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EXECUTIVE SUMMARY

Travel time is an important parameter for evaluating the operating efficiency of traffic networks, assessing the performance of traffic management strategies, and developing real-time vehicle route guidance systems. The envisioned operational tests of Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) in the Minneapolis/St. Paul area call for a provision of timely and reliable travel times over an entire road network. Travel times can be obtained in a number of ways. They can be measured directly using probing vehicles or advanced detection technologies (e.g., AVI, AVL, and video image processing), or estimated indirectly from traffic data provided by conventional detection technologies such as inductive loop detectors. Directly measuring travel time is usually costly and often requires new types of sensors. A more cost-effective way of obtaining travel time is to estimate it using traffic data, particularly those provided by loop detectors that are already in place in most signalized arterials and freeways.

There are reliable methods for estimating travel time on freeways using loop detector data. The interrupted nature of traffic flow on arterial routes and numerous other factors that affect travel times on arterial links, however, make the estimation of travel times on arterials a much more challenging task. There have been attempts to utilize loop detector data (particularly occupancy) and signal timing parameters to estimate arterial link travel times. Despite the various degrees of success achieved in these studies, few of the models developed to date have been applied to real world situations. The reasons for this are largely twofold: 1) some of the models require traffic data that are not or cannot be routinely collected from loop detectors (such as the arrival time of a vehicle at a detector), and 2) some of the models were site-specific and cannot be applied to other locations without recalibration.

In recognition of the need for an effective yet inexpensive way of estimating arterial travel times, Mn/DOT has sponsored a research project to develop a travel time estimation model using loop detector data. This two-phase project is being jointly conducted by researchers from the University of Iowa and the University of Minnesota. Phase I involves a literature review, traffic data collection and development of a travel time database; Phase II covers model development, calibration and evaluation. This report summarizes the findings of Phase I.

A literature review of existing arterial travel time models was first conducted. We searched three primary transportation databases in the nation and found approximately 100 papers related to travel time. After further screening, we selected 20 articles that studied arterial travel time estimation. A review of the literature identified five approaches to arterial travel time estimation: regression, dynamic input-output, pattern matching, sandglass, and models developed by the Bureau of Public Roads (BPR). These approaches encompass a variety of travel time estimation models with diverse data requirements and application ranges.

Among the reviewed models, the most promising ones are the pattern matching and dynamic input-output models, which can estimate both link and route travel times and are less dependent on site-specific parameters. Without much recalibration, therefore, these models can be easily transferred to other locations, though they cannot be used to predict future travel times. Additionally, because these models require a much higher detector sampling rate than what is currently performed, they cannot be applied to arterials with current detector and controller settings.

The sandglass models, like the pattern matching and input-output models, also require traffic data (queue length) that cannot be gathered by current surveillance systems. The BPR models, on the other hand, only need volume data routinely, which is supplied by loop detectors. Still, the accuracy of these models are not satisfactory for dynamic, short-term traffic management applications.

The regression model, with its ability to take various factors into account, is identified as the most practical approach considering the type of data provided by existing traffic surveillance and control systems. Regression travel time models are diverse among themselves. The main difference between these models is the set of inputs used, which range from register time (microscopic level) to occupancy (macroscopic level). The major advantage of the regression models is also a liability. Various factors that affect travel time can be easily incorporated, but this also makes them more location-dependent.

Considering the availability of data from current traffic control settings, regression-type models are perhaps the only option as a short-term solution to the problem of arterial travel time estimation. The review indicates that all the regression models are link-specific and suffer from limited calibration and validation. Their performances are also less than satisfactory. Before this type of model can be used in field operations, it will need to be significantly improved or new regression types of models will have to be developed.

The literature review also clearly revealed the need for an improved travel time database. A ten-day data collection effort was carried out from July 15 to July 26, 1996, on a segment of Snelling Avenue in Minneapolis. The data collection site has three four-leg intersections of typical detector layout. Travel time data were collected by four floating cars from 6:00 AM to 9:00 AM and from 3:30 PM to 6:30

PM; five-minute traffic flow and occupancy produced by all the detectors were downloaded daily from local controllers; turn volumes not covered by detectors were counted manually; and signal timing data were extracted from the event log of the master controller during the data collection period. These data were processed and entered into spreadsheets. Two travel time databases using different Lotus formats were subsequently developed for the collected data.

In the second phase we plan to use the travel time database to develop and test new arterial link travel time models. We will work in close cooperation with Mn/DOT's Orion project team, which is developing an integrated advanced traveler information system for the Minneapolis/St. Paul metropolitan area.

INTRODUCTION

Travel time is an important parameter for evaluating the operating efficiency of traffic networks, assessing the performance of traffic management strategies, developing real-time vehicle guidance systems, and planning transportation facilities. It has become an increasingly popular level-of-service measure for transportation operations. Compared with similar measures such as travel speed and volume/capacity ratio, travel time has a number of advantages: it is intuitive to travelers, applies to all transportation modes (drive-alone, car pool, and public transport), and can be interpreted in economic terms, which is critical to quantifying the cost and benefit of transportation investments.

With envisioned operational tests of Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) in many urban centers including Minneapolis/St. Paul, it is critical to gather timely and reliable travel time data continually for an entire road network. Travel time is traditionally collected by two methods: the floating car technique and license plate matching (Box and Oppenlander 1976, pp. 93–105). Both methods are labor-intensive, costly for any large-scale collection of travel time data, and as a result, unable to supply travel time on a continuous basis. A number of new technologies have emerged in the past few years that offer promising alternatives to these two methods. These new technologies include Advanced Vehicle Identification (AVI), Automatic Vehicle Location (AVL), and Global Positioning Systems (GPS) (Turner 1996). While these new systems can provide continuous, real-time travel time information, they require considerable new infrastructure investment, and will take years for any full implementation of such a system to be a viable alternative of current traffic surveillance systems. On the other hand, most states and cities have in the past invested considerably in traditional traffic surveillance technology, such as inductive loop detectors. As a result, traffic conditions on most freeways and arterials in urban areas are well monitored through outputs from these detectors. It will be of considerable economic benefit if accurate methods can be developed to estimate travel time based on outputs from these types of traffic sensors.

There are reliable methods for estimating travel time on freeways using loop detector data. Nonetheless, numerous factors that affect travel time on arterial links (including the interrupted nature of traffic flow on arterial routes) make the estimation of travel time on arterials a much more challenging task. There have been attempts to utilize loop detector data (particularly occupancy) and signal timing parameters to estimate arterial link travel time (e.g., Gipps 1977; Gault and

Taylor 1981; Young 1988; Takaba et al. 1991; Sisiopiku and Rouphail 1994, pp. 78–116). Despite the varying degrees of success achieved by these studies, few of the models developed to date have been applied to real world situations. The main reasons are twofold: some of the models require traffic data that are not or cannot be routinely collected from loop detectors (such as the arrival time of a vehicle at a detector), and some of the models are site-specific and cannot be applied to other locations without recalibration.

In recognition of the need for an effective yet inexpensive way to estimate arterial travel time, Mn/DOT has sponsored a research project to develop a travel time estimation model using loop detector data. This research project attempts to develop significantly improved methods for deriving average travel time on arterial streets using loop detectors placed in traditional installation patterns. Specifically, our goal is to develop a model that is: 1) simple yet accurate and 2) applicable to similar locations. Such methods could have widespread applications on arterial streets, allowing significant improvements in monitoring traffic flows and managing traffic congestion.

This project is being jointly conducted by researchers from the University of Iowa and the University of Minnesota. Phase I of this two-phase project involves a literature review and data collection. Phase II will focus on model development, validation, and application. This report describes the results of Phase I.

LITERATURE REVIEW

This review provides an up-to-date summary, in terms of model formulation and performance, of existing link travel time estimation methods using detector data. Special attention is paid to model structure, complexity, accuracy, and transferability. Before proceeding further, however, it is necessary to define some terms for clear exposition. In this study, a “link” refers to a road section between the stoplines of two adjacent intersections and a “route” is a road section that comprises a number of successive links. “Arterial link travel time” is the time a vehicle takes to travel from the upstream of a link to the upstream of the successive downstream link, and “route travel time” is defined as the time a vehicle takes to traverse all the links that form the route. Route travel time is therefore composed of link travel times. It is not, however, the simple summation of each link travel time measured at the same time. Because each arterial link usually comprises several lanes and lane movements (through, left turn and right turn) and travel time for each of these lane movements can differ significantly, link travel time can be further grouped as lane-specific or movement-specific. In the following review, unless mentioned otherwise, link travel time refers to travel time for a through movement vehicle traveling on any through lane. Another important term is “average link travel time” (the arithmetic mean of the link travel time of each vehicle that traversed a link during a specific time period). Consequently, the time interval used to report average link travel time is necessarily greater than the average link travel time itself.

A thorough search of relevant literature was performed on several on-line databases using key words such as travel time, signal delay, loop detector, and traffic congestion. This search resulted in about 100 documents. Most of these documents, however, discuss travel times from a perspective different from that of this research. For example, a fair number deal with the value of travel times, others concern predicting times using probing vehicles, and still others estimate travel times using traffic simulation models or dynamic assignment techniques, none of which are relevant to this study. After further screening, we identified 20 references related to travel time estimation for arterials. A review of these documents revealed five arterial travel time estimation approaches: linear and/or nonlinear regression, dynamic input-output, sandglass, pattern recognition and the Bureau of Public Roads (BPR) approach. Models from each of these approaches are reviewed below.

REGRESSION-TYPE LINK TRAVEL TIME MODELS

It has been recognized that many factors affect travel time on arterial links. Among these factors are traffic demand level, link capacity, signal timing, progression of traffic, turn movements, traffic composition, and intersection layout. Regression-type travel time estimation models relate travel time linearly and/or nonlinearly with those factors and/or their combinations. These models can be expressed in a most general form as:

$$T = f(X, \beta) + \varepsilon \tag{1}$$

where

T is average link travel time,

X is a vector of factors such as occupancy, offsets, and green/cycle ratio,

β is a vector of parameters to be estimated, and

ε is an error term, usually assumed to be normally distributed with zero mean.

Gault and Taylor (1981) are perhaps the first to examine the relationship between detector occupancy and measured travel time. They aggregated detector occupancy at various intervals (one, two, three, five and ten minutes) and found that travel time is highly correlated with average occupancy, with the correlation coefficient ranging from 0.86 to 0.94. One interesting observation Gault and Taylor made is that while this correlation coefficient differs significantly between one-minute interval data and two-minute interval data (0.86 and 0.91, respectively), aggregation intervals longer than two minutes do not lead to any significant increase in correlation.

Young's study (1988) on signal delay and detector occupancy also revealed a strong relationship between these two variables. His results showed that the delay and occupancy relationship contains a linear segment in the lower range of occupancy and a nonlinear segment in the higher range of occupancy, exhibiting an S-shaped curve. The nonlinearity in this relationship is attributed to vehicle queues that spill back to the detector. Young found that if a detector is moved back far enough—such that queues never form near or on the detector location—a linear relationship exists for even high occupancies. This result has significant implications for accurate estimation of travel time under oversaturated conditions. Because we cannot move detector locations freely in the real world the way it is possible to in a simulated environment, our ability to accurately estimate travel time using detector data is severely limited when queues grow beyond a detector. This observation is confirmed by a recent study (Sisiopiku, Rouphail and Sandiago 1994), which reported that travel time is uncorrelated with occupancy when occupancy is greater than 90 percent.

Sisiopiku, Rouphail, and Sandiago (1994) also examined the relationship between detector outputs (volume and occupancy) and link travel time based on a collection of field data and simulated data. They found that travel time is independent of occupancy for low demand (occupancy less than 17 percent), strongly correlated with occupancy for medium to moderately high demand (occupancy within the range of 17 to 60 percent), and uncorrelated with occupancy for high demand (occupancy greater than 90 percent). No conclusions were drawn for occupancy between 60 percent and 90 percent because there were not enough data points.

All of the previous studies have revealed a strong correlation between travel time and detector occupancy in certain ranges of occupancy values. It is therefore logical to develop travel time models that can exploit this relationship. Gipps (1977) is perhaps among the first to propose such a travel time model. His model has two explanatory factors: occupancy ϕ and register time t ; i.e., $X = [t, \phi]$. Register time is a quantity derived from arrival time (the time during a cycle when a vehicle is detected by a detector). Arrival time is measured from the start of the green interval at the downstream signal. Gipps plotted travel time against arrival time and found a distinct jump in the middle points of the plot. To remove this discontinuity, he made a coordinate change and defined register time such that a vehicle detected at register time zero will arrive at the downstream intersection when its signal for that approach just turns red. The model form $f(X, \beta)$ is a quadratic function in $X = [t, \phi]$:

$$\begin{aligned} T = a + (1-\delta)(b_{10}t^* + b_{01}\phi + b_{20}t^{*2} + b_{11}t^*\phi + b_{02}\phi^2) \\ + \quad \delta\,(c_{10}t^* + c_{01}\phi + c_{20}t^{*2} + c_{11}t^*\phi + c_{02}\phi^2) + \varepsilon \end{aligned} \tag{2}$$

where

T is the link travel time of a single vehicle,

t^* is the register time minus the length of the red period R,

ε is a random variable from N(0,T2),

$\delta = \begin{cases} 0 \ when\ t \le R \\ 1 \ when\ t > R \end{cases}$, and

$a,\ b_{10},\ b_{01},\ b_{11},\ b_{20},\ b_{02},\ c_{10},\ c_{01},\ c_{11},\ c_{20},\ c_{02}$ are regression parameters.

By examining the residual errors, Gipps found that terms $b_{10}t^*$, $b_{01}\phi$, $c_{10}t^*$ and $c_{01}\phi$ accounted for most of the variations in travel time. He therefore reduced model (2) to a much simpler form:

$$T = \begin{cases} (a + R) - t + b_{01}\phi & for\ t \le R \\ (a - c_{01}R) + c_{10}t + c_{01}\phi & otherwise \end{cases} \tag{3}$$

Gipps (1976) used a computer program MULTSIM to simulate a single-lane section of roadway about 400 meters long. From this simulation he obtained register time and occupancy data, which were used to calibrate the simplified model. A mean square error of ten to 15 percent was reported.

