumstances. However, the authors were not able to find any prior studies that had done *before* and *after* comparisons of DDI installation using empirical data collected in the field.

## Methodology

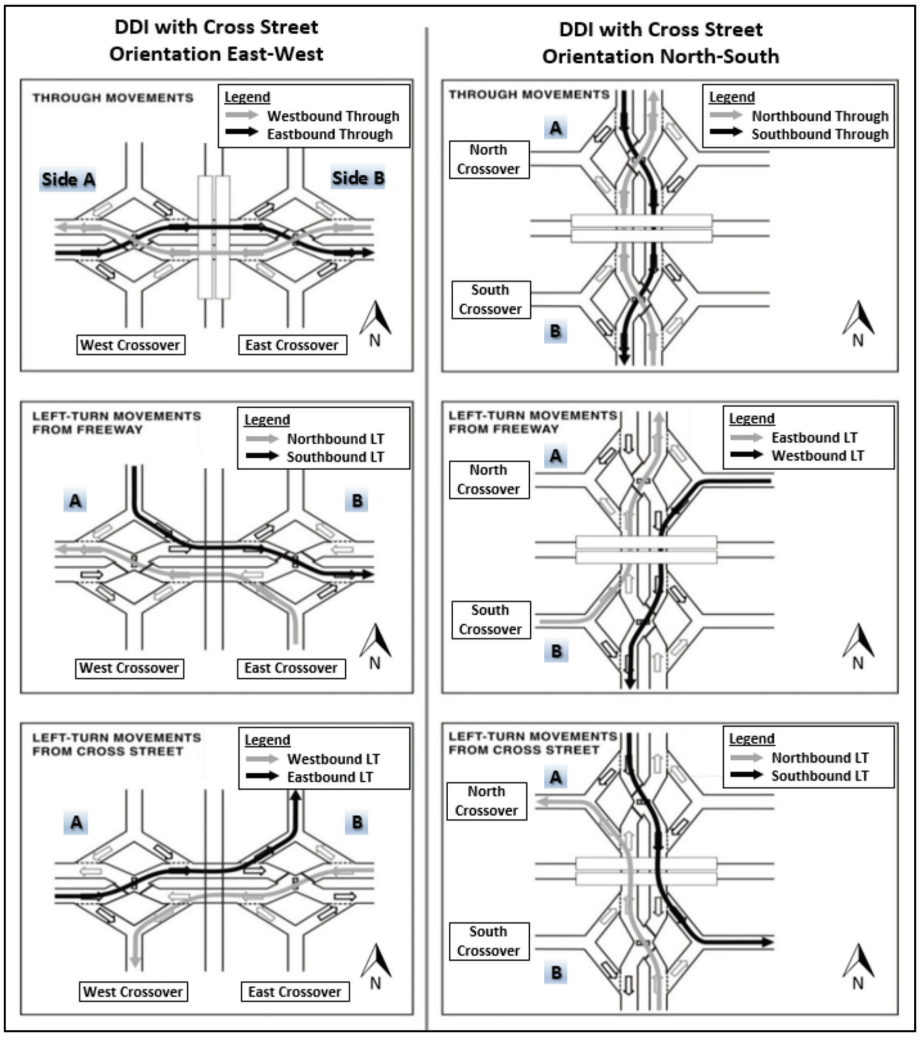
This section shows how the team collected, compared, and analyzed traffic operation field data at both a conventional diamond and a DDI. All studies were conducted between the Monday PM peak period and the Thursday PM peak period to focus on typical operations. The Monday PM peak period was assumed to act in a similar manner to the Tuesday through Thursday PM peak periods, consistent with the literature.[14] There were no extreme adverse weather conditions during any data collection periods. Team members used the same data collection protocol and data collection forms to collect data during all periods.

### *Movement and O-D Labeling at a DDI*

During data collection and analysis, it was important to have an efficient and consistent system for identifying all movements at the conventional diamond and DDI. The research team identified a total of 16 spot points for data collection, as presented in Figure 2. For instance, point 1 of side A in both a conventional diamond and a DDI corresponds to inbound traffic heading east or south, depending on the orientation of the arterial. Note that spot points 15 and 16 in the DDI have been reversed, compared to a conventional diamond interchange, since the direction of travel for each through movement switches at the crossover intersections of the DDI. Data collected at each individual point during both the *before* and *after* analyses were easily compared using the numbering system. Results are provided later, referring to this system.

Figure 3 depicts diagrams of DDI interchanges with east-to-west and south-to-north orientations. Each directional movement was named based on its destination and type of turn. The orientation and destination diagrams represent the six movements that travel times were collected. Our team did not study U-turn or right-turn movements, as these were relatively unchanged compared to the conventional diamond. Through traffic in a DDI has “eastbound” or “westbound” movements in the east-to-west DDI orientation and has “southbound” or “northbound” movements in the south-to-north DDI orientation. Left-turning movements from either arterials or freeways are also named based on turning direction. For instance, using an east-to-west DDI orientation, a left-turn movement from the freeway south of the interchange heading west is expressed as a northbound left turn movement. Note that the arterial road passing through the signals is also called a minor street or a cross street, while the freeway with which the arterial road intersects is called a major street.

Figure 3. Typical Naming Convention for DDIs




*Source:* Vaughan, C., C. Cunningham, B. Schroeder, and J.E. Hummer. "Empirical Study and Assessment of Operational Performance of Double Crossover Diamond Interchanges." *TRB 92nd Annual Meeting Compendium of Papers*. Transportation Research Board, 2013, paper 13-4946.

### *Traffic Volume Analysis*

Traffic volume data for the *before* time period was provided by departments of transportation (DOTs). Missouri DOT provided traffic volume and average speed data for every 30 minutes from April 1 through April 6, 2011, which were used as the base traffic volume for the Kansas City DDI in the *before* time period. Traffic volumes were provided for only the outbound movements along the arterial.

Traffic volume data for the Rochester DDI in the *before* condition were obtained from the *Final Design Report* prepared by the NYSDOT in 2009.[15] It should be noted that the traffic volume data had been interpolated from the data collected in 2005 before the economic recession began.

The AM and PM peak hour traffic volumes for all signalized movements at the DDIs were captured via video in the *after* study. Peak hour traffic volumes were intended to confirm that both *before* and *after* study periods had similar traffic volumes.

### *Saturation Flow Rate Analysis*

The research team expected a relative decrease in saturation flow rate for a DDI interchange due to the unique crossover geometry, given that drivers must cross opposing traffic twice and travel on the opposing side of the road. Through movement saturation flow rates were obtained by direct observation in the field utilizing the methodology described in the ITE *Manual of Transportation Engineering Studies*.[14] This methodology requires the use of a stopwatch to record the elapsed interval between successive queued vehicles (in seconds), only including vehicles four through seven, eight, nine, or ten (depending on the number of vehicles in the queue). The time was recorded using a tally sheet, and the saturation flow rate in vehicles per hour was later calculated using the methodology provided.

The saturation flow study focused on the through movements only. The saturation flow rates for signalized left-turn and right-turn exit ramp movements were not collected, because those vehicles made virtually the same movement in both designs. Using Figure 2, side A and B through movements at points 1 and 2 are considered inbound and outbound movements, respectively.

### *Queue Analysis*

The research team measured the maximum queue length on a per-lane, per-cycle basis during each peak period for each approach for the *before* and *after* periods. Some queue length data were presented using data from multiple days where samples were not sufficient (due to long cycle lengths) or conditions were not conducive to collect both ramp terminals simultaneously. It should be noted that all queue lengths were originally measured in vehicles, and then were converted into feet, assuming an average vehicle spacing of 25 feet. These analyses provide a sense of the congestion levels at the interchange, along with spillback potential at merge and diverge points.

### *Delay and Travel Time Analysis*

The research team examined field-observed delay and percent of FFS to obtain the LOS outlined in the HCM.[13] The result of this analysis provides a sense of the LOS and delays expected for each directional movement.

The field observations included each of the two intersections at the conventional diamond or DDI. Origin-destination travel times were collected using in-vehicle GPS units for the through and left-turning movements, using floating car techniques published by ITE.[14] GPS data were downloaded and processed into the six individual left turn and through routes described previously in Figure 3, using the GeoStats TravTime 2.0 software package.[16] From the raw GPS field data, the team obtained origin-destination travel time, average control delay, FFS, and distance per segment. The team examined the control delay and estimated the percent FFS to obtain LOS results by following the methods in Chapters 22 and 17 of the HCM 2010, respectively.[13] No through travel times were collected for the freeway, since those movements should not have been affected by the installation of the DDI.

When through movements along the arterial were analyzed, two signalized intersections were included in the analysis of the ramp terminals. For left turns from the freeway, one or two signalized intersections were included in the analysis, depending on whether the left-turn from the freeway at the DDI was signalized or controlled by a yield or stop sign. Since the left-turn movement from the arterial at the DDI was a free-flow movement at the second signal, only one signalized intersection was included in this analysis for the *after* period.

## Study Results

### *Traffic Volumes*

Table 2 shows traffic volume data obtained from the Kansas City and Rochester interchanges during the *before* and *after* time periods, subdivided by directional movements and peak hour. Note that the "WBT" in the Direction column refers to westbound through traffic movements from the eastern side of the interchange to the western side, and likewise for the other movements.

Table 2. Peak Hour Traffic Volume in *Before* and *After* Periods

| Kansas City, MO (Arterial E–W) | | | | | |
|---|---|---|---|---|---|
| Movement | | Through—Arterial | | Arterial to Freeway | |
| Side | | A | B | A | B |
| Direction | | WBT | EBT | WBL | EBL |
| AM Peak | *Before* | 1,046 | 256 | 68 | 222 |
| | *After* | 1,048 | 424 | 164 | 128 |
| PM Peak | *Before* | 420 | 98 | 258 | 480 |
| | *After* | 492 | 188 | 244 | 608 |

| Rochester, NY (Arterial N–S) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Movement | | Through—Arterial | | | | Freeway to Arterial | | | | Arterial to Freeway | | | |
| Side | | A | | B | | A | | B | | A | | B | |
| Direction | | NBT | SBT | NBT | SBT | WBR | WBL | EBR | EBL | SBR | NBL | NBR | SBL |
| AM Peak | *Before* | 681 | 420 | 806 | 1,396 | 141 | 999 | 548 | 166 | 198 | 291 | 628 | 23 |
| | *After* | 716 | 476 | 924 | 928 | 164 | 488 | 568 | 180 | 204 | 388 | 424 | 36 |
| PM Peak | *Before* | 544 | 547 | 904 | 976 | 39 | 598 | 373 | 165 | 241 | 525 | 945 | 159 |
| | *After* | 880 | 436 | 1,400 | 620 | 44 | 288 | 292 | 216 | 300 | 736 | 932 | 104 |

At the Kansas City DDI, the team estimated total volume differences between the *before* and *after* time periods to be an increase of 16 percent. There are a few possible explanations for this increase. One potential explanation could be the time of year during which the data were collected (*before* data in May and *after* data in August). Another potential explanation is induced or latent demand, resulting from the added capacity of the DDI. Induced demand would indicate that more drivers used the DDI now that congestion has been reduced. Latent demand would indicate that the *before* condition didn't measure the "true" demand, but rather the volume that was able to be served by the interchange given capacity constraints. With increased capacity, the full demand may be reflected in the observations.

At the Rochester site, the team approximated the *overall* volume differences in the *before* and *after* time periods to be a decrease of 5 percent. However, the variation in traffic volumes at the approaches was interesting. Certain legs of the interchange experienced significant shifts in demand levels and in volume patterns between the *before* and *after* periods, which may explain some of the delay increases discussed later in this paper. Although overall traffic volume levels decreased by 5 percent, isolated movements (westbound left, both AM and PM) decreased by as much as 30 to 50 percent in some cases. Although the traffic volumes provided by the agency could not be checked, the research team did check counts from the *after* period using the prerecorded video logs. A few observations could be made. It is encouraging that the movement patterns based on per-lane volumes were consistent throughout the study periods, as westbound left (WBL) is the predominant movement in the AM period and both northbound right (NBR) and left (NBL) are predominant movements in the PM period. As for differences in volumes, the team presumes seasonal variations, day-to-day traffic fluctuations, and the significant time gap between data collection activities (*before*: originally 2005 data; *after*: 2013 data) may have contributed to some of the observed differences. It is also possible that data provided by the agency could be inaccurate.

When these factors were taken into consideration, the traffic volume differences between the *before* and *after* periods appeared to be reasonable for Kansas City; however, the partial shifts at the Rochester site should at least be considered when looking at observations discussed later in the paper. Traffic volumes for the *before* and *after* periods at Kansas City were determined to be appropriate in comparison with operational data. With the higher *after* period traffic volumes, any observed operational improvement could not be attributed to lower demand, which makes an even stronger case for the benefits of the DDI. For the Rochester site, the *before* and *after* comparison was challenging, given the partial shift in traffic volumes, and results should be considered carefully.

### *Saturation Flow Rate*

Table 3 presents the results of the through movement saturation flow rate analysis. The results show similar saturation flow rates between the diamond and the DDI. The team conducted paired *t*-tests when sample size allowed, but neither of them showed a significant difference at the 95 percent significance level. Specifically, at the Kansas City site, the *before* condition showed around 1,700 vehicle/hour/lane (veh/hr/ln) saturation flow rates, while the *after* showed 1,792 and 1,562 (veh/hr/ln) for inbound and outbound, respectively. However, because of the smaller sample size (outbound), it was hard to emphasize differences. At the Rochester site, the *after* condition showed more consistent saturation flow rates, hovering around 1,700–1,800 (veh/hr/ln), than the *before* condition. Again, it was difficult to insist that there were distinctive differences between those times.

Actually, the authors assumed a decrease in the saturation flow rate in DDIs because the curvatures only existed in DDIs and the interchange type is itself unconventional. However, after analyzing the saturation flow rate data at the two sites, for both the conventional diamond and the DDI design, the team recognized that drivers were consistent throughout interchanges when they departed from the queuing condition at the intersection.

**Table 3. Measured Saturation Flow Rates at the Kansas City and Rochester Interchanges**

| Site | Side | Movement | Study Period | # Queued Vehicles Observed | # Cycles Observed | Saturation Flow Rate (veh/hr/ln) | SD (veh/hr/ln) |
|---|---|---|---|---|---|---|---|
| **Kansas City** | A | WBT | *Before* | 149 | 31 | 1,695 | 233 |
| | | | *After* | 8* | 2* | 1,562* | 126* |
| **Rochester** | A | SBT | *Before* | 48 | 7 | 1,781 | 189 |
| | | | *After* | 215 | 42 | 1,794 | 230 |
| | B | NBT | *Before* | 7* | 2* | 2,110* | 164* |
| | | | *After* | 206 | 35 | 1,867 | 192 |
| | | SBT | *Before* | 54 | 13 | 1,691 | 162 |
| | | | *After* | 132 | 31 | 1,784 | 220 |

*Insufficient sample size

## *Queue Length*

### Kansas City

Table 4 and Figures 4 and 5 summarize the AM and PM peak period queue statistics for both sides of the Kansas City interchange under the *before* and *after* conditions. For the west intersection (side A) *before* case, westbound queues spilled back into the east intersection, located approximately 300 feet upstream, and the maximum queues experienced were in the center and right lanes during the AM peak period. Also, queues were consistent with higher lane utilization in the center and rightmost lane in the AM peak period. Eastbound queues did not cause any spillback at the nearest upstream signalized intersection during the AM or PM peak period. Also, eastbound queues were consistent with higher lane utilization in the leftmost lane during both peak periods, likely due to the eastbound left turn on-ramp movements downstream of this intersection. For the east intersection (side B) *before* data, there was no directional movement spillback at the nearest intersections with the exception of the maximum queue length for the eastbound through right lane movement in the AM peak. Side B queues showed higher lane utilization for the leftmost lane during both peak periods.

For the west crossover (side A) *after* data, neither westbound nor eastbound queues caused any spillback to the nearby intersections during the AM or PM peak period. There was higher lane utilization in the leftmost lane during both peak periods, likely due to the eastbound on-ramp left turn lane downstream of this intersection. The *after* data from the east crossover (side B) showed that neither westbound nor eastbound queues experienced any spillback to the nearest intersections.

Upon comparing queue data between the *before* and *after* time periods, no movement experienced an increase in queue length across any lanes. Statistically speaking, this was the case especially for side B, where decreases in queue lengths between the *before* and *after* time periods were all statistically significant at the 95 percent confidence level. This queue length comparison shows that the Kansas City DDI appeared to result in substantial improvement over the previous conventional diamond interchange, with the average and 95th percentile queues decreasing for virtually all movements.

Figure 4. AM Peak Queue Schematic for Kansas City

**(a) Diamond Interchange [*Before*]** **(b) DDI [*After*]**

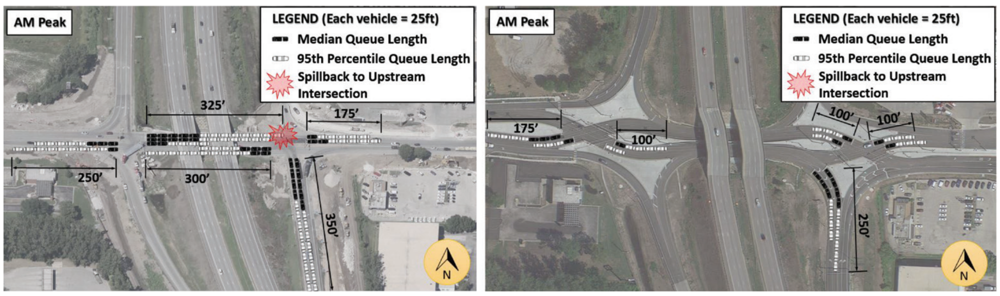
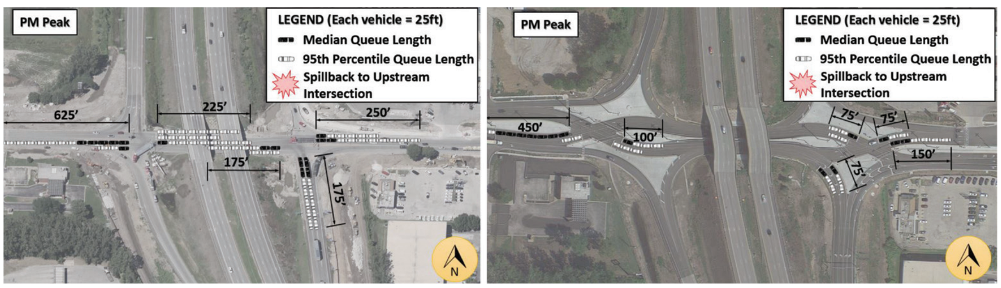



Figure 5. PM Peak Queue Schematic for Kansas City

**a) Diamond Interchange [*Before*** **(b) DDI [*After*]**



## Table 4. Queue Length Statistics at the Kansas City Interchange (unit: feet)

| Side | | A—West Intersection | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Movement** | | **EBT** | | | | **WBT** | | | | |
| **Time period** | | ***Before*** | | ***After*** | | ***Before*** | | | ***After*** | |
| **Lane** | | **Left** | **Right** | **Left** | **Right** | **Left** | **Center** | **Right** | **Left** | **Right** |
| **AM** | **Mean** | 83 | 63[3] | 83 | 35[3] | 52 | 115 | 143[4] | 16 | 37[4] |
| | **Std. dev.** | 64 | 76 | 44 | 29 | 41 | 88 | 106 | 20 | 36 |
| | **95th per.** | 200 | 250 | 175 | 100 | 150 | 300 | 325[1] | 50 | 100 |
| | **# of cycles[2]** | 71 | 71 | 88 | 88 | 71 | 71 | 71 | 88 | 88 |
| **PM** | **Mean** | 190 | 20 | 194 | 17 | 49 | 28 | 41 | 17 | 37 |
| | **Std. dev.** | 190 | 25 | 136 | 24 | 64 | 51 | 63 | 22 | 35 |
| | **95th per.** | 625 | 75 | 450 | 50 | 225 | 150 | 200 | 75 | 100 |
| | **# of cycles[2]** | 76 | 76 | 148 | 148 | 75 | 76 | 76 | 148 | 148 |

| Side | | B—East Intersection | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Movement** | | **WBT** | | | | **EBT** | | | | **NBL** | | | |
| **Time period** | | ***Before*** | | ***After*** | | ***Before*** | | ***After*** | | ***Before*** | | ***After*** | |
| | **Lane** | **Left** | **Right** | **Left** | **Right** | **Left** | **Right** | **Left** | **Right** | **Left** | **Right** | **Left** | **Right** |
| **AM** | **Mean** | 60[3] | 41[3] | 42[3] | 25[3] | 83[3] | 73[3] | 36[3] | 27[3] | 131[3] | 157[3] | 79[3] | 110[3] |
| | **Std. dev.** | 55 | 44 | 38 | 25 | 57 | 85 | 32 | 29 | 84 | 92 | 46 | 66 |
| | **95th per.** | 175 | 150 | 100 | 75 | 175 | 300 | 100 | 100 | 325 | 350 | 175 | 250 |
| | **# of cycles[2]** | 70 | 70 | 171 | 171 | 70 | 70 | 171 | 171 | 72 | 72 | 171 | 171 |
| **PM** | **Mean** | 83[3] | 43[3] | 62[3] | 23[3] | 56[3] | 14[3] | 21[3] | 9[3] | 59[3] | 66[3] | 21[3] | 34[3] |
| | **Std. dev.** | 83 | 48 | 52 | 28 | 51 | 28 | 30 | 16 | 54 | 55 | 24 | 28 |
| | **95th per.** | 250 | 150 | 150 | 75 | 175 | 75 | 75 | 50 | 175 | 175 | 75 | 75 |
| | **# of cycles[2]** | 80 | 80 | 141 | 141 | 80 | 80 | 142 | 142 | 79 | 79 | 143 | 143 |

[1] Queue spillback into upstream intersection

[2] Total number of signal cycles observed during the queue data collection

[3] Significant difference between *before* and *after* at the 95th percentile confidence level

[4] Significant difference between *before* and *after* at the 95th percentile confidence level comparing lanes with the highest mean queue length

## Rochester

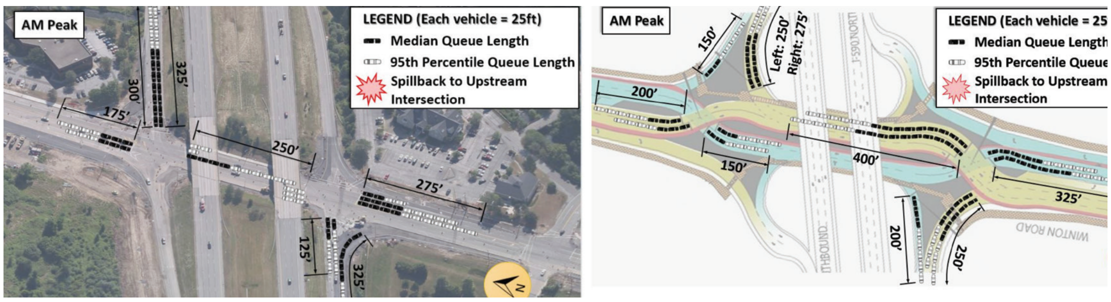
Table 5 and Figures 6 and 7 summarize the AM and PM peak period queue statistics for both sides of the Rochester interchange for the *before* and *after* conditions. For the north intersection (side A) *before* case, the northbound maximum and the 95th percentile queues spilled back into the south intersection during the PM peak. For the south intersection *before* data, the northbound maximum and the 95th percentile queues spilled back into the adjacent south intersection during the PM peak. The northbound queues in the leftmost lane were noticeably longer than any other directions in the AM and PM peak periods.