Others built on the work of Gipps: Gault and Taylor (1981) and Gault (1981) proposed a simpler model based on both register time and occupancy, taking into account a variety of factors such as degree of saturation and signal offset. The model is in the form:

$$T = (1-\delta)at^* + \delta g\phi^{1.6} + K \qquad (4)$$

where

T, δ, t^* and ϕ are defined as in the Gipps model, and

a, g, and *K* are parameters that are functions of signal offset (*off*), running time (*undt* = link length/desired travel speed), and degree of saturation(x=flow/capacity).

Gault and Taylor calibrated this model for two cases (a single-lane case and a two-lane case), using simulated data from MULTSIM. For the single-lane case, the parameters are:

$$\begin{aligned} a &= 0.0168\ off - 0.0266\ undt - 0.375\ x - 0.609 \\ g &= -0.00027\ off + 0.00077\ undt + 0.0104\ x - 0.00386 \qquad (5) \\ K &= 0.392\ off + 0.832\ undt + 11.35\ x - 4.13 \end{aligned}$$

For the two-lane case, the parameters for the model of the inside lane are:

$$\begin{aligned} a &= 0.0061\ off - 0.033\ undt - 0.136\ x - 0.75 \\ g &= 0.00032\ off + 0.00014\ undt + 0.0036\ x - 0.0037 \qquad (6) \\ K &= 0.36\ off + 0.77\ undt + 5.5\ x - 1.35 \end{aligned}$$

and those for the outside lane are:

$$\begin{aligned} a &= 0.0059\ off + 0.0094\ undt - 0.38\ x - 0.62 \\ g &= 0.00032\ off + 0.00025\ undt + 0.0014\ x + 0.0068 \qquad (7) \\ K &= 0.36\ off + 0.85\ undt - 0.34\ x + 1.91 \end{aligned}$$

Evaluation of the model for both one-lane and two-lane cases using simulated data indicated that the model's accuracy is poor when occupancy is above 50 percent, and the model is not robust with respect to changing traffic conditions, such as interruptions caused by bus loading and unloading on the link.

All the aforementioned models are severely limited in their usefulness as operational models because they require the knowledge of register time, a variable that cannot be easily obtained in field operations. Moreover, because the encouraging results obtained by Gipps were based on highly simplified situations, it is not certain that such accuracy would be retained under more complex situations at different locations.

In recognizing the deficiencies of the travel time models based on register time, Gault and Taylor (1981) sought to obtain a more robust model. They developed an occupancy-based travel time model primarily based on occupancy, as follows:

$$\bar{t} = aO + b \tag{8}$$

where

$\bar{t}$ is the average travel time on the link;

O is the average detector occupancy;

a and b are parameters dependent on *undt*, x and P_d;

undt is undelayed travel time;

x is degree of saturation;

P_d is defined as the percentage of green time at the downstream signal; and

P_u is defined as the percentage of green time at the upstream signal.

Gault and Taylor experimented with various factors such as locations of detectors, aggregation intervals for occupancy, and average desired travel times. They found that the optimum detector location is 120 feet upstream of the traffic signal and that aggregation of detector output over more than five minutes does not significantly improve the correlation between average travel time and detector occupancy. Their research also indicated that the relationship between detector occupancy and travel time depends on P_d / P_u. The parameters for a and b were calibrated as:

$$a = 0.33 - 0.004\,undt - 0.57\,x + 0.294\,(P_d / P_u) \tag{9}$$

$$b = 9.95 + 1.42\,undt + 0.996\,x - 10.5\,(P_d / P_u)$$

In comparing results from the occupancy model with those from register time models, Gault and Taylor found that the former model was more accurate and robust than the latter ones, but the difference is marginal. They also compared travel times predicted by the occupancy model with those collected by field surveys, and found that the model's predictions were fairly accurate if occupancy data were aggregated into 20-minute intervals, and not so accurate when the aggregation interval was five minutes. They suspected that using five-minute aggregation intervals might not be a good practice and suggested that a moving average of the previous 10 to 20 minutes of occupancy data be used in the model to improve prediction accuracy.

In a recent research project, Sisiopiku and Rouphail (1994) also developed occupancy-based models to convert detector output into arterial travel times for certain ranges of occupancy values. They assessed the correlation between travel time and flow or occupancy using both field and simulated data (Sisiopiku, Rouphail and Sandiago 1994) and found a significant correlation between link travel time for through movements and occupancy level when occupancy values range from approximately 30 to 90 percent. Sisiopiku and Rouphail (1994) subsequently proposed a piece-wise linear model to fit various portions of the travel time-occupancy plot for a specific link:

$$\begin{aligned} T &= a + b_1 \times PCTOCC + b_2 \times \delta \times (PCTOCC - 27) + b_3 \times \kappa \times (PCTOCC - 42) \\ &= a + b_1 \times PCTOCC + b_2 \times KNOT1 + b_3 \times KNOT2 \end{aligned} \tag{10}$$

where

T is the travel time (in seconds);

$PCTOCC$ is the percent occupancy;

$a,\ b_1,\ b_2,\ b_3$ are regression parameters;

$\begin{aligned} KNOT1 &= \delta \times (PCTOCC - 27) \\ KNOT2 &= \kappa \times (PCTOCC - 42) \end{aligned}$;

$\delta = \begin{cases} 1 & if\ PCTOCC > 27 \\ 0 & otherwise \end{cases}$; and

$\kappa = \begin{cases} 1 & if\ PCTOCC > 42 \\ 0 & otherwise \end{cases}$.

This model contains three linear segments, one for $PCTOCC \le 27$, one for $27 < PCTOCC \le 42$, and one for $42 < PCTOCC$. Clearly, the division points of occupancy in the model are dependent on both the specific site and traffic operating conditions, which may limit the transferability of this model. Validation of this model employed both simulated and field data which were aggregated into 15-minute intervals. The root mean squared error ranges from 1.46 to 25.85 and the error ratio ranges from 4.84 percent to 26.5 percent when using simulated data. The root mean squared error ranges from 7.77 to 29.83 and the error ratio ranges from 30 percent to more than 100 percent when using field data.

In the same research, Sisiopiku and Rouphail (1994) also developed a more general travel time model with two components (free-flow travel time and delay time):

$$\begin{aligned} T &= FFTIME + DELAY \\ &= 0.682 \times \frac{LINKLEN}{FFSPEED} + DELAY \end{aligned} \tag{11}$$

where

FFTIME is the free flow travel time (cruise time) (in seconds),

DELAY is the delay time (in seconds),

LINKLEN is the link length (in feet),

FFSPEED is the free flow speed (cruise speed) (in miles per hour), and

0.682 is a unit conversion factor.

The delay time is determined by the following linear equation:

$$DELAY = \beta_0 + \beta_1 \times DETLOC + \beta_2 \times PCTOCC + \beta_3 \times GREENRAT \tag{12}$$

where

DELAY is delay time (in seconds);

DETLOC is the ratio of detector setback distance to link length;

PCTOCC is the percent occupancy;

GREENRAT is the green ratio, or green over cycle length; and

β_0, β_1, β_2, β_3 are regression parameters.

After calibrating the delay time model using simulated data, Sisiopiku and Rouphail obtained the following:

$$\begin{aligned} T &= FFTIME + DELAY \\ &= 0.682 \times \frac{LINKLEN}{FFSPEED} + (39.4 + 11.3 \times DETLOC \\ &\quad + 1.5 \times PCTOCC - 53.4 \times GREENRAT) \end{aligned} \tag{13}$$

This model, like their link-specific model, was evaluated using 15-minute interval data obtained from both simulation and field surveys. It was reported that the range of the root mean squared error is 13.24 to 28.24 and the error ratio ranges from 16.7 percent to 76.27 percent when simulated data are used. The range of the root mean squared error is 20.55 to 31.77 and the error ratio ranges from 53 percent to more than 100 percent when field data are used. Although this general model considered a number of important factors other than occupancy, its prediction error is still very high; and the model should be improved significantly before it is used in any field operations.

All the works reviewed thus far examined the relationships between link travel time and several factors on a link-specific basis. The following two researchers developed models to predict route travel times using detector information.

Oda (1990) proposed a predictive route travel time estimation model based on traffic sensor data. His model divides the route into subsections, and each subsection has a group of sensors (ultrasonic vehicle sensors in this case) that produce volume and occupancy time. An Auto Regressive (AR) time series model is used to predict future volume and occupancy times for each subsection. The travel speed for each section is calculated based on volume, occupancy time and mean vehicle length (average speed = average vehicle length x traffic volume / occupancy time). A predicted travel time for vehicles starting from a particular time interval is obtained by tracing the travel time on each subsection from the starting time until the vehicles reach their destination. Oda applied this method to a route seven kilometers long in Japan and obtained fairly good results (the predicted travel times are within seven percent error of measured travel times). Oda's method for estimating travel time for a subsection is similar to the method commonly used to estimate freeway travel times. Because the accuracy of such methods is very sensitive to average vehicle length and detector location on a subsection, the results Oda obtained may not be replicated when this method is applied to other arterials.

A route travel time model was also developed by Abours (1986). By first fitting a polynomial relationship between average link travel time and detector occupancy, she used this relationship to estimate link travel times. She also traced the link travel times as a vehicle traversed each link and pieced these times together to obtain a route travel time. In a field traffic study in Paris, occupancy data were collected for every three-minute interval, and travel time data were collected using three floating cars for two weeks. Having calibrated her model using the first week's data, she then used the model to estimate the average travel time on a route comprised of several links and compared the estimated travel time with the measured travel times for the second week. A relative mean square root error of 12.74 percent was reported. Because the specific details of both the model and the calibration process are not described, not much can be said about this model.

In general, the above occupancy-type models have a simple model structure and are relatively easy to calibrate if all the data required are available. Various factors such as signal offset and degree of saturation can be easily incorporated into regression models. The drawback of these models is that they are all site-dependent. This means that a model may need to be recalibrated if used at a different location. The accuracy of these models also needs to be improved.

DYNAMIC INPUT-OUTPUT LINK TRAVEL TIME MODELS

Dynamic input-output travel time models use time series methods and traffic data to predict travel times. Strobel (1977, p. 61) proposed a travel time estimation method based on input-output relationships of traffic flow measured at two points. He postulated that traffic flow measured by a downstream detector (output) at a particular time interval $k\Delta t$ is a linear combination of traffic flow measured 1) by an upstream detector during time intervals $[(k-m)\Delta t, (k-n)\Delta t]$ plus 2) traffic flow entering/leaving the system at time $k\Delta t$ from sources/sinks in the mid-blocks of the road. Apparently Strobel assumes that the travel times for the input flows that contribute to the output flow at time $k\Delta t$ are in the range of $[m\Delta t, n\Delta t]$.

For each contributing input flow measured at a time interval $(k-s)\Delta t$, the travel time taken by this traffic to cover the road section between the two detectors is $s\Delta t$ ($m \le s \le n$). The average travel time for the traffic flow measured at the downstream detector is therefore the weighted sum of the travel times of the contributing flows. The weighting factors are functions of the linear coefficients of the dynamic input-output models.

His formulation is as follows:

$$\hat{y}(k) = \sum_{s=m}^{n} g(s) q(k-s) \tag{14}$$

where

$\hat{y}(k)$ is the estimated output flow at time $k\Delta t$.

$g(s)$ is the fraction of vehicles having a travel time $s\Delta t$ and reaching the output in the interval $(s-1)\Delta t < T_R < s\Delta t$, and

$q(k-s)$ is the input flow at time $(k-s)\Delta t$.

The average travel time between the two measured points is then calculated as:

$$T_a = \sum_{s=m}^{n} \left(s\Delta t \frac{g(s)}{\sum_{s=m}^{n} g(s)} \right) \tag{15}$$

Strobel proposed least-squares identification algorithms to estimate these coefficients $g(s)$ and applied his method to a 1,000-meter long arterial route in Germany. Satisfactory results were obtained by comparing estimated travel times to travel times collected by a license-plate-matching survey. Luk (1989, pp. 29–42) also confirmed the model's validity in a comparison study with another travel time estimation method based on wheel base matching.

Luk and Cahill (1986) used an approach similar to Strobel's to estimate queuing delays at intersections. The input-output model used in Luk and Cahill's formulation is a platoon dispersion model with a rectangular link travel time distribution. The arrival flow profile at the downstream stopline is obtained from dispersing the platoons discharged from the upstream intersection. This arrival flow profile is used together with its departure flow profile to calculate the vehicle queue at that intersection, and therefore the queuing delay. The departure flow profile of a link was estimated from the departure profiles of all approaches that contribute flow to the link. Because the departure profile is closely related to the phasing of the signal, the effects of signal timing on travel time are implicitly modeled. Luk and Cahill tested their model using a traffic simulation program. Two parameters were varied in these tests: offsets and step size Δt. Results showed that offsets clearly influence vehicle delays and that estimation error increases significantly with increases in step size: percentage estimation error varies from six to seven percent when the step size is two seconds, and varies from 73 percent to 94 percent when the step size is ten seconds.

The advantages of the input-output model are: it can be used to estimate both link and route travel times; it is less dependent on site-specific parameters; and it therefore could have greater transferability than regression-type models. This model has several disadvantages, however. One is that it requires some knowledge of the range of average travel time $[m\Delta t, n\Delta t]$, which differs from location to location and time to time. The model also requires that the time interval used to collect traffic data, Δt, be much smaller than the average travel time. For example, if the average link travel time is one minute, the sampling interval Δt should at least be less than 30 seconds, usually approximately two to ten seconds. Such a high sampling rate could place a heavy burden on traffic data collection and usually cannot be achieved in field operations under current controller settings. Second, this model is prone to traffic noises; that is, the interruption of traffic flow by signals and traffic flow from mid-intersections between the input-output locations. A third drawback of this model is that it cannot be used to predict travel times because estimating the model's coefficients requires current and past traffic flow measurements, not predicted ones.