For the north crossover *after* data, neither the northbound nor the southbound queues caused any spillback to the nearby intersections during the AM or PM peak periods. For the south crossover *after* data, only the northbound through movement spilled back onto the adjacent intersection during the PM peak, which was likely due to the adjacent intersection being located so close to the signal at the crossover.

When comparing queue data between the *before* and *after* time periods, the north and south intersections showed mixed results, as queue lengths decreased for most movements at the north intersection (except the southbound PM peak), whereas queue lengths increased for most movements at the south intersection (except the eastbound right turn in the PM peak). For example, the total queue length across all lanes for the NBT approach at side A in the PM decreased from 236 feet to 171 feet, while the same approach in the PM peak increased from 87 to 317 feet. However, it should be noted that the number of points with spillback decreased from three to two. Moreover, it is important to mention that all three of the previous three-lane approaches were reduced to two-lane approaches with the installation of the DDI. Also, the severe leftmost lane utilization in the northbound direction on side A disappeared in both the AM and PM peak periods.

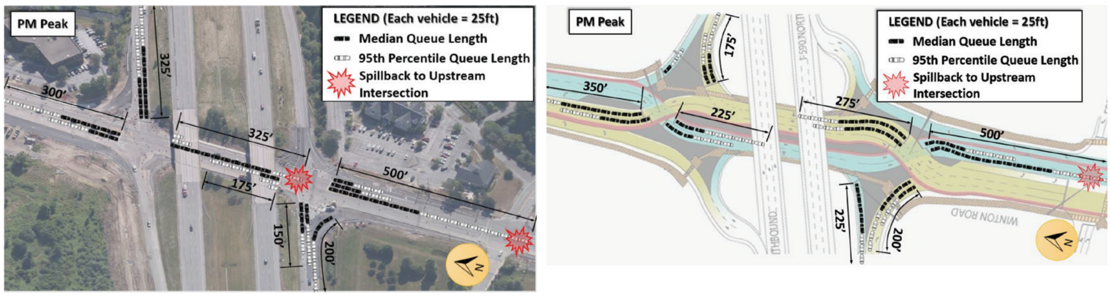
### Figure 6. AM Peak Queue Schematic for Rochester

**(a) Diamond Interchange [*Before*]** **(b) DDI [*After*]**




### Figure 7. PM Peak Queue Schematic for Rochester

**(a) Diamond Interchange [*Before*]** **(b) DDI [*After*]**



## Table 5. Queue Length Statistics at the Rochester Interchange (Unit: feet)

| Side | | A—North Intersection | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Movement | | SBT | | | | NBT | | | | | WBL | | | |
| Time period | | *Before* | | *After* | | *Before* | | | *After* | | *Before* | | *After* | |
| Lane | | Left | Right | Left | Right | Left | Center | Right | Left | Right | Left | Right | Left | Right |
| AM | Mean | 90 | 74 | 77 | 76 | 102[4] | 9 | 7 | 71[4] | 66 | 186[3] | 170[3] | 126[3] | 133[3] |
| | Std. dev. | 60 | 45 | 57 | 59 | 73 | 18 | 15 | 45 | 43 | 79 | 65 | 65 | 77 |
| | 95th per. | 175 | 150 | 200 | 175 | 250 | 25 | 50 | 150 | 150 | 325 | 300 | 250 | 275 |
| | # of cycles[2] | 72 | 72 | 139 | 139 | 72 | 71 | 71 | 139 | 139 | 72 | 72 | 139 | 139 |
| PM | Mean | 158[3] | 79[3] | 212[3] | 119[3] | 214[4] | 14 | 8 | 75 | 96[4] | 172[3] | 103[3] | 92[3] | 48[3] |
| | Std. dev. | 72 | 53 | 73 | 50 | 88 | 18 | 14 | 47 | 61 | 78 | 54 | 50 | 34 |
| | 95th per. | 300 | 175 | 350 | 231 | 325[1] | 50 | 25 | 181 | 225 | 325 | 225 | 175 | 125 |
| | # of cycles[2] | 72 | 72 | 54 | 54 | 72 | 72 | 72 | 54 | 54 | 72 | 72 | 54 | 54 |

| Side | | B—South Intersection | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Movement | | NBT | | | | | SBT | | | | | EBL | | | EBR | | |
| Time period | | *Before* | | | *After* | | *Before* | | | *After* | | *Before* | | *After* | *Before* | *After* | |
| Lane | | Left | Center | Right | Left | Right | Left | Center | Right | Left | Right | Left | Right | Center | Center | Left | Right |
| AM | Mean | 116[4] | 96 | 48 | 189[4] | 124 | 13[4] | 11 | 10 | 216 | 242[4] | 51[4] | 42 | 93[4] | 129 | 99 | 125 |
| | Std. dev. | 74 | 52 | 34 | 75 | 59 | 21 | 19 | 18 | 75 | 83 | 35 | 39 | 51 | 90 | 50 | 63 |
| | 95th per. | 275 | 225 | 100 | 325 | 250 | 50 | 50 | 50 | 375 | 400 | 125 | 125 | 200 | 325 | 200 | 250 |
| | # of cycles[2] | 72 | 72 | 72 | 66 | 66 | 72 | 72 | 72 | 66 | 66 | 72 | 72 | 66 | 72 | 66 | 66 |
| PM | Mean | 261 | 76 | 53 | 313 | 100 | 65[4] | 14 | 8 | 179[4] | 138 | 69[4] | 54 | 113[4] | 80[4] | 97 | 57[4] |
| | Std. dev. | 173 | 48 | 37 | 125 | 56 | 56 | 20 | 14 | 59 | 55 | 36 | 43 | 54 | 57 | 55 | 37 |
| | 95th per. | 500[1] | 150 | 125 | 500[1] | 225 | 175 | 50 | 25 | 275 | 233 | 125 | 150 | 225 | 200 | 200 | 125 |
| | # of cycles[2] | 72 | 72 | 72 | 56 | 56 | 71 | 71 | 71 | 56 | 56 | 71 | 71 | 56 | 71 | 56 | 56 |

[1] Queue spillback into upstream intersection

[2] Total number of signal cycles observed during the queue data collection

[3] Significant difference between *before* and *after* at the 95th percentile confidence level

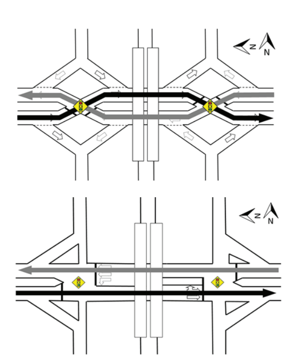
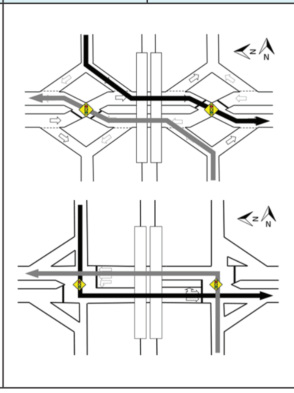
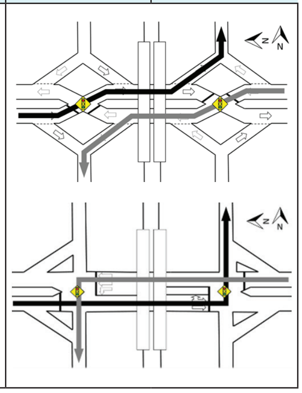
[4] Significant difference between *before* and *after* at the 95th percentile confidence level comparing lanes with the highest mean queue length

### *Delay and Travel Time*

This section summarizes the AM and PM peak period delay and percent FFS results for the Kansas City and Rochester interchanges, respectively, during the *before* and *after* conditions. The data were based on GPS travel time runs through the two interchange ramp terminals, which were compared to free-flow travel time to estimate the two performance measures. Since no official methodology for DDIs exist in the HCM, two different chapters were used in the comparison: first, an interchange ramp terminal analysis using the total delay for both signals (HCM 2010, Chapter 22), and second, an urban street facility analysis based on percent FFS (HCM 2010, Chapter 16).

Table 6 shows the interchange ramp terminal delay and percent FFS with corresponding LOS data by directional movement for Kansas City and Rochester. For each cell, the top data represent the *before* and the bottom data represent the *after* condition.

Table 6. Kansas City Interchange Ramp Terminal MOE Comparisons

| | | | Through Routes | | Left-Turn from Freeway | | Left-Turn from Arterial | |
|---|---|---|---|---|---|---|---|---|
| | | | WBT or NBT | EBT or SBT | NBL or EBL | SBL or WBL | WBL or NBL | EBL or SBL |
| Site | MOE | Peak |  | |  | |  | |
| Kansas City | Delay (sec/veh) | AM | 89.0[1] [E]<br>42.2[1] [C] | 158.9[1] [F]<br>32.7[1] [C] | 48.6[1] [C]<br>18.5[1] [B] | 81.2[1] [D]<br>13.8[1] [A] | 91.3[1] [E]<br>16.8[1] [B] | 132.0[1] [F]<br>36.8[1] [C] |
| | | PM | 112.3[1] [E]<br>23.4[1] [B] | 78.8[1] [D]<br>44.2[1] [C] | 154.1[1] [F]<br>15.9[1] [B] | 90.6[1] [E]<br>36.2[1] [C] | 70.5[1] [D]<br>17.2[1] [B] | 91.0[1] [E]<br>45.1[1] [C] |
| | Percent FFS (%) | AM | 36 [E]<br>48 [D] | 23 [F]<br>55 [C] | 48 [D]<br>71 [B] | 24 [F]<br>75 [B] | 22 [F]<br>65 [C] | 20 [F]<br>58 [C] |
| | | PM | 31 [E]<br>63 [C] | 37 [E]<br>48 [D] | 23 [F]<br>74 [B] | 22 [F]<br>53 [C] | 27 [F]<br>64 [C] | 27 [F]<br>53 [C] |
| Rochester | Delay (sec/veh) | AM | 18.0 [B]<br>28.1 [B] | 42.7 [C]<br>38.8 [C] | 33.2 [C]<br>40.8 [C] | 31.7 [C]<br>39.7 [C] | 11.0[1] [A]<br>32.0[1] [C] | 59.1[1] [D]<br>32.9[1] [C] |
| | | PM | 6.2[1] [A]<br>25.1[1] [B] | 18.7[1] [B]<br>55.1[1] [D] | 53.3 [C]<br>72.8 [D] | 16.4[1] [B]<br>54.7[1] [C] | 45.0[1] [C]<br>9.1[1] [A] | 58.2[1] [D]<br>40.1[1] [C] |
| | Percent FFS (%) | AM | 55 [C]<br>49 [D] | 33 [E]<br>38 [E] | 51 [C]<br>46 [D] | 52 [D]<br>44 [D] | 77 [B]<br>49 [D] | 34 [E]<br>51 [C] |
| | | PM | 78 [B]<br>52 [C] | 53 [C]<br>30 [E] | 39 [E]<br>32 [E] | 68 [B]<br>36 [E] | 44 [D]<br>77 [B] | 34 [E]<br>46 [D] |

[1] Significant difference at the 95th percentile confidence level when comparing *before* (top) and *after* (bottom)

## Kansas City

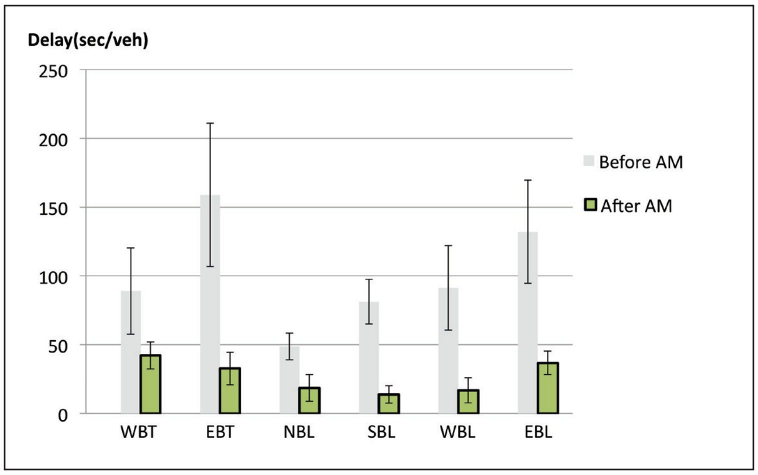
Table 6 summarizes the AM and PM peak period delay and percent FFS results for the Kansas City interchange under the *before* and *after* conditions. In the *after* period, the DDI operated at LOS C or better for all movements, whereas several movements for the conventional diamond interchange showed LOS F in the *before* period. The percent FFS analysis also showed considerable LOS improvements for those same movements. The predominant improvements in delay and FFS were seen at the left-turn movements, as expected, especially for the left turn onto the freeway, where motorists traverse only one signal in the case of the DDI, but two signals for the conventional diamond.

For both delay and percent FFS, all left-turn movements experienced LOS C or better with the DDI. Based on the traffic volumes, the dominant left-turn movement was the northbound left turn off-ramp movement in the AM peak period. This movement operated at LOS B during the AM peak hour in the *after* time period, since vehicles from the south typically progress through the next crossover signal after entering the DDI. The signal coordination in the AM peak was focused on this dominant left-turn from the south. The dominant flow in the PM peak was the eastbound left turn movement, which operated at LOS E or F in the *before* period and at LOS C in the *after* period.

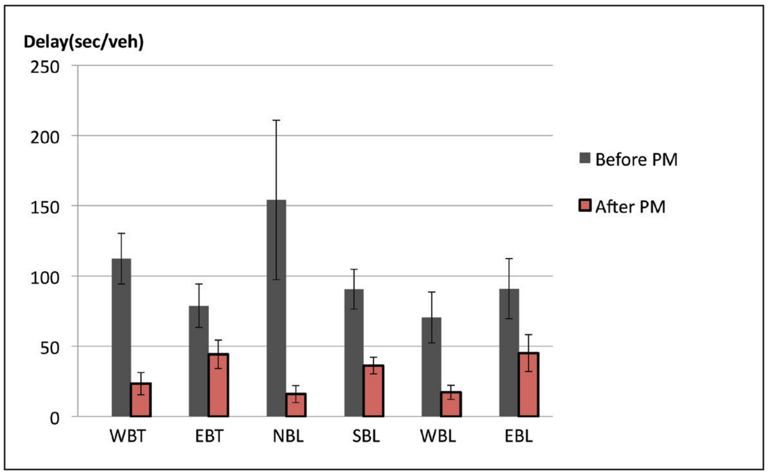
Figure 8 is provided to show the difference in delay for each directional movement between the *before* and *after* periods at the Kansas City site. As already mentioned, all directional movements show a significant decrease in delay.

### Figure 8. Delay Analysis Results for Kansas City

**(a) AM Peak**




**(b) PM Peak**



## Rochester Interchange

Table 6 summarizes the AM and PM peak period delay and percent FFS results for the Rochester interchange under the *before* and *after* conditions.

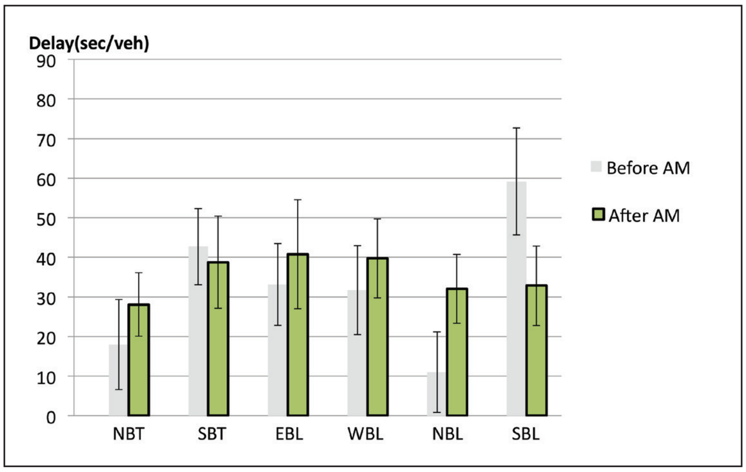
During the *before* and *after* periods, all movements at the interchange operated at LOS D or better based on delay, and LOS E or better based on the percent FFS. Some movements experienced a better LOS in the *before* period, and some had a better LOS in the *after* period. Overall, there were better LOSs in the before period than the *after* period. Based on the traffic volumes, the dominant movement during the AM peak is the westbound left turn from the freeway. Surprisingly, this movement operated very similarly in the *before* and *after* time periods when comparing delays and FFS. In the PM peak, conditions improved significantly for the dominant flow, which was the northbound left turn from the arterial. In the *after* time period, the movements operated at LOS A and B based on delay and percent FFS, respectively.

This difference in findings for the predominant movements during the AM and PM peak periods is likely explained by the number of signals traversed by each movement. In other words, left turns from the arterials generally received the greatest advantage of a DDI installation, since those vehicles need to traverse only one signal before making a free-flow left turn at the downstream intersection, compared to two signals when making a left turn from the freeway to the arterial. In addition, as pointed out earlier in this paper, NYDOT had taken great strides to make the preexisting diamond interchange work at its optimal level.

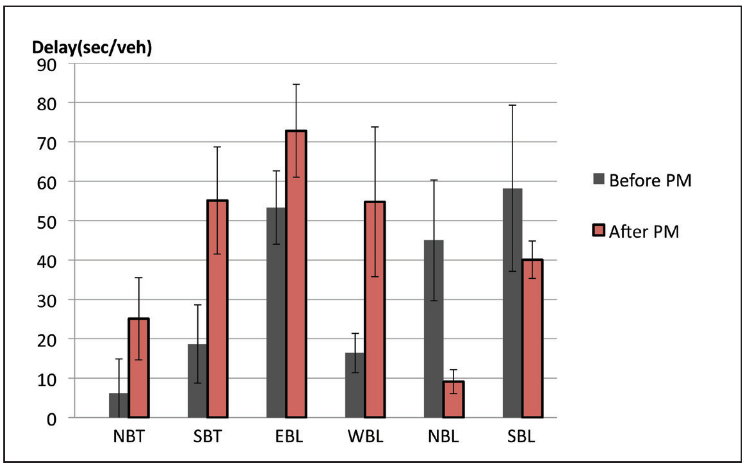
Figure 9 is provided to show the difference in delay for each directional movement between the *before* and *after* periods at the Rochester site. Again, left-turn movements from the arterial are mostly beneficial in terms of delay at the Rochester site.

### Figure 9. Delay Analysis Results for Rochester

**(a) AM Peak**




**(b) PM Peak**



## Summary And Conclusions

The results in this paper came from data collected in the field for two diamond-to-DDI conversion projects, allowing an empirically based comparison of the two interchange forms for the first time. While there may be some differences between the *before* and *after* periods, such as directional volume changes in Rochester, most traffic conditions were similar enough that good comparisons were possible.

Saturation flow rates were similar at the two interchanges, while queue and delay analyses showed somewhat different results for the two interchanges. The Kansas City site showed considerable reductions in queue lengths and delays with the DDI, while the Rochester site showed somewhat lower queue lengths and delays for the conventional diamond. This difference from the two sites might be explained by different signal timing optimization or by impact from an adjacent signalized intersection. At this time, a study of the impact on DDIs in a corridor context is under way, and the results of the study would be helpful for further understanding of DDIs in a more holistic framework that considers the effects of other nearby intersections.

More specific summaries and conclusions for each traffic operational performance are as follows:

- The traffic volume for the *before* and *after* conditions for the two sites showed a sixteen percent increase and a 5 percent decrease in demand for the Kansas City and Rochester sites, respectively. Based on the traffic volume observations, it appears that the unconventional nature of the DDIs did not discourage drivers from using the interchange, and may have in fact encouraged more drivers to use the interchange.
- A decrease in saturation flow rate is expected for a DDI interchange; however, data collected for this project does not confirm this assumption for the two sites, demonstrating no significant statistical difference in saturation flow rate between the two study periods.
- At the Kansas City DDI, when queues were observed across all lanes and separated by movements and peak times, queue lengths were reduced by 19 to 83 percent and 34 to 56 percent for through and left-turn movements, respectively.
- At the Rochester DDI, although the queue lengths increased slightly, the DDI installation elicited more balanced lane utilization. Since the DDI had a free-flow left turn beyond the bridge at the second signal, the queue spillback between ramp terminals from this left turn all but disappeared for AM and PM peak periods.
- The Kansas City DDI showed a notable improvement in delay and percent FFS, with equivalent improvements in LOS. Of the 12 studied movements, LOS improved by at least two letter grades for 10 movements, and by one letter grade for the other two. All three movements with LOS F in the *before* period were improved to a LOS B or C.
- At the Rochester DDI, left turns from the arterial mostly showed improvements in delay between the *before* and *after* periods, exemplifying the DDI's operational capability to handle heavy left turns onto the freeway. The LOS of several movements declined between the *before* and *after* periods in Rochester; however, none of them showed a serious failure from the conversion.

After comparing two conventional diamonds and DDIs, the team observed operational advantages for the DDI design in its ability to process traffic more efficiently, especially for left turns onto the freeway as hypothesized in the introduction. It is evident, especially at the Kansas City site, that traffic conditions improved after DDI installation, even though traffic volumes were generally higher by 16 percent in the *after* period.

This paper was based on several operational data collections from two sites. In addition to the data collected and comparisons in this paper, other studies related to traffic safety, geometric effects (especially for the "no right turn on red" condition), signal timing, adjacent intersections, and pedestrian and bicycle behaviors warrant further investigation.

Lastly, this paper compared the conventional diamond to DDIs. However, there are many other forms of service interchanges that may be strong competitors with the DDI and offer similar operational improvements over the conventional diamond. Field and simulation data on operations at these other forms would help ensure that agencies choose the optimum interchange design at a particular location. In addition, if simulation is the anticipated comparison tool, it is extremely important that those models are well calibrated.


## Acknowledgments

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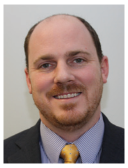

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# Modeling Telecommuting Decisions in Diverse Socioeconomic Environments

By Ata M. Khan, Ph.D., P.Eng.

This paper advances a Bayesian model that can explain how a potential commuter decides whether to telecommute or not and identifies the optimal option under defined personal, work, and traffic conditions. The variables that influenced the development of the model include urban structure, employer policy regarding telecommuting, personal utility structure of potential telecommuter, and traffic conditions that are encountered in regular commuting. For the sake of realism, the model is applied to the National Capital Area (Canada), where attitude survey, land use, and travel data are available. The results show that the Bayesian model has the potential to account for diverse socioeconomic environments under which telecommuting decisions are made. The model can be used by a potential telecommuter to identify the most favorable telecommuting option. Private and public sector organizations can apply the model to infer the acceptance of telecommuting by employees whose jobs are potentially suitable for telecommuting. Parts of this paper were presented at conferences, but these were not published.

## Introduction: Telecommuting as a Substitute for Work Trip

The 2011 National Capital Area (NCA) (Canada) household origin-destination survey included a question on telecommuting.[1] This indicates that public agencies are keen on finding out the extent of telecommuting in a manner similar to understanding other travel-related behavioral characteristics of the population. This is a very significant development in terms of viewing the potential of this demand management tool to serve as a substitute for commuting. *Telecommuting* refers to the use of information technology to partially or completely replace daily trips to and from the workplace.

Telecommuting could involve working at home or at a location other than the central workplace (e.g., a telecenter close to home) during normal work hours.[2] Although the objective of substituting telecommunications for physical transport has been of interest since the early 1940s, telecommuting was never pursued seriously due to technology limitations and the prevailing attitudes at the time. The interest in the substitution objective was renewed in the 1970s. However, one of the main reasons that telecommuting was not accepted widely in the 1970s and even in later years was the technological constraint. Computer hardware and software, as well as telecommunication systems, were deficient.[3]

Since the 1990s, concerns about the inability of governments to add capacity to roads to serve growing travel demand, predicted adverse effects of severe traffic congestion, and developments in computer and telecommunication technology resulted in considerable interest in telecommuting. During the same time period, the convergence of technological and institutional developments induced the widespread use of information technology. In turn, this has enhanced worker ability to effectively communicate with customers as well as the office. Although availability and use of computers is not a prerequisite for telecommuting, most tasks that require the exchange of information between the telecommuter and the main office can be carried out effectively by the use of computer and communication systems.