SANDGLASS LINK TRAVEL TIME MODELS

The so-called sandglass travel time models divide travel time into two parts: undelayed travel time and deterministic queuing delay. The name sandglass model derives from the image of sand flowing through an hourglass as an analogy for a vehicle queue discharging at an intersection. Usami, Ikenoue, and Miyasako (1986) were the first to propose a sandglass type of travel time model for an oversaturated link. In their formulation, a congested link was divided into sections, where there is no inflow of vehicles from external sources nor outflow to other roads. Travel time for a link is the summation of travel times in each section. For the uncongested section, travel time is calculated using a constant speed; for congested sections, travel times are the deterministic queuing delays. These delays are expressed as functions of link length, traffic volume, and traffic spacing:

$$T_C = \sum_i (L_i / H_i)(1/Q_i) \tag{16}$$

where

T_C is the portion of link travel time on the congested sections (in seconds);

L_i is the length of congested section i (in meters);

H_i is the average spacing in congested section i (in meters/vehicle); and

Q_i is the traffic volume of congested section i (in vehicles/second).

Considering the inverse of average spacing is density, and density over volume is the inverse of space-mean speed, Eq. (16) is identical to:

$$T_C = \sum_i L_i / U_i \tag{17}$$

where

U_i is the space-mean speed of congested section i.

Usami and his collaborators further assumed that the density of section i is a linear function of its flow,

$$(1/H_i) = K_i = k_m - wQ_i \tag{18}$$

yielding the following formula:

$$T_C = k_m \sum_i (L_i / Q_i) - w \sum_i L_i \tag{19}$$

where k_m (jam density, in vehicles/meter) and w (travel pace, in seconds/meter) are two model parameters.

Calibration using travel time data obtained by license plate survey yielded k_m and w values of 0.107 vehicles/meter and 0.181 seconds/meter, respectively.

Once the parameters k_m and w are known, the estimation of travel time using equation (19) requires the knowledge of the vehicle queue $\sum_i L_i$, and traffic flow Q_i on each congested section. Traffic detectors are assumed to be present in each section to measure traffic volume, occupancy, and speed. Both speed and occupancy are used to decide if a section is congested, and queues for congested sections are estimated (how this is carried out was not indicated). The model was evaluated using travel time data collected from a license-plate-matching survey. Relative mean square errors in the range of ten percent to 19 percent were reported.

Takaba et al. (1991) further tested the sandglass travel time model proposed by Usami and his colleagues on a congested arterial in Tokyo. They collected detector data and measured both travel times and queue length from field surveys. The travel times estimated by the sandglass model closely matched the measured travel times. The relative estimation error was reported to be within 14.4 percent to 24.5 percent.

In the same paper, Takaba et al. (1991) extended the sandglass model by further decomposing the travel time on a congested section into two parts: running time L_i / v and delay time D_i, where L_i is the queue length and v is the traffic running speed in a congested section. The delay time is calculated as the summation of delay in each cycle over the number of cycles needed to discharge the queue,

$$\begin{aligned} D_i &= d_i \times m_i \\ &= (C - G_i) \times (k_m \frac{L_i}{Q_i C}) \\ &= (C - C\frac{Q_i}{s}) \times (k_m \frac{L_i}{Q_i C}) \end{aligned} \tag{20}$$

where

d_i is delay time per cycle;

m_i is the number of cycles while vehicles run through section i;

C is cycle length;

G_i is effective green time;

k_m is jam density;

L_i is queue length;

Q_i is flow volume; and

s is saturation flow rate.

The link travel time is now the summation of undelayed travel time, running time, and delay time:

$$
\begin{aligned}
T_i &= D_i + L_i / v + (L_i^0 - L_i) / v_a \\
&= k_m \frac{L_i}{Q_i} - L_i\left(\frac{k_m}{s} - \frac{1}{v}\right) + \frac{L_i^0 - L_i}{v_a}
\end{aligned} \tag{21}
$$

where v_a is the travel speed in an uncongested section, and L_i^0 is the length of section i.

The structure of this model is similar to the sandglass model. In fact, if one sets $(k_m / s - 1/v)$ to the parameter w, the congested component of T_i is identical to the sandglass model. To apply this model, jam density, saturation flow rate, and running speed are estimated and then traffic volume and queue length are collected. The same data set used to evaluate the sandglass model was applied to test the new model, with a reported relative error within 11.5 percent to 24.2 percent.

Sandglass models are capable of estimating both link and route travel times, and the accurate travel time estimates reported in the validation tests are encouraging. These models, however, are not without limitations: they are more applicable to heavily congested arterials than arterials with regular traffic conditions, and the presence of queue length in the models may hinder their applicability because it is as difficult to collect or estimate queue length as to collect or estimate travel time.

LINK TRAVEL TIME ESTIMATION BASED ON PATTERN MATCHING

Bohnke and Pfannerstill (1986) proposed a pattern recognition approach for estimating travel times using loop detectors. This approach recognizes that each type of vehicle produces a unique signature (a voltage signal) on an inductive loop detector when passing through its detection zone. A sequence of such signatures extracted from an upstream detector is compared with successive sequences of signatures extracted from a downstream detector to find two sequences with the most matches. The time shift between these two sequences is the average travel for the platoon of vehicles that form the signature sequence from upstream.

In addition to estimating travel times, this approach can also estimate traffic density and space mean speed. To use this method, however, the detector data have to be polled at a much higher frequency than is usually the case in practice. This means that an additional signal processing unit in the controller cabinet may be required to process those data and perform pattern matching. Because it does not relate travel time to other traffic measurements such as volume or occupancy, this method cannot be used to predict travel times. Moreover, its accuracy deteriorates when there are traffic sources or sinks at points mid-block between the two observation points. An attractive feature of the pattern recognition approach, though, is that it does not depend on site-specific parameters such as traffic signal settings or intersection geometry and can therefore be applied in the same manner to any type of intersections.

BPR-TYPE LINK TRAVEL TIME MODELS

Another family of travel time models is the BPR type. These models have been widely used in transportation planning, particularly traffic assignment, as well as intersection studies. The actual Bureau of Public Roads (BPR) model consists of free-flow travel time and intersection delay (BPR 1964):

$$t = t_0\left(1 + \alpha\left(\frac{q}{c}\right)^{\beta}\right) \tag{22}$$

where

t is link travel time,

t_0 is free-flow link travel time,

q is link flow,

c is the capacity of the link, and

α and β are two model parameters (usually $\alpha = 0.15$ and $\beta = 4.0$ are used).

Davidson (1966) proposed a travel time function that is similar to (22) but has the property that travel time is asymptotic to flow capacity, an key property in traffic assignment. Davidson's travel time function is as follows:

$$\begin{aligned} t &= t_0\left(1 + J\frac{q}{c-q}\right) \\ &= t_0\left(1 + J\frac{x}{1-x}\right) \end{aligned} \tag{23}$$

where J is a model parameter and $x = q/c$ is called the volume/capacity ratio.

Both the BPR model and Davidson's model require only traffic flow as input to the model. The other parameters, including free flow travel time and capacity, are relatively easy to obtain. The only parameters that must be calibrated with travel time data are the α and β in the BPR model and J in Davidson's model. Rose and Raymond (1991) and Rose, Taylor, and Tisato (1989) have discussed some of the issues in estimating parameters for Davidson's model. Although the simplicity and ease for calibration of these two models are appealing, their predictions represent long-term averages that are more suitable for planning applications than for real-time traffic management applications. Moreover, Davidson's model breaks down when the volume/capacity ratio exceeds one.

Akcelik (1978) extended Davidson's model by adding a linear segment in the travel time-volume curve at a properly chosen volume/capacity point (x_c) to take account of delay under oversaturated conditions. His travel time-volume curve contains two segments: a nonlinear segment given by Davidson's model when x is below x_c, and a linear segment that is tangent to the nonlinear segment at x_c. The Highway Capacity Manual (HCM) also gives a similar procedure for calculating intersection signal delays (Transportation Research Board 1994, pp. 11.7–11.17). Both of these procedures tend to produce unreliable estimates at high volume/capacity ratios (the HCM recommends that caution should be taken when using HCM delay procedures at volume/capacity ratios higher than 1.2).

REVIEW SUMMARY

We have reviewed arterial travel time estimation models commonly found in literature and practice. These models employ diverse techniques (e.g., require different data inputs. Some require register time, occupancy, and green splits, while others require queue length and flow rate. These different techniques also apply to different ranges of traffic conditions (e.g., oversaturated conditions for sandglass models but moderate traffic conditions for regression models with occupancy under 90 percent). All of these factors make a quantitative comparison of these models almost impossible, so we summarize them qualitatively instead.

Perhaps the approach with the greatest potential is pattern matching. This approach does not depend on site-specific parameters such as intersection layout and traffic signal timing, so its models have greater transferability than other models. It could provide accurately measured travel times for individual vehicles or platoons of vehicles in large quantities within a reporting interval (e.g., five minutes). Because this approach depends on vehicle signatures from detectors, some hardware changes in the local controllers may be needed to collect and process detector data at the desired rate. Its algorithm is also necessarily more complex than most other approaches. The quality of travel time estimates provided by this approach and a lesser need for recalibration when applying them to different sites, however, may more than offset this additional cost.

The dynamic input-output models have properties similar to those of the pattern-matching models. As such, these models also require higher sampling rates of detector data, usually in the range of one to five seconds to produce accurate estimates. Because input-output models, like the pattern matching models, do not require travel time data for model calibration (travel time data are used for model validations), only a limited amount of travel time data is needed. The performance of the input-output models degrades when major traffic sinks and/or sources are present between the input and output measurement points. These models are therefore best suited for estimating arterial link travel times rather than route travel times.

Although the treatment of traffic flow in sandglass models is simplistic, the results reported from the limited evaluation of these models are encouraging. The structure of the sandglass models is simple, and the models involve only a few parameters that can be easily collected from field surveys. Also, sandglass models do not require travel time data to calibrate parameters, which will save data collection cost. The application range of these models is limited (i.e., only heavily congested traffic). A more severe limitation, however, is the necessity for queue length as an input, where queue length is almost as difficult to estimate or measure as travel time.

The BPR-type models are the simplest among those reviewed. Because they typically have only one or two parameters, the calibration of such models is a straightforward task. On the other hand, BPR-type models are also the most coarse in terms of accuracy. They do not consider the dynamic changes of traffic flow and traffic control or other travel time estimation models and therefore are more suitable for estimating long-term averages of travel times used in planning, rather than for estimating dynamic travel times used in real-time traffic management.

Diverse among themselves, regression travel time models are primarily differentiated by the inputs they use. These inputs range from register time at the microscopic level to occupancy at the macroscopic level. The major advantage of the regression models is also a liability. Various factors that affect travel time can be easily incorporated, but this also makes them more location-dependent.

Considering the availability of data from current traffic control settings, the regression-type models are perhaps the only option in a short-term solution to the arterial travel time estimation problem. The review indicates that all the regression models are link-specific and calibration and validation are limited. Their performances are also less than satisfactory. To significantly improve these models or develop new regression models, we need to build a more extensive travel time database.

DATA COLLECTION

The literature review makes clear the importance of an accurate and complete travel time database whether one is evaluating the applicability of existing models for estimating arterial travel times in the Minneapolis/St. Paul area or developing improved travel time estimation models. It is practically impossible to develop a database that accommodates the data needs of existing models because of these models' diverse data requirements and different application ranges as well as the practical limitations of traffic control hardware setup and project resources. We collected as much information as possible under these limitations.

As our review indicates, travel time on arterials is influenced by a multitude of factors: traffic demand, intersection and road layout, traffic signal settings, driver characteristics, traffic composition, lane movements, and so forth. Considering the importance of each of these factors and the resources at our disposal, we decided that information related to travel time, link and intersection layout, traffic signal timing and traffic demand should be collected for a selected route in the Minneapolis/St. Paul area. A data collection plan was subsequently developed and the data collection was carried out from July 15 to July 26, 1996. The following sections describe the data collection process.

DEVELOPMENT OF A DATA COLLECTION PLAN

Candidate sites and route selection

The major factors in selecting the route for this research include traffic demand levels of the route, representativeness of the route, and the availability of detectors and types of data that can be obtained from the detectors. Three different sites were recommended by Mn/DOT traffic engineers in charge of signal operations. They are 1) Trunk Highway (TH) 61 from I–694 to County Road E in Vadnais Heights, Minnesota, 2) TH–13 from Nicollet Avenue to County Road 11 in Burnsville, Minnesota, and 3) Snelling Avenue from County Road C to Lydia Avenue in Roseville, Minnesota. All three routes have loop detectors installed at intersections along each route and can be monitored by the Mn/DOT central computer.

TH–61 in Vadnais Heights. The Vadnais Heights route is approximately 2.5 miles long and has five intersections equipped with the Traconex controller system. Most intersections in this route are three-approach T-intersections and the southern boundary included one construction site.

TH–13 in Burnsville. The Burnsville location is approximately two miles long and has four intersections which could be used for data collection. All the intersections are typical four-approach intersections equipped with the Econolite signal controllers. The field study showed that the traffic demand for this route was relatively low even during the peak periods.

Snelling Avenue in Roseville. The Roseville route is approximately two miles long and has three typical four-approach intersections equipped with the Econolite signal controllers. The south boundary, County Road B2, included a construction section which left only one lane open.

After consultation with Mn/DOT traffic engineers and field inspections on each of the three sites, it was decided to use the Snelling Avenue route for data collection. This route represents the typical urban arterial route and has substantial peak hour demand that often results in oversaturated traffic conditions at the intersections. Highway 61 and Highway 13 were both rejected as data collection sites primarily because they do not have sufficiently high demand to develop congestion. The detector configuration at the controller was also an important consideration in rejecting the Highway 13 route.

Figure 1 presents a sketch of the selected site with proper dimensions. This site consists of three intersections: County Road C, County Road C2, and Lydia Avenue, bounded by Glenhill and County Road B2. The three intersections form Control Zone 215, which is coordinated by a master controller located at the intersection of County Road C and Snelling Avenue. Each approach to each of the three intersections is detectorized. Detector data can be downloaded from the master controller at 15-minute intervals or directly from the local controllers at shorter intervals. Appendix B shows the detailed intersection and detector layout of the selected route.

Data collection period

The primary objective for the data collection effort is to obtain a representative set of link travel time, traffic signal timing, and traffic flow for developing and evaluating link travel time estimation models. A shorter but more intensive data collection effort is preferable as long as enough representative samples are collected to perform model calibration and validation. It was therefore decided to collect data for ten weekdays over two consecutive weeks. This would generate enough data points for our research and also allow us to examine to some degree the travel time variations across days. To cover a wide range of traffic conditions, two data collection time periods in each day were selected based on historical traffic flow patterns: a morning period from 6:00 AM to 9:00 AM, which encompasses the morning peak period and portions of the nonpeak period in the morning, and an evening period from 3:30 PM to 6:30 PM, which includes the evening peak period and some nonpeak portions of the evening.

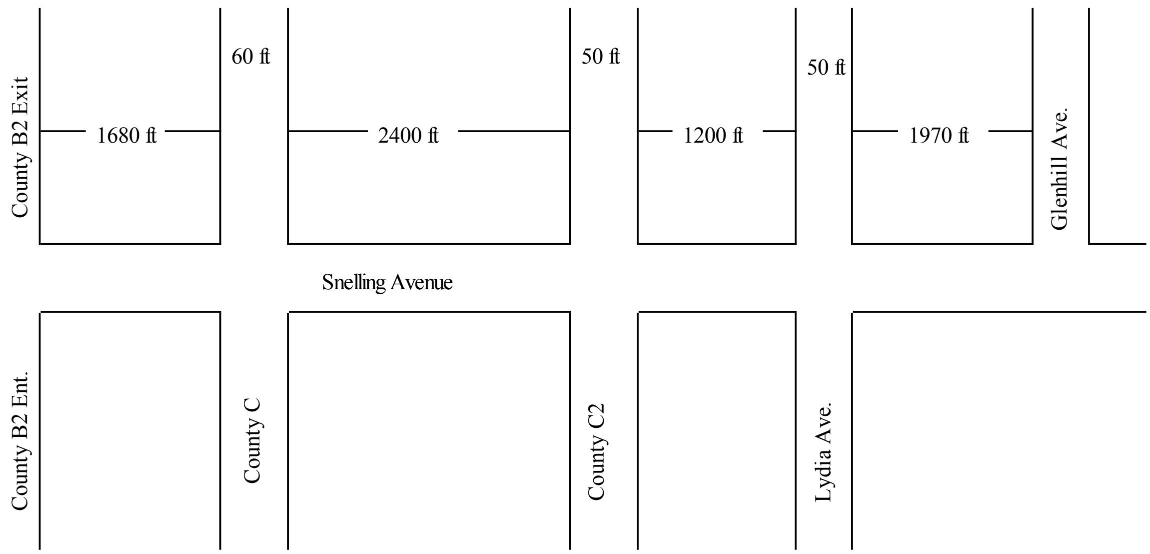

Figure 1: Selected site along Snelling Avenue

Data types and collection procedures

Geometric data. Geometric data include the length of the links and right and left turn bays, intersection and road layout, numbering and location of detectors, lane channelization, and other special features such as lane closures during road construction. Those data were obtained from Mn/DOT design maps, signal design plans, and field inspections.

Travel time data. Travel time data include the link travel times for each link, collected at various times in the data collection period. A number of methods can be used to collect travel time data: one is the floating car method, and another is the license plate matching method. The former requires that a person drive through a road section and record the actual time it takes to cover this section, while the latter requires two or more persons stationed at two points on a road to record a vehicle's license plate number and the time this vehicle passes that observation point. The license plate numbers recorded from the two observation points are matched and their associated times are subtracted from each other to obtain travel times. Each method has its own advantages and disadvantages. The floating car method requires less manpower (typically a driver and a recorder) and can acquire both running time and stopped delays, but collects fewer samples in a given period of time per floating car. License plate matching, on the other hand, can collect many more travel time samples (the number of samples equals the number of matched plate numbers) in a given period of time, but requires more manpower and cannot differentiate running time and delay time. We adopted the floating car method to collect link travel time because it is relatively easy to carry out and it can collect delay time at intersections (believed to be the major contributor to link travel time variations).

It is important that sufficient samples of travel time data (used to average detector outputs) be gathered during each time interval to ensure that the sample average is representative of the average travel time during that interval. Although it is always desirable to have more observations by deploying more floating cars, this is not always financially feasible. In Phase I of our study, we tried to maintain a balance between the number of observations needed and the cost of obtaining them. The number of floating cars required in the data collection effort depends on the number of observations needed, round trip time, data aggregation interval, and travel time fluctuations. After carefully considering all these factors, we decided to use four cars to measure travel time. Test runs showed that it takes on average about five minutes to make a round trip on the selected route, so that each floating car could make three observations (on average) during every 15-minute interval (one observation every five-minute interval), and four floating cars could obtain 12 observations during every 15-minute interval (four observations every five-minute interval).

To ensure a more or less uniform sampling of travel times in the data collection period, we established the following spacing rule between the floating cars: depart at a time headway of average round trip time divided by the number of floating cars. In this study, this rule gives a spacing of five minutes for every four cars, or one minute and 15 seconds. Because of the stochastic nature of travel times, it is difficult to maintain such a spacing for a long period of time. To avoid clustering of floating cars (which would give a biased sample of travel times), the spacing is reestablished every hour at the starting point.

Two people are on board each vehicle during data collection. One drives the vehicle along the route and the other uses a stopwatch to record the time as the vehicle passes designated control points or encounters special events. Those control points include the clearance point of an intersection (as shown in Figure 2) and the first stop the vehicle makes before an intersection. The drivers are instructed to drive at the pace of the traffic stream on any of the two through lanes, subjective to their own judgment. The recorders are asked to record times for each direction of travel and any events that cause the vehicle to stop (e.g., red lights at signals, accidents, and so forth). Specifically, the following data are collected:

- clock time at the beginning of the test section (i.e., 10:30:32),
- time when a vehicle clears an intersection,

- time when a vehicle stops due to a traffic signal or special event (e.g., an accident),
- cause of vehicle stopping (i.e., a traffic signal), and
- trip number, date, and weather conditions.

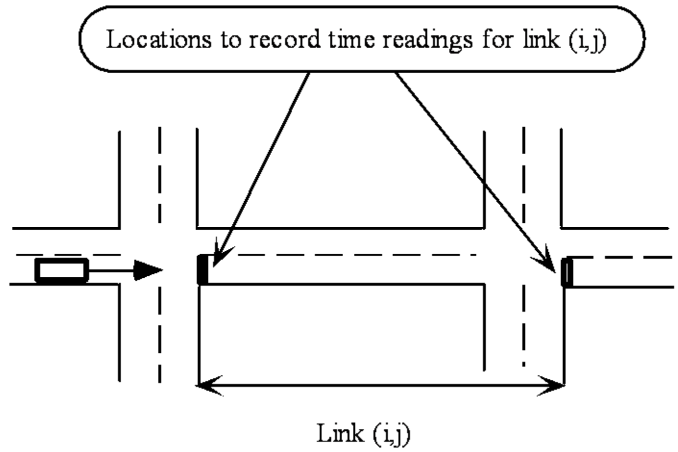

Figure 2: Travel time collection control points

Detailed instructions for the data collection protocol are given to the data collection crew. A travel time data collection sheet was also designed to aid the data collection effort. Its format is shown in Appendix A.

Traffic flow data. The following traffic flow data were to be collected:

- volume and occupancy data from existing loop detectors, and
- right turn volumes, left turn volumes not covered by existing loop detectors and volumes at both boundaries.

The turn volumes and boundary flows are counted manually at five-minute intervals. Each intersection except County Road C is counted by two observers, one for left turns and one for right turns. The right turns at County Road C are counted by one observer, as is each boundary. Data collection sheets are designed for each location and the observer at that location marks in the appropriate box on a data sheet for each turning vehicle at an intersection or passing vehicle at a boundary. The marks are counted at the end of each data collection period to obtain the five-minute traffic volumes.

Detector occupancy and volume outputs are downloaded from local controllers. Due to hardware limitations, five-minute interval data are currently available from existing loop detectors. The following sections briefly describe the available data from the local controllers and the manual downloading procedure (Econolite Control Products 1987).

The detector log stores the vehicle counts and occupancy data at the loop detectors at an intersection. There are four time intervals that can be selected for gathering this data: 5, 15, 30, and 60 minutes. Every individual controller logs the counts and occupancy of its assigned local detectors in its circular memory, which will be overwritten after a period of time. The length of time volume counts are stored in the individual controllers is determined by the number of detector inputs assigned to be logged. For instance, if a controller is logging 16 detectors for 24 hours at five-minute intervals, then its memory will be filled in approximately 30 hours. So, if the data is not downloaded from the controller, it will be lost in a first-in/first-out manner (i.e., the oldest data are overwritten by the latest). Any ASC/2 controller can log up to 32 local detectors, some of which are assigned as system detectors. Assignment of detector logging is done through Zone Monitor software, and there can be up to 32 local detectors from all the intersections in a zone assigned as system detectors. Only the counts and occupancy data of these system detectors are reported to the main computer via telephone lines. The local detector data for individual intersections have to be downloaded directly through a null modem at the controllers. If downloading the counts locally from the controllers, the time interval can be set to five minutes. This is not possible if data are downloaded using Zone Monitor IV. The local downloading procedure is as follows:

1) Connect a laptop to a local controller through a null modem cable.

2) Run the *Terminal* software on the laptop windows. Set the communication parameters to be the same as that of the controller. Choose *Receive Text File* from the *Transfer* menu. Give the file a name.

3) Press the *MAIN MENU* button on the controller's front panel.

4) Select option 8 to go to the submenu *UTILITIES*.

5) Select option 6 from the submenu to go to the submenu *BUFFER*.

6) Select option 2 from the submenu to go to the submenu *PRINT*.

7) Select option 3, *DETECTOR ACTIVITY LOG* to print to the RS232 port.

8) The data will be displayed on the laptop's screen. Stop the transfer when it is completed.

The five-minute interval detector log contains the volume and occupancy for an intersection provided by all the local detectors assigned to the controller of that intersection. For instance, the County Road C and Snelling Avenue intersection has 13 detectors assigned for logging. The detector log for that intersection therefore consists of volume and occupancies for those 13 detectors.

The detector log does not explain which count is from which local detector, but reports the volume and occupancy in a numbered sequence. To relate a number in a detector log to any of the local detectors of an intersection, one must refer to a database in Zone Monitor IV, where the assignment of local detectors is given in a chart similar to the one shown in Table 1.

Table 1. Correspondence of sensor numbers to detector log numbers

	Sensor numbers		
Detector log number	County Road C	County Road C2	Lydia Avenue
1	D1–1	D1–1	D1–1
2	D2–1	D2–1	D2–1
3	D3–1	D3–1	X
4	D4–1	D4–1	D4–1
5	D5–1	D5–1	D5–1
6	D6–1	D6–1	D6–1
7	D7–1	D7–1	X
8	D8–1	D8–1	D8–1
9	D2–2	D2–2	D2–2
10	D4–2	D4–2	D4–2
11	D5–2	D4–3	D4–3
12	D6–2	D4–4	D6–2
13	D8–2	D6–2	D8–2
14	X	D8–2	D8–3
15	X	D1–2	D8–4
16	X	D3–2	X

Signal timing data. Signal timing is an important factor in travel time estimation. Signal timing parameters such as offsets and green splits directly influence the delays experienced by vehicles. Ideally, we should collect all the necessary information about the signal settings, including the control logic, control parameters, and actual green splits. Due to controller hardware and software limitations, however, much important information such as the actual phasing and green time cannot be obtained. The only two signal parameters we can collect that respond to traffic changes are cycle length and offset time. Because the system is running in a traffic-actuated coordinated mode, the actual splits can deviate from the designated split times. The others are nominal parameters including minimum green, maximum green, yellow time and clearance time for each phase, all of which are preset in the controller.

All three intersections in the data collection site are under traffic-responsive control. The traffic control plans are generated according to a traffic condition index called Computed Level (CLEV). Because this parameter is a function of traffic volume and occupancy, it may be a good indicator for travel time changes, and for this reason is included in the database.

The aforementioned signal timing data can be extracted from the event log of the master controller. The following section explains the procedure for collecting the signal timing data from the Econolite control system (Econolite Control Products 1987).

Event reports represent the behavior of the signal. The traffic engineer can set different alarms and events to be reported back to the main computer through event reports. Upon detecting a failure, an alarm, or a requested event, the master controller stores that information in its memory. This data can later be automatically transmitted to Zone Monitor IV or can be uploaded manually by the traffic engineer. Events from each zone master reported to Zone Monitor IV are stored on the hard drive. A separate file is created for each zone for each day. Each report includes a three-character preamble to signify priority, time, date, and type of event. Different events and alarms are prioritized to reduce incoming calls from the zone master.

For our purpose, we need Event Report from the master controller through Zone Monitor so that we can determine when the master is running which timing plan (i.e., the values of offset, split, and cycle length at a particular instance in time).

The event reports we obtained reported only the program change events. Whenever the master controller switched to a different timing plan after calculating different parameters, the event was reported to the remote computer. At that moment, all the controllers (including the master) switched to new cycle length, offsets, and splits, depending on the traffic-responsive plan.

Let's take for example the following two lines found in an event report:

215..0637 07/17/96 AUTO PROGRAM CHANGE—CLEV 2 COFT A SPL/SF 1 ART

215..0637 07/17/96 IN-EFFECT PROGRAM CHANGE—TRP CYC 6 OFT 1 SPL 1 CYCL 75

using the following abbreviations:

CLEV	Computed Level
COFT	Computed Offset
SPL/SF	Split/Special Function
ART	Arterial
TRP	Traffic-Responsive Plan
CYC	Cycle
OFT	Offset
SPL	Split
CYCL	Cycle Length

The above example indicates that the master controller has calculated the level *2* and offset *average* for the current volume and occupancy. It is then switching to a *Traffic Responsive Plan* which has CYC value *6*, OFT value *1*, SPL value *1*, and CYCL *75*. If one looks in the master's signal timing database, one can find a match for the traffic-responsive plan with the above CYC, OFT, SPL, and CYCLE values. From that plan, one can obtain the exact values of these parameters in terms of percentages of the cycle length in seconds.