Access to new-generation information technology has been improving in Canada and the USA, and this trend is likely to continue in the future.[4] For example, the City of Ottawa has announced plans to provide affordable, high-quality, equitable broadband access to all its citizens. According to this vision, Ottawa's new broadband network will form an integral part of the infrastructure of the region. It will be rapidly deployed and is expected to be competitive, cost-effective, and scalable for future growth. Further, for efficient and barrier-free communications, it will be compatible with existing and emerging provincial and national high-speed networks.[5]

Advances in communications technology, including broadband and high-speed Internet access, are making new types of working arrangements and enterprises possible for the first time.[6] The availability of broadband infrastructure is reducing the monopoly of the central city on the highest paying jobs. According to recent studies, knowledge-based industries and their employees in Canada and the United Stares are becoming less dependent on the services of a central city. As a result, interest in telecommuting is likely to increase.[6,7] As a qualifying note, the above observations may not apply in all employment locations. According to the 2013 status of telework in the U.S. federal government, some potential telecommuters still face inadequate technology and data security as a barrier to telework.[8]

In general, new opportunities in the form of employer-initiated programs have become available that make it possible to telecommute and therefore modify commuting behavior. For example, according to a 2011 report, the City of Ottawa (Canada) developed a $20 million plan to allow staff to work from home or satellite offices in order to save $5 million per year.[9] Key benefits of telecommuting have been identified in the literature. See Table 1.[2,6,10–12]

Table 1. Key Benefits of Telecommuting*

| Benefits for Employees | Benefits for Employers | Societal Benefits |
| --- | --- | --- |
| ■ Eliminating wasted time commuting<br>■ Flexibility in balancing their professional and personal lives<br>■ Saving on commuting costs<br>■ Reducing job and commuting stress | ■ Less employee turnover as a result of happier workers<br>■ Less need for office space<br>■ Possibly greater productivity<br>■ Improved position in the labor market | ■ Less traffic congestion<br>■ Less pressure to expand infrastructure capacity<br>■ Less traffic accidents<br>■ Conservation of energy and reduction of greenhouse gas emissions<br>■ Reduced air pollution from vehicles |

*Based partly on literature sources noted in text.

This paper advances a Bayesian model that is intended to explain how a potential commuter decides whether to telecommute or not and also identifies the optimal option under defined personal, work, and traffic conditions. Parts of this paper were presented at conferences but were not published.

## Concerns Regarding Telecommuting

In spite of many benefits, telecommuting is not without concerns. The main ones are:

- increased travel distance for telecommuters in the case of location/relocation to outlying areas;
- potential increased nonwork-related travel; and
- less physical presence in the office.

Research at Carleton University and elsewhere studied the role of telecommuting as a factor in the employee's decision to locate/relocate in outlying areas. There are, of course, other reasons (e.g., cost of housing, desire to have extra space, etc.). The Carleton University research showed that telecommuting is a significant factor in the residential location choice decision.[3,13,14] A study by Mokhtarian found similar results.[15] That is, it was found that a connection exists between telecommuting and relocations to distant communities. However, it should be noted that telecommuting is not the only reason, although it enhances the option of moving to a more distant location.

Therefore, in estimating the benefits of telecommuting, the additional distance covered by telecommuters compared to nontelecommuters should be taken into account. Surveys show the acceptance of longer but infrequent commuting trips by actual and potential telecommuters.[3] A related subject that should be discussed here is the concept of travel time budget. Past research found that commuters residing in various parts of the urbanized region may have a travel time budget, and if they spend less time on their commuting trips during a week, they are likely to increase their nonwork-related travel.[16–18] However, there is much uncertainty surrounding the issue of the potential increase in nonwork-related travel as a part of the concept of travel time budget. There is little evidence in the context of telecommuting that the reduction of vehicle-kilometers (veh-km) of travel achievable through telecommuting is completely offset by an increase in off-peak nonwork-related travel. However, it would be prudent to discount the benefits of telecommuting due to a possible increase in nonwork-related travel on telecommuting days.

## Level of Telecommuting

Information-technology-assisted telecommuting has been noted in the literature as a transportation demand management strategy. It is seen by many policy experts as one of the most cost-effective measures to achieve sustainability in urban transportation. It has much potential in this regard, given that it can potentially reduce traffic congestion, conserve fuel, reduce greenhouse gases, and improve air quality in urban areas.[12,19,20]

The benefits of telecommuting, described earlier, have induced its acceptance by a growing number of employees, employers, and urban governments. On the policy and institutional front, significant developments have taken place in the United States. For example, the Telework Enhancement Act of 2010 was signed.[8] Historically, in November 1999, U.S. Congress adopted and the president signed the National Telecommuting and Air Quality Act.[21]

In 2012, 14 percent of all U.S. federal employees teleworked to some degree.[8] A 2007 study of the National Science Foundation (U.S.) employees showed about a one-third participation level.[22] In the United States in 2007, about 3 percent of the total workforce telecommuted at least once a month, and 4.2 percent of the overall U.S. federal government workforce telecommuted.[23]

Some cities across Canada and the United States have included telecommuting as a demand management measure in their long-term planning and expect that it would reduce peak period work trips. Transportation planners and policy analysts have been making an adjustment to transportation demand by recognizing a certain amount of substitution of telecommuting for travel. They expect that telecommuting will result in a reduction in the number of peak hour trips due to fewer commutes. For instance, in the late 1990s, the Regional Municipality of Ottawa-Carleton in Ontario, Canada, included telecommuting as a transportation demand management measure in its transportation master plan. They expected that this measure alone would reduce peak hour work trips by 7 percent.[12]

As for the future, there has been considerable optimism in developing forecasts. For example, according to Mitomo, Jitsuzumi, and Ota, in 2020 in Japan, 15 percent to 28 percent of the total workforce will telecommute either from home or from satellite offices.[10] A study by Mitomo and Jitsuzumi estimated a 6.9 percent to 10.9 percent reduction in congestion in Tokyo (Japan) due to telecommuting by white-collar employees.[24] In the case of Washington, DC, a Brookings Institution study pointed out that there is evidence that telecommuting is likely to become a larger and more important aspect of the workplace.[2] According to an article published in *Urban Transportation Monitor*, the Washington, DC, area had set a goal of 20 percent telecommuting by 2005, but in 2009, the U.S. General Services Administration stated its goal to increase the future participation level to 50 percent.[25,26] Although telecommuting is seen as one of the most cost-effective measures for solving the urban area sustainability problem, policy and planning studies on telecommuting are scarce.

## Public Sector Perspective

Traffic congestion keeps on rising in many urban areas around the world, and as a result commuting trip time, fuel consumption, and emissions are outstanding issues. Multinucleated urban regions (defined below) that have achieved a certain degree of balance between jobs and housing in satellite communities have experienced a reduction in commuting trips to the central city. However, in most such regions, the balance of jobs and housing is far below the level that could offer work opportunities to a majority of residents of outlying satellite communities. Consequently, there is still a high degree of commuting during peak periods.

A number of travel demand management measures could be considered for reducing automobile traffic in major corridors of multinucleated urban regions that are already well served by public transit. Electronic road pricing, vehicle restrictions, and other demand management measures are normally considered in order to avoid severe traffic congestion in the travel corridors and central business district street network. Telecommuting is an attractive concept that has been noted by researchers and policy experts as a potentially very effective strategy for making a favorable impact on traffic congestion, fuel consumption, air quality, and greenhouse gas (GHG) emissions. However, in order to succeed, active support by a number of stakeholders is necessary. These include employees, employers, and civic leaders with policy responsibility.

## Land Use: Multinucleated Urban Regions

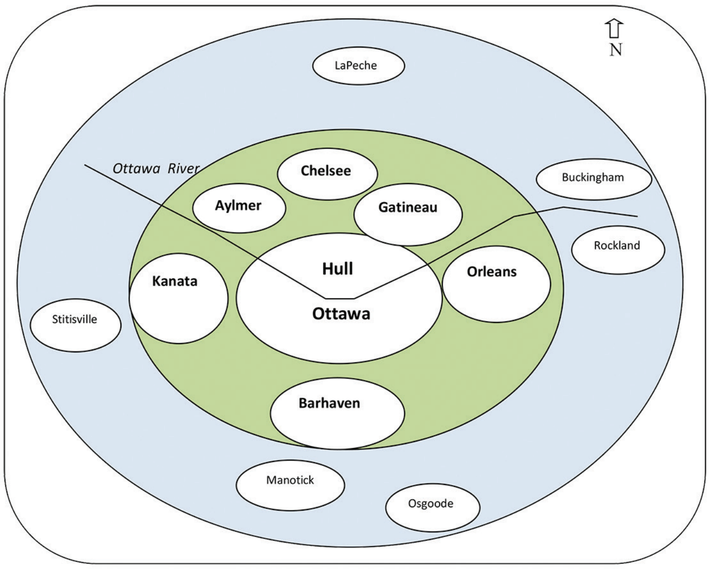
A multinucleated urban region is an urban form that is drawing planning and policy attention around the world. There has been the emergence of such planned urban areas, whose development is guided in part by growth pressures to go out of a central city, even one with a greenbelt (e.g., Ottawa, Canada). Also, the "smart growth" idea has played a role.[27,28] As opposed to accommodating growth in an unstructured, sprawled form, planners and policymakers considered it desirable to direct urban growth in a number of well-defined development nodes that offer the opportunity to some residents to live and work in the same satellite community. These satellite communities can be linked to the central city with high-quality rapid transit. If there is sufficient demand, these can also be linked with each other by rapid transit.

If people can live, work, and find their leisure and entertainment in these satellite communities, they can cut down on commuting, avoid traffic jams, and reduce emissions. Since these outlying community centers can offer cheaper good-quality housing opportunities, some residents are likely to locate or relocate in such centers, provided that they can commute efficiently to the central city if they have to do so. As a side benefit, they can also conserve green space and agricultural land between these intense nodes of development.[28]

The NCA of Canada serves as an example of a multinucleated region. Figure 1 shows the central cities of Ottawa (in the province of Ontario) and Gatineau/Hull (in the province of Quebec). Outside the main cities, a number of first tier community centers are located. The map also shows a second tier of outlying communities that are a part of the multinucleated urban region. All satellite communities are served with highways. The first tier satellite communities either are already served with bus rapid transit or will be served with bus rapid transit or light rail transit as a part of the strategic plan. Some second tier communities are served with bus services.

The household size is low in the central city as compared to satellite communities, and this trend will continue into future years (Table 2). The residence location choices made by households are in part influenced by the need for space at relatively low prices. The satellite communities do offer employment opportunities, but these are much fewer than in the central city (Table 3). Unless future employment opportunities in satellite communities improve, it is inevitable that a majority of residents of satellite cities will have to commute to employment locations in the central business district of the main city or to other job sites. In spite of the presence of public transit, freeways, and other roads in the travel corridors experience traffic jams.

Figure 1. Multinucleated National Capital Region (Canada)




*Note:* Sample tier 1 and tier 2 communities shown

## Table 2. Population/Household Ratio, Ottawa (Canada)

| | 1991 | 2001 | 2011 | 2021 | 2031 |
|---|---|---|---|---|---|
| Inside the greenbelt | 2.46 | 2.46 | 2.19 | 2.08 | 2.13 |
| First tier satellite communities | 3.31 | 3.08 | 2.94 | 2.75 | 2.57 |
| Second tier satellite/rural communities | 3.18 | 3.00 | 2.94 | 2.80 | 2.63 |

*Note:* The above data apply to the Ottawa (Ontario) region (shown south of Ottawa River in Figure 1).