Most of the time the format of program change event is similar to the one explained above, although sometimes the master controller reports only the number of the selected traffic-responsive plan in the second line instead of reporting the different values for CYC, OFT, SPL, and CYCL. So, for instance, if the master controller reports data like this:

215..0637 07/17/96 AUTO PROGRAM CHANGE—CLEV 2 COFT A SPL/SF 1 ART

215..0637 07/17/96 IN-EFFECT PROGRAM CHANGE—TRP PLAN 30,

it means that every controller should switch to its own "Pattern 30" which can be found in the individual intersection's timing plan database where one can get the exact values of cycle length, offsets, and splits for that intersection at that moment.

DATA COLLECTION ACTIVITIES

Based on the data collection plan, 15 people were recruited to carry out data collection, starting from Monday, July 15, and continuing through Friday, July 26 (ten weekdays). Of those 15 people, four drove test cars, four recorded travel time, five counted turn volumes, and two counted boundary flows.

On July 11 and July 12 prior to the data collection, we held two training sessions to fill out necessary paperwork, familiarize the data collection crew with the project, assign data collection tasks, and instruct the crew about data collection protocols. At the end of the training, dry runs were made to give the data collection crew a warm-up and to detect any potential problems that might be encountered during actual data collection so that they could be corrected before data collection began. Handouts of data collection protocols in the form of questions and answers were also provided to the data collection crew for their reference. Examples of these handouts are included in Appendix A.

Data collection began on July 15th. All individuals involved in the data collection effort, including two graduate students, gathered at 5:45 AM in a parking lot near Snelling Avenue and County Road C to go over the data collection plan one more time, and to synchronize all the stopwatches to be used with the controller's clock. At 6:15 AM, the data collection crew started collecting data.

After the first day, a graduate student was assigned to monitor the data collection process. The data collection crew handed in all travel time and volume counts to this graduate student every day at the end of each three-hour data collection period. The graduate student checked the collected data randomly to spot possible errors. Sensor data were downloaded from each controller once per day by another graduate student with the help of Ray Starr, the Mn/DOT technical liaison for this project. The signal timing event log data was collected by the Mn/DOT signal operator, Bob Betts, and given to the project team. The geometric data for the test site were read from the detector maps provided by Mn/DOT, except when these distances were not available, in which case the data were measured at the site.

TRAVEL TIME DATABASE

Data processing

The collected data were processed at the University of Iowa and the University of Minnesota from August 1 to September 15. The University of Iowa team was responsible for processing the travel time and detector data, and the University of Minnesota team was responsible for processing the geometric, manual turn and boundary flow counts, and signal timing data. The UI team was also responsible for designing a database format and placing all the processed data in the designed database.

A total of 2,940 travel time records were collected: 1,470 records for each direction. Each record contains a sequence of times recorded at each control point and indicates causes of delays. The travel time records were double-entered onto an electronic medium, and thorough error checking was performed to ensure that all records were entered correctly.

The raw travel time data were then imported into Excel, and both link travel times and intersection delays were calculated. The data was sorted by travel time and delay time for each link to identify “bad” records. A record is considered “bad” if it has negative link travel times, link travel times under the time it would take to cover the links at a speed of 65 mph, or link travel times over ten minutes (a cutoff point is based on judgment). This results in the following cutoff points for unrealistically short travel times: 17 seconds on link B2–C, 25 seconds on link C–C2, 12 seconds on link C2–Lydia, and 20 seconds on link Lydia–Glenhill. Using the above criteria, a total of 241 bad records were identified, 133 from northbound data and 108 from southbound data. We checked the original travel time data sheets to determine whether the bad records were the result of electronic data entry error and found that all were due to recording errors made during data collection. Bad records were subsequently removed from the data set, leaving 1,337 travel time records for northbound, and 1,362 travel time records for southbound travel.

The calculated link travel times and delays were then averaged over five-minute intervals. The following rule was used to calculate average link travel time at an interval t : assuming that the recorded time at the upstream end of the link is t_1 and at the downstream end of the link is t_2 , if $t - 5 \le t_1 < t$ and $t - 5 < t_2 \le t$, then link travel time $T = t_2 - t_1$ is assigned to time interval t ; if $t - 5 \le t_1 < t$ but $t < t_2 \le t + 5$, we make a subjective judgment about which interval this link travel time belongs to. If $t_2 - t < t - t_1$, then the link travel time is assigned to interval t , otherwise it is assigned to interval $t + 1$. There are no cases in which t_1 and t_2 are more than one interval apart from each other; therefore, the cases in which $t_2 > t + 5$ are not considered.

A program was also written to convert the detector outputs into a standard format. The processed volume and occupancy data were imported into Excel and the detector log numbers associated with these data were replaced by the detector ID numbers using the correspondence in Table 1. The manual counts of right and left turns and boundary flow were also entered into Excel.

The signal event log generated by the master controller and a signal timing plan database provided by Mn/DOT were carefully examined to extract relevant signal timing information. Changes in signal timing patterns and cycle lengths were obtained from the event log, and signal parameters including cycle length, offset, minimum green time, yellow time, and the clearance time for each phase used by the signals during the data collection period were extracted directly from the signal timing plan database. Maximum green times and signal offsets, listed as percentages of the cycle length, were calculated from information about the various signal plans. For each phase, the maximum green times were calculated as follows:

FOR PHASES 1, 3, 4, 5, 7, and 8:

Max Green = (cycle length ∗ percentage of cycle) – yellow time – clearance time

FOR PHASES 2 and 6:

Max Green = (cycle length ∗ (percent of cycle + split extension)) – yellow time – clearance time

It should be noted that Lydia Avenue does not have a phase 3 or a phase 7. Each signal offset was calculated as follows:

Offset = cycle length ∗ offset percentage

Graphics were also created to express the geometric information of the data collection sites, which include intersection and road layout, detector numbering and locations, link lengths, and lane closures.

The database

After consulting our Mn/DOT technical liaison, Ray Starr, we selected Lotus, a computer spreadsheet program, to store all the data that had been collected. Two database formats were designed. One utilizes the workbook feature of Lotus to store data in separate worksheets within a workbook, according to data type and location (the workbook format); the other places all the data in one worksheet (the worksheet format). The workbook format database is easier to navigate through than the worksheet format database. The name for each piece of data in the workbook format is self-explanatory, while those in the worksheet format are encoded. On the other hand, the worksheet format allows easier access, for example, if one would like to perform a simple regression between different variables. (Although newer versions of Lotus allow users to reference variables across worksheets, this is not straightforward to novice Lotus users.) The worksheet format also allows more users to access the database using older versions of Lotus that do not support workbooks.

The following sections explain in detail the format and contents of the travel time database.

Workbook database. We begin with the workbook database format, which is organized in multiple worksheets in a Lotus workbook. The names of each worksheet appear on the top panel of the Lotus spreadsheet file. These names are listed in Table 2 in the same order from top to bottom table as they appear in the workbook from left to right.

Table 2. Names of worksheets in the workbook database

Worksheet name	Contents
General	General information about the database
Travel Time NB	Northbound (NB) travel times
Travel Time SB	Southbound (SB) travel times
Ave. Trav. Time	Average travel times in five-minute intervals for both NB and SB traffic
Vol Rd C	Volume collected at the intersection of Road C and Snelling
Vol Rd C2	Volume collected at the intersection of Road C2 and Snelling
Vol Lydia	Volume collected at the intersection of Lydia and Snelling
OCC Rd C	Occupancy collected at the intersection of Road C and Snelling
OCC Rd C2	Occupancy collected at the intersection of Road C2 and Snelling
OCC Lydia	Occupancy collected at the intersection of Lydia and Snelling
Signal Rd C	Signal timing data, intersection of Road C and Snelling
Signal Rd C2	Signal timing data, intersection of Road C2 and Snelling

A brief description of each worksheet is provided in the following paragraphs.

- ***General:*** general information, including comments about the database and geometric information (expressed in graphical format). There are seven figures in this worksheet (included in Appendix B). Figure B–1 shows the overall picture of the data collection route, marked with lengths of various links. Figures B–2 and B–3 show the geometric layout of the south boundary at County Road B2. It is important to note that the County Road B2 exit was closed during July 22–24 and in the morning of July 25. Figure B–4 depicts the geometric layout of the intersection at County Road C. It shows the direction of travel, allowable traffic movements for each lane, detector location and number, length of left turn bays, and distances of side roads to the stopline of the intersection. Figures B–5 and B–6 show the geometric layout of intersections at County Road C2 and Lydia, respectively. Both figures contain information similar to that in Figure B–4. Figure B–7 shows the layout of the north boundary at Glenhill. The distances of detectors to stoplines are also contained in these figures.

- ***Travel Time NB:*** original travel time data records for northbound traffic organized by date, time of day, and location. Two columns associated with each intersection are: arrival time and departing time. Arrival time refers to the time when a vehicle stops before the intersection, and departing time refers to the time when a vehicle clears the intersection.

Not all cells of an arrival time column have a data record because no data is recorded if a vehicle did not stop at an intersection; but each cell of a departing time column must have a record. Following the original record are the computed link travel times, which are calculated by subtracting the departing times at two intersections that define a link. Following the link travel times are the trip times, calculated by taking the difference of the departing times at the north boundary and the arrival times at the south boundary. Intersection delays are also included in this worksheet and are calculated by subtracting the arrival time from the departing time at an intersection. If no arrival time record is present in a cell (which means no stop), delay is treated as zero. The causes of delay are also included.

In this worksheet, dates are in a month/day/year format, and times are in an hour/minute/seconds format.

- ***Travel Time SB:*** original travel time records for southbound traffic, organized in the same manner as in the *Travel Time NB* worksheet.

- ***Ave Trav Time:*** computed five-minute average link travel times and delays for both northbound and southbound traffic organized by date, time interval, and average travel times and delays. Dates are in a month/day/year format, time intervals are in an hour/minute format, and average link travel times and delays are in seconds.

- ***Vol Rd C:*** traffic volume collected both manually and from detectors at County Road C. The data is reported in five-minute intervals. Each volume record is associated with the end time of the time interval (e.g., the volume collected from 6:00 to 6:05 is assigned to the interval 6:05 rather than the interval 6:00). The data is organized by date and direction of travel (i.e., *NB*, *SB*, *EB*, *WB*, in that order). For each direction, if the volume data in a column is produced by a detector group, the detector group's ID number is placed in that column for quick identification. Right turns obtained by manual counts are named *RT*, and left turns obtained by manual counts are named *Perm. LT*. The data for each direction always start from those of the left turn lane, then are followed by those of the inner through lane, the outer through lane, and the right lane. The unit of volume data is vehicles every five minutes.

- ***Vol Rd C2:*** traffic volume collected both manually and from detectors at County Road C2. The organization of the data in this worksheet is the same as in *Vol Rd C*.

- ***Vol Lydia:*** traffic volume collected both manually and from detectors at Lydia. The organization of the data in this worksheet is the same as in *Vol Rd C*.

- ***Vol Boundary:*** traffic volume collected manually at both the south and north boundaries.

- ***OCC Rd C:*** five-minute interval occupancy data at County Road C. The organization of this worksheet is similar to the organization of the volume worksheets, except that all the occupancy data were obtained from detectors. They are therefore named by the ID numbers of the detectors that produced them.

- ***OCC Rd C2:*** five-minute interval occupancy data at County Road C2. The organization of this worksheet is the same as that of *OCC Rd C*.

- ***OCC Lydia:*** five-minute interval occupancy data at Lydia. The organization of this worksheet is the same as that of *OCC Rd C*.

- **S*ignal Rd C:*** signal timing data for the intersection at County Road C. The data are reported in five-minute intervals so that they can be easily matched with other traffic data. This worksheet is organized by date, time interval, control zone, and intersection. The control zone parameters include computed level, computed offset, and COS, which are common to all three intersections in the same control zone (Zone 215, in this case). The signal timing data for each intersection include cycle length, actual offset, nominal parameters for each phase—minimum green, maximum green, yellow and clearance intervals, in that order. The naming convention is as follows: Road Name + Phase number + the name of the data. For example, CP3CLR represents the Clearance interval (CLR) of Phase 3 (P3) at County Road C (C), and LP2MAX represents the maximum green time of Phase 2 at Lydia. The data for each phase appear from left to right sequentially from Phase 1 to Phase 8. Note that the numbering of signal phases is in accordance with the numbering of the detectors and complies with the NEMA convention. The unit of all parameters that involve time is seconds.

- ***Signal Rd C2:*** signal timing data for the intersection at County Road C2. The organization of this worksheet is the same as that of *Signal Rd C*.

- ***Signal Lydia:*** signal timing data for the intersection at Lydia. The organization of this worksheet is the same as that of *Signal Rd C*.

Note that except for data fields (columns) in the General, *Travel Time NB* and *Travel Time SB* worksheets, all data fields in this database are named and these names appear in the row that is immediately above the data records. Only these names should be used when referencing data in formulas, macros or other analysis procedures.

This ends our description of the workbook database. Below is a brief description of the worksheet database.

Worksheet database (MnLink). The worksheet database format is much simpler than the workbook database format. It is comprised of two separate worksheets: one contains the same information as the General worksheet in the workbook database, and another contains the rest of the data, arranged in order by:

- date,
- time interval,
- average travel time and delay for each link for northbound traffic,
- average travel time and delay for each link for southbound traffic,
- boundary flow at B2 and Glenhill,
- volume and occupancy for each intersection organized by direction of travel (i.e., NB, SB, EB, WB, in that order), and
- signal timing data.

There are a number of columns (namely those for computed through volumes) that do not contain any data because of multiple counting of vehicles by detectors in left turn lanes.

All the data in this worksheet are reported in five-minute intervals. The unit is vehicles every five minutes for volume, seconds for travel time and delay, and percentage for occupancy.