Source: City of Ottawa (2014).

## Table 3. Employment/Population Ratio, Ottawa (Canada)

| | 1991 | 2001 | 2011 | 2021 | 2031 |
|---|---|---|---|---|---|
| Inside the greenbelt | 0.70 | 0.78 | 0.85 | 0.87 | 0.86 |
| First tier satellite communities | 0.19 | 0.29 | 0.60 | 0.42 | 0.38 |
| Second tier satellite/rural communities | 0.19 | 0.23 | 0.26 | 0.25 | 0.31 |

*Note:* The above data apply to the Ottawa (Ontario) region (shown south of Ottawa River in Figure 1).

Source: City of Ottawa (2014).

## Sustainability Factors for Multinucleated Urban Regions

A multinucleated urban region has well-defined interconnected and interacting components. This research is closely concerned with three major parts, namely, land use, transportation, and communications. Such an urban region should offer its present and future inhabitants the opportunity to attain economic, social, recreational, and other goals. Given the imbalance of jobs and housing in satellite communities, it is necessary to implement policies and programs to avoid future problems of traffic congestion, inefficient use of fuels, and emissions. That is, transportation between the central city and satellite communities should be made sustainable, and the supplemental measure of telecommuting should be given careful consideration.

For multinucleated urban regions, the sustainability solutions include (1) efficient use of scarce urban land, (2) a balanced transportation system that offers users the opportunity to use modes that are alternatives to the automobile (i.e., public transportation, nonmotorized modes for local travel, telecommuting), (3) efficient use of nonrenewable petroleum fuels and substitution of renewable energy sources for petroleum fuels, (4) control of air quality pollutants, (5) reduction of GHG emissions, (6) reduction of other ecological effects of transportation, and (7) control of noise from transportation.

The City of Ottawa's strategic directions regarding transportation that were defined as a part of the official plan include the following: use of alternative fuels, increased use of public low- or zero-emission transit, and transportation demand management. It is interesting to note that telecommuting is included in the list of demand management measures.[29]

## Case Study of National Capital Area (Canada)

A research study was carried out at Carleton University under the supervision of the author for the investigation of the impacts of telecommuting and related intelligent transportation systems (ITS) on land use patterns.[3] The focus of the study was on households' residential location choice decisions, in order to verify whether telecommuting and ITS play a role in decentralization of land use.

To study these effects, discrete choice methodology within the well-developed random utility theory framework was adopted for model development. As a part of the research framework, combined revealed preference (RP) and stated preference (SP) logit analysis was performed to estimate the parameters of the utility function. A part of the survey data collected and conclusions derived from the residential location choice decision models are used in the case study described here.

### *Attitude Survey*

The required data were collected through an attitudinal survey of employees of selected private and public organizations within the multinucleated Ottawa region (Canada). Literature sources indicate that job type and human factors play a role in considering telecommuting.[30] In addition to high technology industry employees, telecommuting is adopted by industries such as finance, consulting services, education and research, insurance, and retail.[31] Research also shows that both private and public sectors use telecommuting successfully. Therefore, it was decided to survey both sectors. The sampling process for each sector is explained next.

For the private sector, the simple random sampling method was applied, which is based on the use of random numbers. The private sector organizations that participated in the survey were within the following industries: high technology such as web design, software development, telecommunications, consulting services, finance, and research and education.

In the case of the public sector, it was found that there were a few organizations (six in total) in the region that permitted telecommuting for some of their employees. All six organizations were requested to participate in the survey. Out of these, three agreed. Within these agencies, only those divisions where a telecommuting program was in effect participated in the survey. Although this approach did not provide a true random sample of all public agencies in the region, the method could be considered as quasi-random sampling, since the employees within these organizations were surveyed randomly.[3]

The final survey was carried out between August 1998 and February 1999. Although the survey was carried out some years ago, the information on attitudes is believed to be current for the purpose of this research. The survey consisted of three parts. Part one contained an introduction letter that outlined the purpose of the survey plus explanations about telecommuting. Part two contained questions about the respondent's housing choice, travel behavior, employment, and demographic information. Part three contained the stated preference task.

### *Analysis of Survey Data*

A total of 1,252 surveys were sent out to private and public sector organizations. Of these, a total of 390 usable questionnaires were returned, yielding an overall response rate of 31 percent (384 surveys were usable for RP analysis, and 385 surveys were usable for SP analysis).[3] A part of the information collected is used here to model the decision to telecommute and to show the effects of telecommuting.

Most respondents were professional/technical persons. In general, they were engineers, analysts, computer programmers, etc. The sample consists of 25 percent telecommuters and 75 percent non-telecommuters. Males accounted for 54 percent of the sample, and 75 percent were homeowners.

The location of residence of respondents is shown in Table 4. Fifty-eight percent of respondents lived in the central area of the region, 25 percent resided in suburban first tier satellite communities, and 17 percent lived in outlying second tier satellite communities. As compared to non-telecommuters, a higher percentage of telecommuters lived in outlying areas.

### Table 4. Residence Location of Non-Telecommuters and Telecommuters

| Location | Non-Telecommuters | Telecommuters | Total |
|---|---|---|---|
| Central | 172 (60%) | 51 (53%) | 223 (58%) |
| Suburban (tier 1 satellite) | 72 (25%) | 24 (24%) | 96 (25%) |
| Outlying (tier 2 satellite) | 43 (15%) | 22 (23%) | 65 (17%) |
| | **287 (100%)** | **97 (100%)** | **384 (100%)** |

*Source*: Adapted from Tayyaran, M.R., "Impact of Telecommuting and Related Aspects of Intelligent Transportation Systems on Residential Location Choice: A Combined Revealed and Stated Preference Approach," Ph.D. Thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, 2000.

Table 5 presents selected transportation characteristics of the sample in aggregate terms. Mode of travel and average commute time data for telecommuters and non-telecommuters can be observed in Table 6.

It can be seen that automobile mode choice for telecommuters and non-telecommuters is roughly the same. However, telecommuters use public transit more than their counterparts, whereas the reverse is true with respect to walk/cycle mode. Although not shown in the table, the sample as a whole uses public transit more than the transit market share for the region.

Statistical analysis reported by Tayyaran indicates that:

- gender did not have an impact on the adoption of telecommuting by workers;
- there is no significant difference between telecommuters and non-telecommuters with respect to their job category; and
- there is a significant difference between the two groups with respect to age—the average age of telecommuters is higher than that of non-telecommuters.[3]

### Table 5. Sample Characteristics

| Item | Average for the Sample |
|---|---|
| Vehicles/household | 1.48 |
| Vehicles/licensed driver | 0.74 |
| Average distance from residence to work (km) | 19.00 |
| Average one-way commute time (minutes) | 29.00 |
| Average speed (km/h) | 39.30 |

*Source:* Adapted from Tayyaran, M.R., "Impact of Telecommuting and Related Aspects of Intelligent Transportation Systems on Residential Location Choice: A Combined Revealed and Stated Preference Approach," Ph.D. Thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, 2000.

### Table 6. Transportation Characteristics of Respondents

| Travel to Work Information | Non-Telecommuters | Telecommuters | Total |
|---|---|---|---|
| **Mode of travel:** | | | |
| Automobile | 64% | 62% | 63% |
| Public transit | 24% | 32% | 26% |
| Walk/cycle | 12% | 6% | 11% |
| Average one-way commute time | 28 min. | 32 min. | 29 min. |
| Average one-way commute distance | 18.6 km | 21.0 km | 19.0 km |

*Source:* Adapted from Tayyaran, M.R., "Impact of Telecommuting and Related Aspects of Intelligent Transportation Systems on Residential Location Choice: A Combined Revealed and Stated Preference Approach," Ph.D. Thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, 2000.

Table 7 presents characteristics of respondents in terms of selected telecommuting variables. The average duration of telecommuting per week is 11 hours (equivalent to 1.57 days/week). This amounts to 30 percent of the workweek. The average number of years of participation in a telecommuting program is 2.9 years.

In response to a question on whether the survey participant ever contemplated moving or actually moved because of telecommuting, 13 percent of telecommuters said yes.

Forty-six percent of non-telecommuters indicated that their jobs are suitable for telecommuting. A very high percentage (69 percent) of this group stated that they would either definitely or probably telecommute if they were given the opportunity to do so. This shows an interest among respondents in adopting telecommuting. However, the reader is cautioned that it does not necessarily imply that they would telecommute if they had the opportunity.

### *Saving of Travel Time and Vehicle-Kilometers*

The survey data and selected results of the Carleton University research on telecommuting and related ITS provide an opportunity to estimate travel distance and time savings. In turn, these are used to estimate fuel and GHG emission reduction attributable to telecommuting (please see the following sections of this paper). The steps and assumptions are as follows:

**Table 7. Telecommuting Information**

| Item | Non-Telecommuters | Telecommuters |
|---|---|---|
| Number in the sample | 287 (75%) | 97 (25%) |
| Average number of hrs/week of telecommuting | N/A | 11 hours |
| Average duration of participation | N/A | 2.9 years |
| Ever contemplated moving or actually moved because of telecommuting | N/A | 13% |
| **Suitability of job for telecommuting?** | | |
| Yes | 46% | N/A |
| Not sure | 17% | N/A |
| **Whether or not they would telecommute if given the opportunity:** | | |
| Definitely or probably YES | 69% | N/A |
| Not sure | 15% | N/A |
| Definitely or probably NOT | 16% | N/A |

*Source:* Adapted from Tayyaran, M.R., "Impact of Telecommuting and Related Aspects of Intelligent Transportation Systems on Residential Location Choice: A Combined Revealed and Stated Preference Approach," Ph.D. Thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, 2000.

1. Average telecommuting time/week is 11 hours. This amounts to 30 percent of a working week of 37 hours. Therefore, for a telecommuter, a 30 percent reduction in work trips can be achieved. If 25 percent of workers in the region telecommute, the reduction in peak period work trips is 7.5 percent. If 10 percent of workers telecommute, the peak period work trip reduction is 3 percent.
2. On the assumption of automobile dependence and single occupancy, savings of veh-km = (reduction due to less travel) – (additional veh-km due to extra distance covered by telecommuters). This is a realistic adjustment to veh-km saved, given the decentralization effect of telecommuting. Telecommuters on average travel an extra 2.4 km/one-way trip.

Prior to telecommuting veh-km = (18.6 km/one-way trip for non-telecommuters)(2) × (225 commuting days/year) = 8,370 veh-km/year.

Veh-km after switching to telecommuting for 30 percent of the workweek = (21 km/one-way commute)(2)(225)(1-0.3) = 6,615 veh-km/year.

Percent saving of veh-km = [(8,370 - 6,615)/(8,370)] × 100 = 21.0 percent.

Please note that the acceptance of an additional 2.4 km (or 4 minutes/trip) (average) by telecommuters as shown in Table 6 reflects a partial effect of the concept of travel time budget.

3. It is realistic to make a further adjustment for the effect of travel time budget. Assume that 30 percent of the above computed savings for a telecommuter is offset by increased nonwork types of travel. Therefore, the percent savings becomes (21.0 percent)(0.7) = 14.7 percent.

## Bayesian Model of Telecommuting Decisions

The principles of statistical decision theory are used here to model the potential telecommuter's decision to identify the optimal choice in situations when the outcomes are not known with certainty. Bayesian decision-making under risk and uncertainty involves probabilistic states of nature (e.g., states of traffic congestion) and utility/payoffs that have to be defined for the applicable actions (i.e., to telecommute or not) and states-of-nature combinations. It is a fundamental statistical approach that enables one to assess the probability of an event, given prior information. A very useful feature is that it adds much flexibility to decision analysis DUE to the ability to update probabilities as a result of new information.[32,33]

### *Structuring the Decision-Making Problem*

Modeling the travel vs. telecommunication decision has been a subject of much challenge since the 1970s.[34] This is the first time that a Bayesian approach is being used to model the decision of a potential telecommuter of whether to telecommute or not and to identify the most suitable option.