Definition of ranges. To aid the quick access of data in the large worksheet database, all the fields are properly named. We also give names to various ranges of data that share common attributes, such as travel time data for northbound traffic. By referencing these range names of the database rather than physically highlighting the ranges, one can perform more quickly some of the database functions such as querying, finding, deleting and appending data records. Field and range names also make the referencing of data records in functions and macros a less daunting task in large databases. In the worksheet database, field names appear in the row immediately above the first data record. Their definitions are listed in Appendix C. The definition of range names and their corresponding column ranges are also listed in Appendix C.

The workbook database uses the same field names as the worksheet database for the same data. These field names appear in the row immediately above the first row of data. Anything above this row is intended to explain the content of the data more clearly and should not be used for data referencing. The fields in travel time worksheets that contain the original travel time data are not named. Because each worksheet is self-contained and easy to access, no ranges are defined for the workbook database.

NOTE: Missing data in both databases are reported by blanks. Therefore, blanks should not be treated as zeros.

SUMMARY

The primary goal of this two-phase research project is to develop a better travel time model for arterial traffic using information provided by inductive loop detectors in current installation patterns. In this report, we have attempted to summarize the findings of Phase I in three parts: literature review, data collection, and travel time database development.

Our literature review identified five approaches to arterial travel time estimation: regression, dynamic input-output, pattern matching, sandglass, and BPR. These approaches encompass a variety of travel time estimation models with diverse data requirements and application ranges. Despite the theoretical appeal of the pattern matching and dynamic input-output models, they have limited applicability to arterials where traffic surveillance systems cannot provide short interval traffic data. The sandglass models, like the pattern matching and input-output models, require traffic data (queue length) that cannot be accommodated by current surveillance systems. The BPR models, on the other hand, only need volume data (routinely supplied by loop detectors) but are not accurate enough for dynamic, short-term traffic management applications. Regression models, with their ability to take various factors into account, are the most practical considering the type of data provided by existing traffic surveillance and control systems. All regression models developed thus far are link-specific and the calibration and validation are limited. The need for further development of such models is evident from the review.

The literature review also showed clearly the need for a good travel time database. This study carried out a ten-day data collection effort on a segment of Snelling Avenue in Minneapolis. The data collection site has three four-leg intersections of typical detector layout. Travel time data were collected by four floating cars from 6:00 AM to 9:00 AM and from 3:30 PM to 6:30 PM; traffic flow and occupancy data gathered at five-minute intervals and produced by all the detectors were downloaded daily from local controllers; turn volumes not covered by detectors were counted manually; and signal timing data were extracted from the event log of the master controller during the data collection period. These data were processed and entered into spreadsheets. Two travel time databases using different Lotus formats were subsequently developed for the collected data.

PHASE II: LOOKING AHEAD

In Phase II of this research, we are using the data gathered in Phase I to develop improved arterial travel time models applicable to sites with similar geometric and traffic control features. As a first step, we have studied the travel time patterns over different observation periods. If travel time exhibited stable and distinctive patterns over a period of days, these patterns were used to provide a rough estimate of travel times. Next we examined how the observed travel time patterns were related to traffic flow and traffic control parameters such as traffic flow rate, occupancy, signal cycle length, green splits, and offsets. We also have derived secondary factors from these parameters and studied their relationships to travel times. For example, we used traffic flow, cycle length, green splits, and saturation flow rate to calculate volume/capacity (v/c) ratio; used offsets, green splits and cycle length to calculate greenband; then studied the effects of greenband and v/c ratio on travel times.

Major factors that affect travel time patterns having been identified; the remaining task is to develop a travel time model based on these factors. Our principle in specifying a travel time model is accuracy, simplicity, and transferability. The accuracy required of a model depends on its applications. In this project, the primary application of the travel time model is to provide information on congestion levels for arterial routes and to display this information on visual maps through a variety of media accessible to the public (e.g., the world wide web, information kiosks, and on-board vehicle guidance systems). It is therefore sufficient and necessary to divide travel time into a limited number of bands and focus on predicting the transitions of travel time from one band to another. Because field engineers usually do not have time to calibrate and fine-tune algorithms, models should not be made excessively complicated to effect an increase in accuracy that is only marginal. We therefore will use parameters from existing surveillance systems that are directly obtainable or that can be calculated from parameters that are directly obtainable. Also, we will choose the simplest model specification that does not compromise model accuracy. There are two ways to make a model transferable: one is to tune its parameters on-line, and the other is to extract site-independent information from site-dependent variables and use it to specify a model. The second approach has been used in this project, with some exploration of the first approach as time has allowed.

Upon completion, Phase II should provide a timely addition to Project Orion's arterial traveler information component, contributing to the efficient management of traffic congestion in the Twin Cities.

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APPENDIX A

DATA COLLECTION SHEETS AND INSTRUCTIONS

LETTER TO PARTICIPANTS

Dear participant:

Thank you for agreeing to participate in our traffic data collection project. The purpose of this project is to develop a database for future development of models to predict travel times on major streets. The ability to accurately predict travel times will allow traffic management centers to inform motorists about congested routes through radio broadcasts, Variable Message Sign displays, and In-vehicle Navigation Systems, so that motorists can make informed decisions about which routes to take.

Our data collection effort will involve three tasks: driving a vehicle on a designated route, recording how much time it takes for the vehicle to travel various links on the route using stopwatches, and counting how many vehicles at a given intersection turn left, go through, and turn right. Because the data you collect will be used in conjunction with data collected by traffic sensors during the same time period, it is extremely important for you to observe strictly all of the data collection protocols set forth in the attached document. For your participation, you will be paid $10/hour. As discussed earlier, you will collect traffic data for three hours in the morning and three hours in the afternoon for ten weekdays from July 15 to July 26. Taking account of preparation time before and after data collection in each day, your paid working hours are eight hours per day.

We will provide the vehicles and stopwatches used in the data collection. You will be required to obey all traffic rules and regulations while driving these vehicles and the vehicles are to be used for data collection only. They should be parked at the designated parking place every day when the data collection is done for that day. Whether you are driving a vehicle, recording travel time, or counting turn volumes, it will be important to observe safety rules and protect yourself from potentially hazardous situations.

To ensure the success of this project, it is extremely important for all participants to follow the work schedule exactly. If your plans change in any way, please inform us as early as possible.

Thank you for your participation.

Michael Zhang, Principal Investigator
Eil Kwon, Co-Principal Investigator

QUESTIONS AND ANSWERS FOR DRIVERS

Q: How should I drive?

A: It is extremely important to remember that the objective is not to show how fast you can drive or how many round trips you can make over a three-hour time period. Rather, it is to observe how much time it takes, on average, to traverse each segment of the road. It is therefore essential for you to pace yourself at the AVERAGE speed of the traffic stream (WITHOUT EXCEEDING THE POSTED SPEED LIMIT). In other words, you should "go with the flow" as you drive, trying not to beat traffic or slow traffic down around you.

Q: How far APART should the data collection vehicles be from each other?

A: The data collection vehicles should ideally be spaced at a time interval of ROUND TRIP TIME divided by NUMBER OF DATA COLLECTION VEHICLES. For example, if there are four vehicles and each takes an average of eight minutes to make a round trip, then their spacing should be two minutes. Such spacing is difficult to maintain over time because travel time will most likely be different for each vehicle, and there is a real chance that some of the data collection vehicles will catch up with each other at certain times. If that happens, you need to adjust your starting time at the return trip to the proper spacing established in the above formula. Do not slow down or speed up to adjust your spacing before you reach the end point in your current travel direction.

Q: Can I stop for a break during the three-hour data collection period?

A: Except for usual circumstances (such as illness or yielding to ambulances), you will be expected to drive the route without making any stops other than those required at intersections. If you have to stop driving because of an unusual situation, you should record on the data sheet when, where, how long, and for what reason you had to stop.

Q: Where should I park each day?

A: You will park the vehicle at the Traffic Safety, Health and Transportation Parking Ramp after each data collection period every day, and return the car key to the designated person at the Center for Transportation Studies.

Q: Who will fill the gas tank for the data collection vehicle?

A: The driver will be responsible for keeping the gas tank full for the data collection vehicle. We will provide a credit card in the vehicle for paying gas bills. You should ask for a receipt when you use the credit card to pay for the gas charge and leave the receipt in the vehicle. You should always keep the credit card in the vehicle. Any use of this credit card other than paying for gas for the data collection vehicle is strictly forbidden, and will be subject to penalties.

Q: What else should I do as a driver?

A: You should write down the mileage on the odometer reading sheets we provide you before you leave the parking ramp and after you return the vehicle to the parking ramp each day.

Q: What if I have an accident?

A: We hope this will never happen. But if you have an accident during data collection, contact the local law enforcement agency, and Dr. Kwon at the Center for Transportation Studies.

TRAVEL TIME DATA COLLECTION SHEET (Snelling Avenue) _____ of _____

MORNING COLLECTION

Date: ____________ Recorder: _________________________ Weather: _______________

SOUTHBOUND TRAFFIC		
Location	Time	Code
Glenhill		
Lydia		
Cnty C2		
Cnty C		
Cnty B2		

NORTHBOUND TRAFFIC		
Location	Time	Code
Cnty B2		
Cnty C		
Cnty C2		
Lydia		
Glenhill		

CODES:
A = stalled vehicle / accident
D = double parked vehicles
S = traffic signal
B = bus loading or unloading passengers
P = parked vehicles
W = pedestrians

TRAVEL TIME DATA COLLECTION SHEET (Snelling Avenue) _____ of _____

EVENING COLLECTION

Date: ____________ Recorder: _________________________ Weather: _______________

NORTHBOUND TRAFFIC		
Location	Time	Code
Cnty B2		
Cnty C		
Cnty C2		
Lydia		
Glenhill		

SOUTHBOUND TRAFFIC		
Location	Time	Code
Glenhill		
Lydia		
Cnty C2		
Cnty C		
Cnty B2		

CODES:
A = stalled vehicle / accident
D = double parked vehicles
S = traffic signal
B = bus loading or unloading passengers
P = parked vehicles
W = pedestrians

FLOW DATA COLLECTION SHEET (South Boundary) _____ of _____

Date: _____________ Recorder: ___________________________ Weather: ________________

Time	County B2			
	Northbound	Total	Southbound	Total

FLOW DATA COLLECTION SHEET (North Boundary) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

Time	Glenhill Avenue			
	Northbound	Total	Southbound	Total

FLOW DATA COLLECTION SHEET (Cnty C) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

Time	Snelling Avenue				County Road C			
	NB right turns	Total	SB right turns	Total	EB right turns	Total	WB right turns	Total

FLOW DATA COLLECTION SHEET (Cnty C2) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

Time	Snelling Avenue		County Road C2			
	NB right turns	Total	WB right turns	Total	WB right turns	Total

FLOW DATA COLLECTION SHEET (Cnty C2) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

Time	Snelling Avenue		County Road C2			
	SB right turns	Total	EB right turns	Total	EB right turns	Total

FLOW DATA COLLECTION SHEET (Lydia Avenue) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

Time	Snelling Avenue		Lydia Avenue			
	NB right turns	Total	WB right turns	Total	WB right turns	Total

FLOW DATA COLLECTION SHEET (Lydia Avenue) _____ of _____

Date: ____________ Recorder: _________________________ Weather: _______________

	Snelling Avenue		Lydia Avenue	
Time	SB right turns	Total	EB right turns	Total

APPENDIX B

GEOMETRIC INFORMATION ABOUT THE SITE

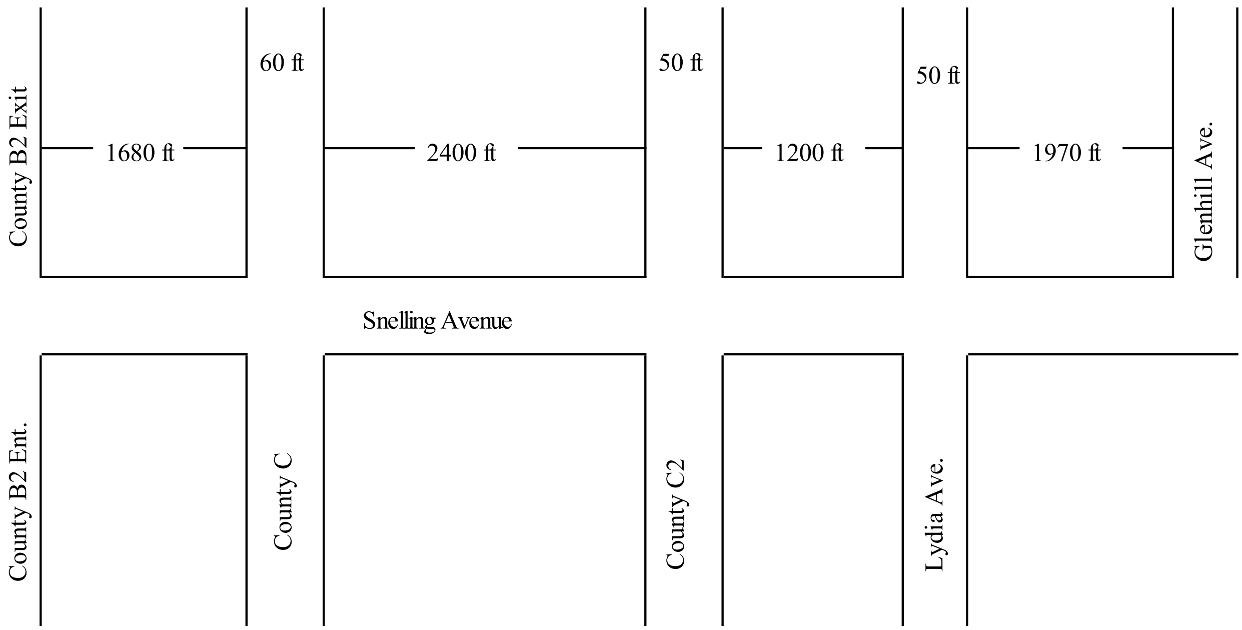

Figure B–1. Link lengths for the data collection route (Snelling Avenue from County B2 to Glenhill Avenue)