The potential telecommuter has three mutually exclusive decision alternatives under consideration (*D1*, *D2*, and *D3*), called terminal decisions.

- *D1*: Do not telecommute.
- *D2*: Telecommute for 30 percent of the work hours per week.
- *D3*: Telecommute for 50 percent of the work hours per week.

These are characterized under three traffic condition scenarios (*T1*, *T2*, *T3*), with the middle scenario *T2* considered the most likely one to occur.

- *T1*: Moderate traffic congestion during peak period
- T2: Congested traffic condition during peak period
- *T3*: Highly congested traffic condition during peak period

In the language of statistical decision theory, these are called uncertain "states of nature." The states of nature listed above have the possibility of occurrence, but, after one of the mutually exclusive alternatives has been selected by the decision-maker, only one will be experienced. Due to the stochastic nature of the states of nature, probabilities have to be assigned to each state in the set of states of nature.

In this decision analysis problem, an experiment (i.e., a trial period of telecommuting) is under consideration. This information acquisition activity, called an experiment ($E_1$), is designed to obtain more information about the state of nature (i.e., traffic conditions) prior to the selection of an alternative decision *D*. The option of no experiment is designated as $E_0$. The set of outcomes/results of the experiment (i.e., experimental results) are *r1*, *r2*, and *r*3. These correspond to *T1*, *T2*, and *T3*, respectively. The option of not undertaking the experiment $E_0$ results in no new information $r_0$.

### *Evaluation of Telecommuting Alternatives*

In concept, a number of factors can be defined for evaluating telecommuting alternatives from the viewpoint of an employee who has to decide whether to participate in a telecommuting program, if offered the opportunity by the employer. In such a situation, it is customary that the cost of the telecommunication services and the computer is borne by the employer. Therefore, from the perspective of a potential telecommuter, telecommuting can be credited with the following positive effects: travel time savings, travel cost savings, flexibility in balancing professional and personal lives, reducing job and commuting stress, increased productivity, etc.

On the negative side, employees who participate in telecommuting programs feel that lack of physical presence in the office even for a part of the working hours puts them at a disadvantage in terms of face-to-face interaction with colleagues and supervisors. Kurland and Cooper provide additional information on manager control and employee isolation in telecommuting environments.[35] The 2011 Telework Research Network publication notes that management fear and mistrust are the biggest barriers to telecommuting.[19] According to Galt, even for the most productive telecommuters, some "face time" is often necessary if they want to stay on the corporate radar.[36]

A major challenge in the assessment of telecommuting alternatives is the task of quantifying their "utility," expressed by variable *u*. For a given D&T combination, a number of "utility" factors (i.e., $u_1, u_2, \ldots u_m$) could be quantified in their original units or in qualitative terms. In this research, three "utility" variables were quantified. These are travel time saving, travel cost saving, and "lack of physical presence in the office." It should be noted that the potential telecommuter wishes to maximize the utility variables of saving of travel time and travel cost. On the other hand, it is in the best interest of the employee to minimize the "lack of physical presence in the office," or in other words to maximize "face time."

For the alternative of no telecommuting (i.e., *D1*), under *T1*, the average travel time is 28 minutes/one-way work trip (Table 6). On a weekly basis, the travel time amounts to 28 minutes/direction × 2 × 5 days/week = 280 minutes. Under *T2*, the average speed of travel is 85 percent of the average speed under *T1*, and this results in 33 minutes for one-way travel time and 330 minutes for one week. Commuting in the *T3* scenario is slower to the extent that the average speed becomes 75 percent of the speed under *T1*. The one-way travel time is 37 minutes, and 370 minutes for a week. Since decision *D1* does not involve telecommuting, the travel time savings is zero. For the same reason, travel cost savings is zero for *D1* under all traffic states.

Decision alternative *D2* calls for a 30 percent reduction in a telecommuter's travel time and cost. Under *T1*, a telecommuter on average travels an additional 4 minutes due to residence location. So, one-way travel time becomes 32 minutes, and on a weekly basis, the travel time is (32 × 2 × 5)(1 – 0.3) = 224 minutes. The travel time reduction under *T1* due to telecommuting is 320 – 224 = 96 minutes. It is assumed that 30 percent of this savings is lost to additional non-work travel that a telecommuter is likely to engage in. So, the travel time savings becomes 96(0.7), or 67 minutes.

For alternative *D2*, under *T2*, the additional travel time for a commuter is 4 × (1/0.85) minutes, and travel time savings due to a 30 percent reduction in travel time amounts to 80 minutes per week.

Under *T3*, the additional travel time for a telecommuter is 4 × (1/0.75) minutes and the weekly travel time saving is 88 minutes.

Alternative *D3* is based on a 50 percent reduction in commuting travel time. The travel time savings per week due to telecommuting is 112 minutes, 133 minutes, and 147 minutes under traffic states *T1*, *T2*, and *T3*, respectively.

Savings of travel cost for each alternative and traffic state (i.e., *D&T*) combination exhibits the same relative position as travel time savings. The reason is that these savings are attributable to travel distance reduction and driving conditions. The saving of parking charges may not materialize for two reasons. In the central business district, employees usually arrange a low-rate yearly contract with a parking garage or a parking lot. Also, some employers provide parking spaces as an employment benefit.

The variable of "physical presence in the office" is quantified on a relative value (i.e., utility) scale of 0 to 1. Under *T1*, *D1* is given 1.0 due to the absence of telecommuting. The *D2* and *D3* alternatives initially receive 0.7 and 0.5 in accordance with the extent of physical presence in the office. These relative value scores are adjusted under *D2* and *D3* according to time wasted in traffic jams, which may result in less time spent in the office.

The next step is to transform the "effects" that are measured in diverse units into a relative value scale so that these can be weighted and then added. Since the physical presence in the office is estimated on the relative value scale, its values can be used directly. However, the travel time savings and travel cost savings have to be transformed from their original units of measurement into relative values, measured on the 0 to 1 relative value or utility scale.

The theoretical basis of scale transformation is described next. A methodology is used here that can treat evaluation factors or "effects" measured on diverse scales (e.g., time, dollars, subjective ratings) into an overall value score for each alternative. This methodology, based on the principles of multi-attribute utility theory, enables the treatment of multiple "effects," differential weighting of "effects," and diminishing marginal utility property (if applicable).

Weights can be used as indicators of the relative importance of the "effects." These weights can express the potential telecommuter's trade-offs for saving travel time and travel cost and absence from the office. The weights can be selected from a scale of 1 to 5, which is commonly used in psychological studies. These can be used as raw weights or can also be normalized. Logically, the decision-maker (i.e., the potential telecommuter) has to assign weights to "effects" of telecommuting.

As noted earlier, the levels of various "effects," originally measured in their raw units, or in some cases expressed subjectively (e.g., excellent, very good, good, etc.), can be mapped on a relative value scale of 0 to 1.0. A value function with the property of diminishing marginal utility property can be expressed as

$$z(u) = L[q(u)]^k \text{ for } k<1, \quad (1)$$

where

- $z(u)$ is the transformed value of a given $u$
- $q(u)$ is the value of $u$ expressed in its original units (e.g., time measured in minutes, cost measured in dollars, lack of physical presence quantified as face time on a relative value scale)
- $L$ and $k$ are constants
- In case of linear transformation, $z(u) = yq(u)+ b$, where $y$ and $b$ are constants.

Another form of the linear transformation function that was used in this research is

$$z(u) = [q(u)/q(u_{max})] \times 1.0. \quad (2)$$

In this case, $u_{max}$ is assigned the highest value, which is 1.0, and the $q(u)$ under consideration is found by the ratio, as shown in Equation 2. If the relative value scale used is from 0 to 100, then the above equation becomes $z(u) = [q(u)/q(u_{max})] \times 100.0$.

The "utility" elements can be weighted and then combined:

$$U = w_1 z(u_1) + w_2 z(u_2) + \ldots + w_m z(u_m) \quad (3)$$

where $U$ is the combined weighted utility and $w$ is a scale transformation on $z(u)$—a relative "weight" reflecting the importance of "utility" $u$.

The unweighted utility matrix is shown in Table 8. It can be seen that the scores for physical presence in the office are adjusted under *T2* and *T3* to take into account time wasted in traffic jams. Three scenarios of relative weights were considered, and the weighted utilities are presented as three versions of the utility matrix $U(E, r, D, T)$.

A *utility* matrix represents the value for the course of action defined by E, $r$, $D$, $T$ combinations. In accordance with the principles of utility theory, it is assumed that the utilities $U(E,r)$ and $U(D,T)$ are additive. In this paper, a $U(D,T)$ matrix is used and $U(E,\mathrm{r})$ is kept as a variable that is internal to the computation process, since no monetary cost is assigned to the experiment. For a comprehensive analysis of the decision problem including the sensitivity analysis, three versions of the $U(D,T)$ matrix are presented as Table 9. On a scale of 1 to 5, the travel time savings was assigned weights of 2, 1, and 1 in utility matrix versions 1, 2, and 3, respectively. Travel cost was given a weight of 1 in all three utility matrix versions. The "office presence" received weights of 5, 5, and 4 in utility matrix versions 1, 2, and 3. It should be noted that these weights are used for sensitivity analysis purposes. If the methodology reported in this paper is applied to another case study, the analyst can apply different weights.

We are interested in finding the best course of action. This involves determining the best action and the expected value of information using the probability distributions over the possible states of nature (i.e., T1, T2, or T3). However, to find these answers, a joint probability $P(T,r|E)$ must be assigned to the joint distribution of $T$, $r$, for each experiment $E$. This requires the reliability of each possible outcome to be defined for the prediction of the true state of nature. When that is done, four other probability measures are determined. These are prior probability $\{P'(T)\}$, conditional probability $\{P(r|T,E)\}$, marginal probability $\{P(r|E)\}$, and posterior probability $\{P''(T|r,E)\}$.

Table 8. Effectiveness of Alternatives (Relative Value Unit on a Scale of 0 to 1) (Unweighted)

| | *T1*<br>*Moderate Peak Period Congestion* | *T2*<br>*Congested Peak Period* | *T3*<br>*Very Congested Peak Period* |
|---|---|---|---|
| **Alternative *D1* (0% telecommuting time)** | | | |
| Travel time savings | 0 | 0 | 0 |
| Travel cost savings | 0 | 0 | 0 |
| Physical presence in the office | 1.0 | 0.85 | 0.75 |
| **Alternative *D2* (30% telecommuting time)** | | | |
| Travel time savings | 0.46 | 0.54 | 0.60 |
| Travel cost savings | 0.46 | 0.54 | 0.60 |
| Physical presence in the office | 0.70 | 0.60 | 0.53 |
| **Alternative *D3* (50% telecommuting time)** | | | |
| Travel time savings | 0.76 | 0.90 | 1.00 |
| Travel cost savings | 0.76 | 0.90 | 1.00 |
| Physical presence in the office | 0.50 | 0.43 | 0.38 |

The probability distributions of P'($T$) and $P(r|T,E)$ serve as a starting point for the estimation of the joint probability measure $P(T,r|E)$ for each information acquisition option $E$. The $P'(T)$ is the decision-maker's judgment about the relative likelihood of values of $T$, and $P(r|T,E)$ characterizes each $E$ as the probability that the outcome $r$ will be observed if the experiment $E$ is performed and $T$ is the state of nature.

Table 9. Utility Matrix $U(D,T)$ (Relative Value Units)

| | *T1* | *T2* | *T3* |
|---|---|---|---|
| ***Version 1*** | | | |
| *D1* | 5.00 | 4.25 | 3.75 |
| *D2* | 4.88 | 4.62 | 4.45 |
| *D3* | 4.78 | 4.85 | 4.99 |
| ***Version 2*** | | | |
| *D1* | 5.00 | 4.25 | 3.75 |
| *D2* | 4.42 | 4.08 | 3.85 |
| *D3* | 4.02 | 3.95 | 3.90 |
| ***Version 3*** | | | |
| *D1* | 4.00 | 3.40 | 3.00 |
| *D2* | 3.72 | 3.48 | 3.32 |
| *D3* | 3.52 | 3.52 | 3.52 |

### *Solving the Telecommuting Decision Problem*

The decision problem can be represented by a sequence of experiment, outcome, decision, and state of nature. The desirability of that sequence or course of action ($E, r, D, T$) or ($E_0, r_0, D, T$) is completely described by the utility matrix $U(E, r, D, T)$ or $U(D, T)$.

Given the prior probability and the conditional probability, the marginal probability can be computed as follows:

$$P(r|E) = \sum P'(T)P(r|T,E), \tag{4}$$

The posterior probability is computed using the Bayes theorem:

$$P''(T|r,E) = \frac{P'(T)P(r|T,E)}{\sum P'(T)P(r|T,E)} \tag{5}$$

The assumption is that each experiment option ($E_0$, $E_1$) can be described by a conditional probability of $P(r|T,E)$, such that the linkage between the prior and posterior probabilities is provided by the Bayes theorem.

To find the optimal course of action, this analysis should be extended. This involves determining the utility of each combination (i.e., $U(E, r, D, T)$). The utility matrix $U(E,r,D,T)$ represents the decision maker's values for all $E,r,D,T$ combinations.

The sequence of the decision maker's course of action is as follows. The decision maker selects an information acquisition activity $E$, observes a result $r$, decides on a particular $D$, and then a particular state of nature $T$ occurs.

The utility functions reflect the value structure of the potential telecommuter. Therefore, it is not useful to generalize the characteristics of utility functions. For example, the following special cases may be encountered. The diminishing marginal utility property may be applicable. In other cases, utility functions with well-defined threshold values as steps may be applicable. Due to the diverse nature of utility functions, the analyst has to estimate or acquire applicable utility functions.

The expected utility for each decision $D$ for each (experiment, outcome) combination can be found as follows:

$$U^*(D,r,E) = \sum \text{ for all } T\,(P''(T|r,E).\,[U(E,r,D,T)] \tag{6}$$

In the case of no experiment, $U^*(D,r_0,E_0) = \sum_{\text{for all T}} P''(T|r_0,E_0).[U(E_0,r_0,D,T)].$

For each (experiment, outcome) combination, an optimal $D$ and its associated maximum utility are found:

$$U^*(r,E) = Max_D\, U^*(D,r,E). \tag{7}$$

For each $E$, the expected utility can be found:

$$U^*(E) = \sum_r [P(r|E)\, U^*(r,E)]. \tag{8}$$

If more than one experiment can be performed, the optimal experiment is that for which $U^*(E)$ is maximum:

$$U^*(E^*) = Max_E U^*(E). \tag{9}$$

### *Value of Information from Trial Period*

If the optimal experiment turns out to be other than the "null" one, it could be of interest to know the value of information acquired. This requires the estimation of the increase in utility obtainable for each *r* if the prior choice of terminal decision *D* was altered after posterior information was attained.

In operational terms, the expected utility of the optimal *D* under posterior information ($D_r$) is to be subtracted from the expected utility of the optimal *D* under prior probabilities ($D'$). Or,

$$V_t^*(E) = \sum_r P(r|E) \left[\sum T\, P''(T|r,E)\, U_t(D_r,T) - \sum_T P''(T|r,E)\, U_t(D', T)\right] \tag{10}$$

where $V_t^*(E)$ is the value of information and subscript "*t*" refers to the terminal utility in terms of the optimal course of action.

The expected terminal utility of a particular experiment *E* is the expected terminal utility of an immediate terminal decision *D* plus the expected value of information obtained from the experiment. This can be expressed in equation form as shown below:

$$U_t^*(E) = U_t^*(E_0) + V_t^*(E). \tag{11}$$

Next, the expected net utility of an *E* can be determined to be the expected value of new information less the expected cost of obtaining sample information $c_s^*(E)$. In equation form,

$$v^*(E) = V_t^*(E) - c_s^*(E) \tag{12}$$

where

$$c_s^*(E) = U_s^*(E) = \sum_r P(r|E) U_s(E, r). \tag{13}$$

From the above, it can be inferred that the expected cost (in relative value units) of the telecommuting experiment should not exceed the expected value of information $V_t^*(E)$ obtainable from *E*.

### *Bayesian Methodology Application*

The Bayesian methodology was applied to the telecommuting decision problem as follows. First, the prior probability distributions were specified as shown in Table 10. The experience of traffic engineers points in the direction of the use of the normal probability distribution function for the states of traffic congestion.

Further, the amount of deviation from the midpoint that is commonly observed in the data suggests a standard normal deviate equal to 1. Therefore, these were used as a basis to specify prior probabilities. Alternatively, discrete prior probability distributions can be specified subjectively.

The conditional probabilities, which represent the reliability of the experiment (i.e., the trial telecommuting period), shown in Table 10, were assigned on the basis of experience with traffic studies in general. The posterior probabilities and marginal probabilities were computed by using the equations noted above. These results are shown in Table 11.

The decision problem was solved by using the probabilities (presented in Table 11) and the utility matrix shown in Table 9. Table 12 presents the results of posterior and pre-posterior analysis. The telecommuting alternative *D3* turns out to be the choice when utility matrix versions *1* and *3* are used. These are based on favorable weights assigned to travel time savings or slightly reduced weights given to office presence. From a behavioral perspective, these results appear logical. The value of information results show the $V_t^*(E)$ to be positive. Therefore, an experiment can be carried out.

Table 10. Input Probabilities

| Prior Probability P'(T) | | | Conditional Probability P(r\|T,E) | | |
|---|---|---|---|---|---|
| | | | *T1* | *T2* | *T3* |
| *P'(T1)* | 0.16 | *r1* | 0.7 | 0.15 | 0.1 |
| *P'(T2)* | 0.68 | *r2* | 0.2 | 0.7 | 0.2 |
| *P'(T3)* | 0.16 | *r3* | 0.1 | 0.15 | 0.7 |
| | **1.0** | | **1.0** | **1.0** | **1.0** |

Table 11. Computed Probabilities

| Marginal Probability *P*(*r*\|*E*) | | Posterior Probabilities *P"*(*T*\|*r*,*E*) | | | | |
|---|---|---|---|---|---|---|
| | | | *T1* | *T2* | *T3* | Sum |
| *r1* | 0.23 | *r1* | 0.487 | 0.443 | 0.070 | **1** |
| *r2* | 0.54 | *r2* | 0.059 | 0.882 | 0.059 | **1** |
| *r3* | 0.23 | *r3* | 0.070 | 0.443 | 0.487 | **1** |
| | **1.00** | | | | | |

Table 12. Bayesian Analysis Results

| Prior Branch, $E_0$ | Posterior Branch, $E_1$ | Value of Information |
|---|---|---|
| **Utility matrix version 1** | | |
| Optimal decision: *D3* | Optimal decison under: | Vt* + ve |
| | *r1: D3* | |
| | *r2: D3* | |
| | *r3: D3* | |
| **Utility matrix version 2** | | |
| Optimal decision: *D1* | Optimal decison under: | Vt* + ve |
| | *r1: D1* | |
| | *r2: D1* | |
| | *r3: D1* | |
| **Utility matrix version 3** | | |
| Optimal decision: *D3* | Optimal decison under: | Vt* + ve |
| | *r1: D1* | |
| | *r2: D3* | |
| | *r3: D3* | |

## Effects of Telecommuting

Analyses presented above show that telecommuting saves travel time, travel cost, and veh-km. The level of telecommuting reviewed earlier points out a wide range of 3 to 33 percent, depending on the location, employment sector, and enthusiasm of the employer. The case study of telecommuting carried out in the NCA (Canada), presented in this paper shows that 25 percent of the sample were telecommuters, and if given the opportunity, 69 percent of non-telecommuters would either definitely or probably participate in a telecommuting program.

The Bayesian model shows that under high and very high traffic congestion conditions and if the human factors are favorable, the telecommuting option will be acceptable to an employee.

Forecasts of the level of telecommuting suggest that under well-defined traffic and human factor conditions, for the job types defined in this paper, and with strong employer support, a substantial proportion of commuters will telecommute. Of course it is assumed that public policy is supportive.

Considering the above information, particularly the results of the Bayesian model and assuming favorable conditions, it is likely that 10 percent to 20 percent of commuters will telecommute in the future. According to the 2011 O-D survey in Ottawa (Canada), 6 percent to 7 percent telecommuted.

It was found earlier that a 14.7 percent savings of veh-km can be achieved due to telecommuting. For 25 percent telecommuters out of total workers, savings of veh-km = (0.25)(14.7 percent) = 3.7 percent. For a 10 percent telecommuting level in the region, savings of veh-km = (0.1)(14.3 percent) = 1.4 percent.

Saving of fuel and reduction of GHG emissions are directly proportional to a reduction in veh-km of travel. As a result of fuel consumption, emissions are produced. In addition to other emissions, the following GHG emissions result from the combustion of petroleum fuels. The GHG emissions of interest are carbon dioxide ($CO_2$), methane ($CH_4$), and nitrogen oxide ($N_2O$). The magnitudes of these emissions per liter of fuel vary by type of fuel, engine, and emission control technologies. In order to find the CO2 equivalent of these gases, equivalency factors are used that reflect their relative long-term greenhouse effect. The equivalency factors are 1 for $CO_2$, 21 for $CH_4$, and 310 for $N_2O$.

The overall relationships between veh-km, fuel consumption, and GHG emissions are shown below.

$$\text{Fuel Consumption (litres)} = \text{Veh-km} \times (\text{Fuel Consumption/Veh-km}) \quad (14)$$

$$\text{GHG Emission Factor (million tons/gigaliter)} = \sum(\text{Emission Level}) \times (CO_2 \text{ Equivalency})] \quad (15)$$

$$\text{GHG Emissions (million tons)} = (\text{gigaliters of fuel consumed}) \times (\text{GHG Emission Factor}) \quad (16)$$

In this study, we are not estimating the absolute magnitudes of veh-km, liters of fuel, and tons of GHG emissions. Our interest is in percent reduction, as shown in Table 13.

## Table 13. Fuel Consumption and GHG Emission Reduction

| | 25% of Workers Telecommute | 10% of Workers Telecommute |
|---|---|---|
| **Reduction in peak period work trips** | 7.5% | 3.0% |
| **Fuel consumption and greenhouse gas emission reduction*** | 3.7% | 1.4% |

*Assumption: 30 percent of veh-km saved due to telecommuting is offset by increased nonwork travel due to the effect of travel time budget.

## Conclusions and Policy Implications

Telecommuting has the potential to contribute to urban sustainability. However, this potential cannot be realized unless conditions favorable to telecommuting are created. In multinucleated urban regions, favorable conditions can be achieved with the policy of offering telecommuting incentives, should potential telecommuters decide to locate or re-locate in satellite communities. These incentives can take the form of ensuring the availability of broadband network, as visualized by the City of Ottawa's strategic plan.

An employer-initiated telecommuting program is the prerequisite for telecommuting. Also, a potential telecommuter has to perceive the benefits of telecommuting under prevailing circumstances, including traffic congestion, which plays a role.

Given that telecommuting is a significant factor in the residential location choice decision, in estimating the benefits of telecommuting, the additional distance covered by telecommuters compared to non-telecommuters should be taken into account. Likewise, the benefits of telecommuting should be discounted somewhat due to the effect of the concept of travel time budget. This was done in the case study reported in this paper.

On the basis of the case study presented in this paper, it can be concluded that at a 25 percent level of telecommuting, 7.5 percent of peak period work trips and a 3.7 percent savings of fuel and reduction of GHG emissions can be achieved. At a 10 percent level of telecommuting, 3.0 percent of peak period work trips and a 1.4 percent reduction in fuel consumption and GHG emissions can be attained. These levels of reduction of peak period work trips, fuel savings, and GHG emissions reduction are significant, given that telecommuting is only one of the many initiatives for travel reduction during peak period, energy conservation, and GHG emission reduction.

Methods for estimating the extent of telecommuting require refinement. This calls for new research on the substitution of telecommuting for travel to work.

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