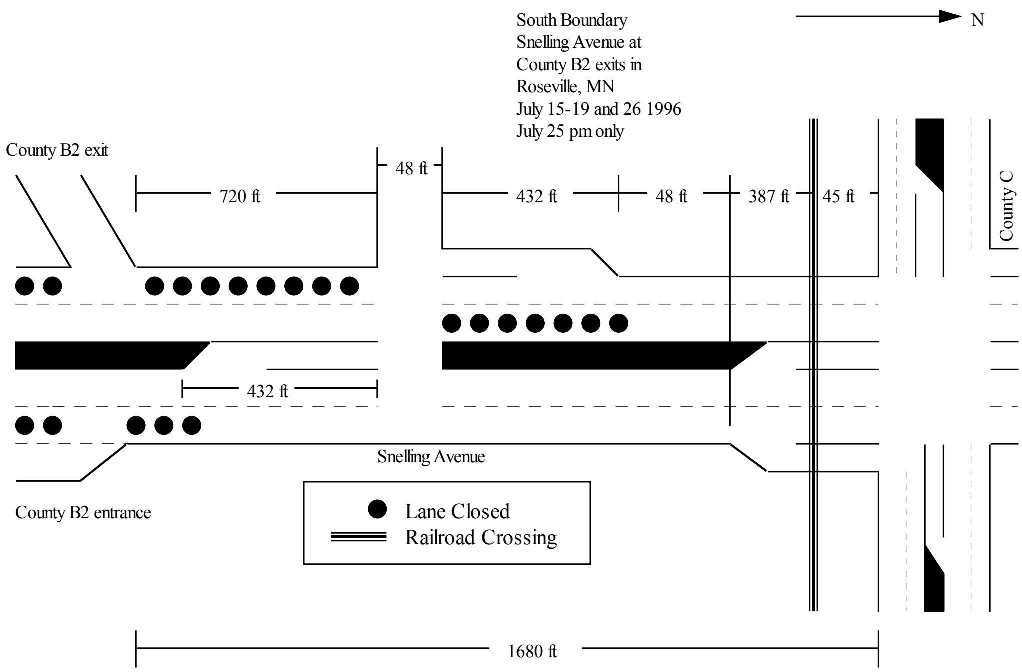

Figure B–2. South boundary at County Road C2, July 15–19, July 25 (afternoon only), and July 26

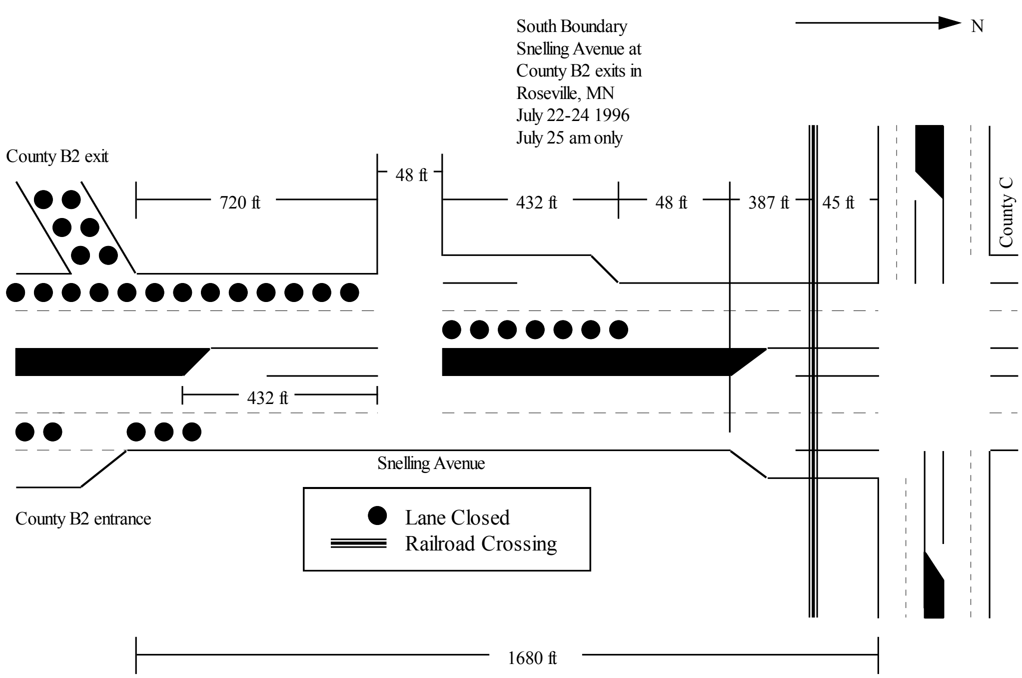

Figure B–3. South boundary at County Road C2, July 22–24 and July 25 (morning only)*

** NOTE: The County Road B2 exit was closed during July 22–24 and in the morning of July 25.*

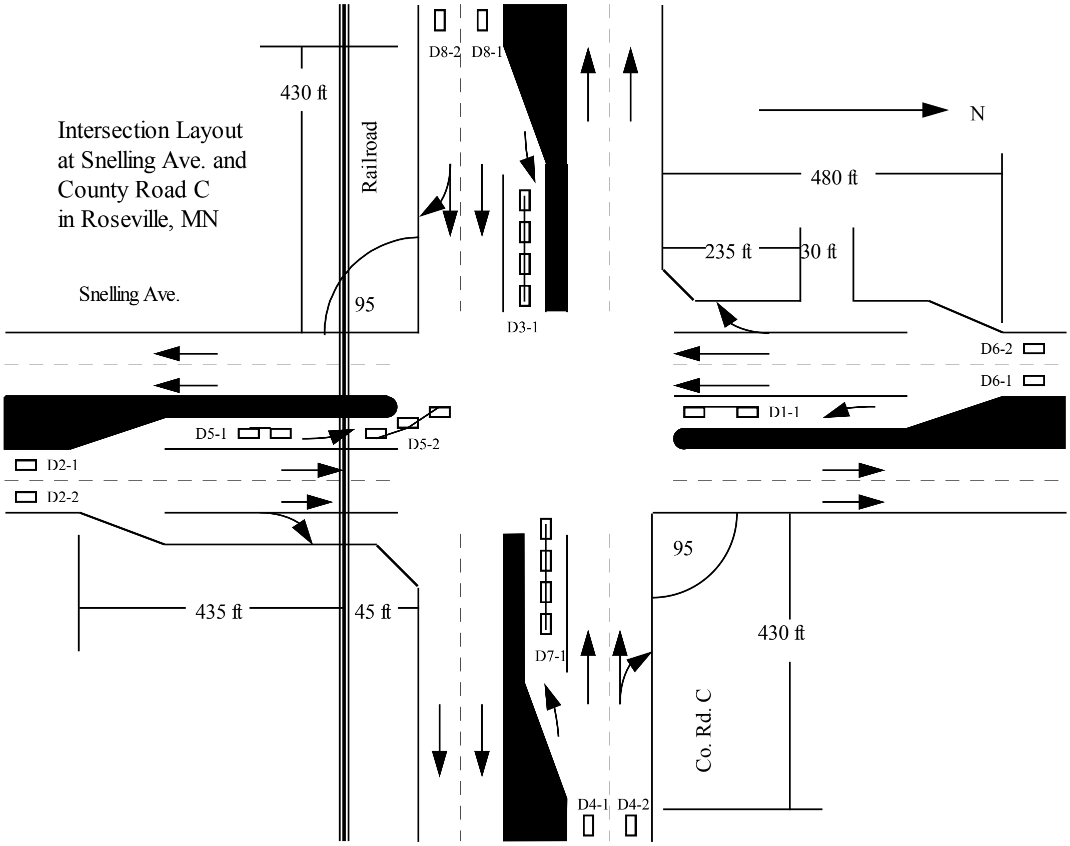

Figure B–4. Intersection at County Road C

Detector number	Distance from stopline
D1–1	10' AND 40'
D2–1	400'
D2–2	400'
D3–1	5'
D4–1	250'
D4–2	250'
D5–1	60'
D5–2	5'
D6–1	400'
D6–2	400'
D7–1	5'
D8–1	300'
D8–2	300'

Note: All sensors are 6'x6'.

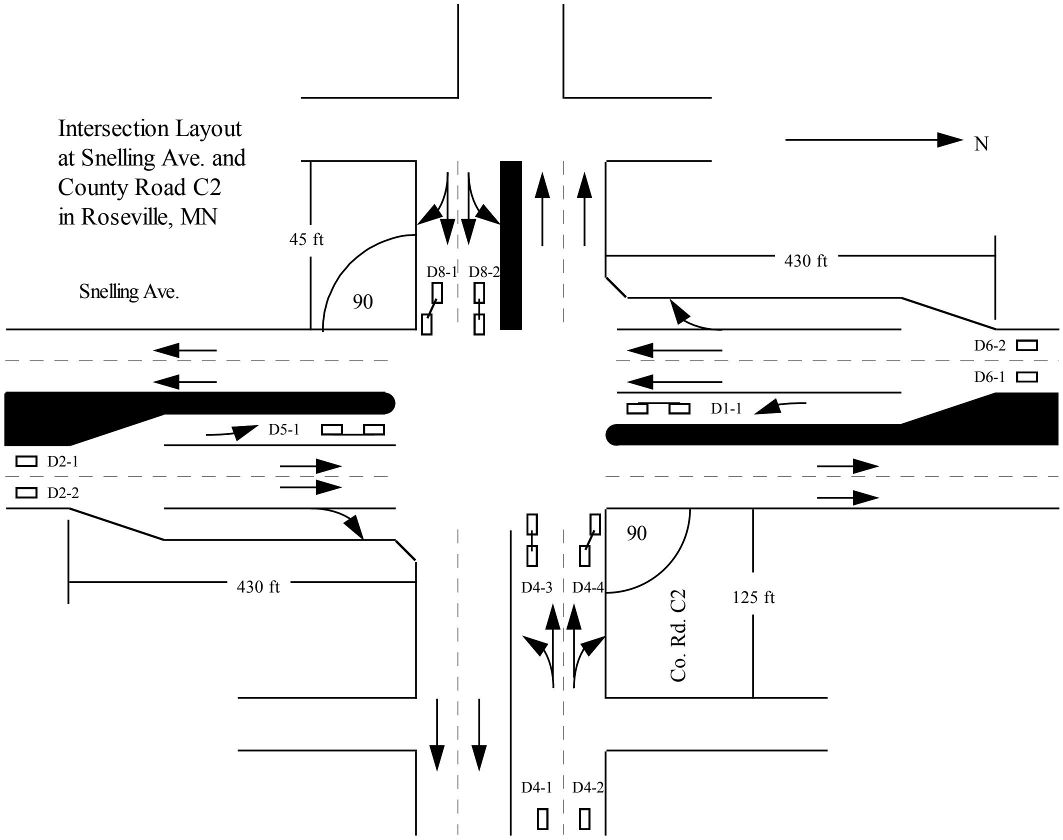

Figure B–5. Intersection at County Road C2

Detector number	Distance from stopline
D1–1	10' and 40'
D2–1	400'
D2–2	400'
D4–1	180'
D4–2	180'
D4–3	5'
D4–4	5'
D5–1	10' and 40'
D6–1	400'
D6–2	400'
D8–1	5'
D8–2	5'

Note: All sensors are 6'x6'.

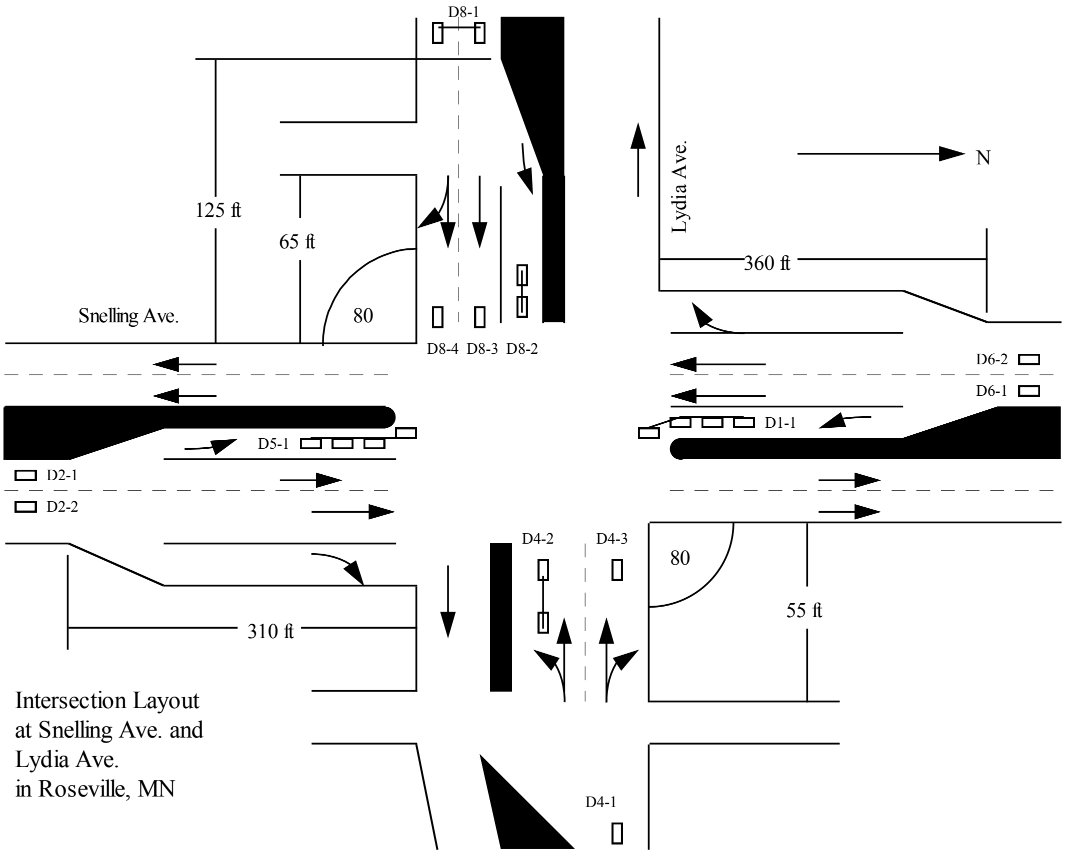

Figure B–6. Intersection at Lydia Avenue

Detector number	Distance from stopline
D1–1	5'
D2–1	400'
D2–2	400'
D4–1	125'
D4–2	0' and 27'
D4–3	0'
D5–1	5'
D6–1	400'
D6–2	400'
D8–1	125'
D8–2	0' and 25'
D8–3	0'
D8–4	0'

Note: D1–1, D2–1, D2–2, D4–1, D6–1, D6–2, D8–1 detectors are 6'x6'; D4–3, D8–3, D8–4 detectors are 6'x20'; D4–2, D8–2 detectors are 6'x20' at stopline and 6'x6' at other locations.

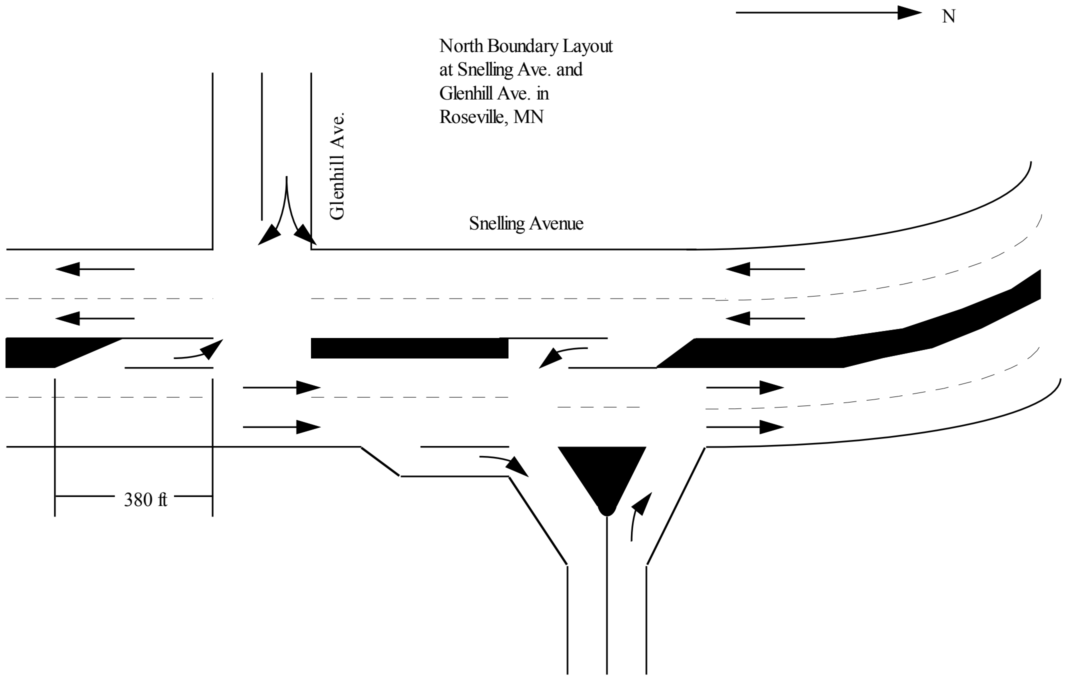

Figure B–7. North boundary at Glenhill Avenue

APPENDIX C

DEFINITIONS OF FIELD AND RANGE NAMES

FIELD NAME DEFINITIONS

Name	Definition
BEGTIME	Starting time of the 5-minute time period relating to the data
NTTB2TOC	Avg. 5-minute travel time for the NB link from County B2 to County C (in seconds)
NDEB2TOC	Avg. 5 minute delay time for the NB link from County B2 to County C (in seconds)
NTTCTOC2	Avg. 5-minute travel time for the NB link from County C to County C2 (in seconds)
NDECTOC2	Avg. 5-minute delay time for the NB link from County C to County C2 (in seconds)
NTTC2TOL	Avg. 5-minute travel time for the NB link from County C2 to Lydia Ave. (in seconds)
NDEC2TOL	Avg. 5-minute delay time for the NB link from County C2 to Lydia Ave. (in seconds)
NTTLTOG	Avg. 5-minute travel time for the NB link from Lydia Ave. to Glenhill Ave. (in seconds)
NDELTOG	Avg. 5-minute delay time for the NB link from Lydia Ave. to Glenhill Ave. (in seconds)
STTGTOL	Avg. 5-minute travel time for the SB link from Glenhill Ave. to Lydia Ave. (in seconds)
SDEGTOL	Avg. 5-minute delay time for the SB link from Glenhill Ave. to Lydia Ave. (in seconds)
STTLTOC2	Avg. 5-minute travel time for the SB link from Lydia Ave. to County C2 (in seconds)
SDELTOC2	Avg. 5-minute delay time for the SB link from Lydia Ave. to County C2 (in seconds)
STTC2TOC	Avg. 5-minute travel time for the SB link from County C2 to County C (in seconds)
SDEC2TOC	Avg. 5-minute delay time for the SB link from County C2 to County C (in seconds)
STTCTOB2	Avg. 5-minute travel time for the SB link from County C to County B2 (in seconds)
SDECTOB2	Avg. 5-minute delay time for the SB link from County C to County B2 (in seconds)
NBB2	NB 5-minute volume count at the County B2 boundary
SBB2	SB 5-minute volume count at the County B2 boundary
CDET21V	5-minute volume count from detector D2–1 at County C
CDET21O	5-minute occupancy from detector D2–1 at County C
CDET22V	5-minute volume count from detector D2–2 at County C
CDET22O	5-minute occupancy from detector D2–2 at County C
CDET51V	5-minute volume count from detector D5–1 at County C
CDET51O	5-minute occupancy from detector D5–1 at County C
CDET52V	5-minute volume count from detector D5–2 at County C
CDET52O	5-minute occupancy from detector D5–2 at County C
CDET61V	5-minute volume count from detector D6–1 at County C
CDET61O	5-minute occupancy from detector D6–1 at County C
CDET62V	5-minute volume count from detector D6–2 at County C
CDET62O	5-minute occupancy from detector D6–2 at County C

CDET11V	5-minute volume count from detector D1–1 at County C
CDET11O	5-minute occupancy from detector D1–1 at County C
CDET81V	5-minute volume count from detector D8–1 at County C

FIELD NAME DEFINITIONS—CON'T

Name	Definition
CDET81O	5-minute occupancy from detector D8–1 at County C
CDET82V	5-minute volume count from detector D8–2 at County C
CDET82O	5-minute occupancy from detector D8–2 at County C
CDET31V	5-minute volume count from detector D3–1 at County C
CDET31O	5-minute occupancy from detector D3–1 at County C
CDET41V	5-minute volume count from detector D4–1 at County C
CDET41O	5-minute occupancy from detector D4–1 at County C
CDET42V	5-minute volume count from detector D4–2 at County C
CDET42O	5-minute occupancy from detector D4–2 at County C
CDET71V	5-minute volume count from detector D7–1 at County C
CDET71O	5-minute occupancy from detector D7–1 at County C
CNBL	5-minute calculated NB left turn volume at County C
CNBR	5-minute collected NB right turn volume at County C
CNBT	5-minute calculated NB through volume at County C
CSBL	5-minute calculated SB left turn volume at County C
CSBR	5-minute collected SB right turn volume at County C
CSBT	5-minute calculated SB through volume at County C
CEBL	5-minute calculated EB left turn volume at County C
CEBR	5-minute collected EB right turn volume at County C
CEBT	5-minute calculated EB through volume at County C
CWBL	5-minute calculated WB left turn volume at County C
CWBR	5-minute collected WB right turn volume at County C
CWBT	5-minute calculated WB through volume at County C
C2DET21V	5-minute volume count from detector D2–1 at County C2
C2DET21O	5-minute occupancy from detector D2–1 at County C2
C2DET22V	5-minute volume count from detector D2–2 at County C2
C2DET22O	5-minute occupancy from detector D2–2 at County C2
C2DET51V	5-minute volume count from detector D5–1 at County C2
C2DET51O	5-minute occupancy from detector D5–1 at County C2
C2DET61V	5-minute volume count from detector D6–1 at County C2
C2DET61O	5-minute occupancy from detector D6–1 at County C2

C2DET62V	5-minute volume count from detector D6–2 at County C2

FIELD NAME DEFINITIONS—CON'T

Name	Definition
C2DET62O	5-minute occupancy from detector D6–2 at County C2
C2DET11V	5-minute volume count from detector D1–1 at County C2
C2DET11O	5-minute occupancy from detector D1–1 at County C2
C2DET81V	5-minute volume count from detector D8–1 at County C2
C2DET81O	5-minute occupancy from detector D8–1 at County C2
C2DET82V	5-minute volume count from detector D8–2 at County C2
C2DET82O	5-minute occupancy from detector D8–2 at County C2
C2DET41V	5-minute volume count from detector D4–1 at County C2
C2DET41O	5-minute occupancy from detector D4–1 at County C2
C2DET42V	5-minute volume count from detector D4–2 at County C2
C2DET42O	5-minute occupancy from detector D4–2 at County C2
C2DET43V	5-minute volume count from detector D4–3 at County C2
C2DET43O	5-minute occupancy from detector D4–3 at County C2
C2DET44V	5-minute volume count from detector D4–4 at County C2
C2DET44O	5-minute occupancy from detector D4–4 at County C2
C2NBL	5-minute calculated NB left turn volume at County C2
C2NBR	5-minute collected NB right turn volume at County C2
C2NBT	5-minute calculated NB through volume at County C2
C2SBL	5-minute calculated SB left turn volume at County C2
C2SBR	5-minute collected SB right turn volume at County C2
C2SBT	5-minute calculated SB through volume at County C2
C2EBL	5-minute calculated EB left turn volume at County C2
C2EBR	5-minute collected EB right turn volume at County C2
C2EBT	5-minute calculated EB through volume at County C2
C2WBL	5-minute calculated WB left turn volume at County C2
C2WBR	5-minute collected WB right turn volume at County C2
C2WBT	5-minute calculated WB through volume at County C2
LDET21V	5 volume count from detector D2–1 at Lydia Ave
LDET21O	5-minute occupancy from detector D2–1 at Lydia Ave
LDET22V	5-minute volume count from detector D2–2 at Lydia Ave
LDET22O	5-minute occupancy from detector D2–2 at Lydia Ave

LDET51V	5-minute volume count from detector D5–1 at Lydia Ave
LDET51O	5-minute occupancy from detector D5–1 at Lydia Ave

FIELD NAME DEFINITIONS—CON'T

Name	Definition
LDET61V	5-minute volume count from detector D6–1 at Lydia Ave
LDET61O	5-minute occupancy from detector D6–1 at Lydia Ave
LDET62V	5-minute volume count from detector D6–2 at Lydia Ave
LDET62O	5-minute occupancy from detector D6–2 at Lydia Ave
LDET11V	5-minute volume count from detector D1–1 at Lydia Ave
LDET11O	5-minute occupancy from detector D1–1 at Lydia Ave
LDET81V	5-minute volume count from detector D8–1 at Lydia Ave
LDET81O	5-minute occupancy from detector D8–1 at Lydia Ave
LDET82V	5-minute volume count from detector D8–2 at Lydia Ave
LDET82O	5-minute occupancy from detector D8–2 at Lydia Ave
LDET83V	5-minute volume count from detector D8–3 at Lydia Ave
LDET83O	5-minute occupancy from detector D8–3 at Lydia Ave
LDET84V	5-minute volume count from detector D8–4 at Lydia Ave
LDET84O	5-minute occupancy from detector D8–4 at Lydia Ave
LDET41V	5-minute volume count from detector D4–1 at Lydia Ave
LDET41O	5-minute occupancy from detector D4–1 at Lydia Ave
LDET42V	5-minute volume count from detector D4–2 at Lydia Ave
LDET42O	5-minute occupancy from detector D4–2 at Lydia Ave
LDET43V	5-minute volume count from detector D4–3 at Lydia Ave
LDET43O	5-minute occupancy from detector D4–3 at Lydia Ave
LNBL	5-minute calculated NB left turn volume at Lydia Ave
LNBR	5-minute collected NB right turn volume at Lydia Ave
LNBT	5-minute calculated NB through volume at Lydia Ave
LSBL	5-minute calculated SB left turn volume at Lydia Ave
LSBR	5-minute collected SB right turn volume at Lydia Ave
LSBT	5-minute calculated SB through volume at Lydia Ave
LEBL	5-minute calculated EB left turn volume at Lydia Ave
LEBR	5-minute collected EB right turn volume at Lydia Ave
LEBT	5-minute calculated EB through volume at Lydia Ave
LWBL	5-minute calculated WB left turn volume at Lydia Ave
LWBR	5-minute collected WB right turn volume at Lydia Ave

LWBT	5-minute calculated WB through volume at Lydia Ave
NBGLEN	NB 5-minute volume count at the Glenhill Avenue boundary
SBGLEN	SB 5-minute volume count at the Glenhill Avenue boundary

RANGE NAME DEFINITIONS

Range name	Range contents	Range
TIMER	Date and end time	A–B
NBTT	NB travel time data	C–J
SBTT	SB travel time data	K–R
B2BF	Boundary flow at B2	S–T
CNBDET	NB detector volume and occupancy at C	U–AB
CSBDET	SB detector volume and occupancy at C	AC–AH
CEBDET	EB detector volume and occupancy at C	AI–AN
CWBDET	WB detector volume and occupancy at C	AO–AT
CMAN	Manual counts at C	AU–BF
C2NBDET	NB detector volume and occupancy at C2	BG–BL
C2SBDET	SB detector volume and occupancy at C2	BM–BR
C2EBDET	EB detector volume and occupancy at C2	BS–BV
C2WBDET	WB detector volume and occupancy at C2	BW–CD
C2MAN	Manual counts at C2	CE–CP
LNBDET	NB detector volume and occupancy at Lydia	CQ–CV
LSBDET	SB detector volume and occupancy at Lydia	CW–DB
LEBDET	EB detector volume and occupancy at Lydia	DC–DJ
LWBDET	WB detector volume and occupancy at Lydia	DK–DP
LMAN	Manual counts at Lydia	DQ–EB
GLBF	Boundary flow at Glenhill	EC–ED
SIGCOM	Common signal timing data	EE–EG
CSIG	Signal timing at C	EH–FO
C2SIG	Signal timing at C2	FP–GW
LSIG	Signal timing at Lydia	GX–HW