4500 SOUTH (300 WEST TO STATE STREET) CLOSURE:
THE EVALUATION OF USERS’ IMPACTS

by
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of a thesis submitted by

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To the Graduate Council of the University of Utah:

I have read the thesis of Dejan Jovanovic in its final form and have found that (1) its format, citations, and bibliographic style are consistent and acceptable; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the supervisory committee and is ready for submission to The Graduate School.

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ABSTRACT

Utah Department of Transportation (UDOT) identified the part of 4500 South (from 300 West to State Street) in Murray City, Utah as a bottleneck. UDOT decided to add an additional lane in each direction (on previously a two-lane section). Three possible alternatives on how this work should be done were developed: (1) complete closure for 8 weeks, (2) closure during the night for 6 months, and (3) closing one direction at a time for 6 weeks in each direction. The goal of this study was to examine the impact of the alternative construction methods for these alternatives on road user delay and emission using macro-simulation. After the geometry of the model was improved and the model was calibrated, three alternatives (besides no-build and after-implementation) were developed and tested. Observed measures of effectiveness were costs of users’ delays, levels of emission (Carbon Monoxide, Nitrogen Oxide, and Volatile Oxygen Compounds) and volume/capacity ratio. Results showed that working during nights (and leaving lanes open during the day) would have had the lowest impact on users in terms of delays. This study also concluded that emissions are insensitive to this kind of work. Volume/capacity ratio showed considerable lane efficiency improvement.
### TABLE OF CONTENTS

ABSTRACT................................................................................................................ iv

LIST OF FIGURES.................................................................................................... vi

LIST OF TABLES...................................................................................................... viii

1. INTRODUCTION.................................................................................................... 1
   - Background of the Research........................................................................... 2
   - Scope of the Research.................................................................................... 5

2. METHODOLOGY................................................................................................... 7
   - Measures of Effectiveness............................................................................. 7
   - Scenarios........................................................................................................ 10
   - Study Area..................................................................................................... 12
   - Data Gathering and Data Adjusting............................................................... 14
   - Improving VISUM Model........................................................................... 15
   - Calibration.................................................................................................... 18

3. RESULTS............................................................................................................. 28
   - Calibration Results...................................................................................... 28
   - Study Results.............................................................................................. 33

4. DISCUSSION...................................................................................................... 46

5. CONCLUSIONS.................................................................................................. 49

REFERENCES......................................................................................................... 50
LIST OF FIGURES

Figure

1.1: 4500 S in Murray City ................................................................................................. 3

1.2: Number of lanes along 4500 S in Murray City........................................................... 4

2.1: Visual representation of scenario occurrences in period ........................................... 12

2.2: Work area (bounded by ellipsoid) within study area (bounded by square) .......... 13

2.3: Intersection before and after updated geometry ....................................................... 16

2.4: Scenarios presented through all diurnal periods....................................................... 18

2.5: TFlowFuzzy parameters ............................................................................................ 22

2.6: TFlowFuzzy input parameters ................................................................................... 24

2.7: VISUM dialog showing BPR function applied to link types..................................... 27

3.1: Initial correlation for base model 6 AM – 9 AM ....................................................... 29

3.2: Correlation for base model 6 AM – 9 AM after first calibration run ....................... 30

3.3: Correlation for base model 6 AM – 9 AM after second calibration run ................... 30

3.4: Correlation for base model 6 AM – 9 AM after third calibration run ....................... 31

3.5: Correlation for base model 6 AM – 9 AM after fourth calibration run ..................... 31

3.6: Correlation for base model 6 AM – 9 AM after fifth calibration run ....................... 32

3.7: Total users’ costs among the alternatives for period July 2007-December 2008 ...... 34

3.8: Users’ daily costs for period July 2007 - December 2008 .......................................... 36

3.9: Cumulative users’ costs for period July 2007-December 2008 .................. 36
3.13: Calculated level of CO for period July 2007 - December 2008 ...................... 40
3.14: Calculated level of NOx for period July 2007 - December 2008 ....................... 41
3.15: Calculated level of VOC for period July 2007 - December 2008 ..................... 41
3.16: Volume/capacity ratio for the period 6 AM – 9 AM EB ................................. 42
3.17: Traffic flow for the period 6 AM – 9 AM EB ........................................ 43
3.18: Volume/capacity ratio for the period 6 AM – 9 AM WB ................................. 44
3.19: Traffic flow for the period 6 AM – 9 AM WB ........................................ 44
LIST OF TABLES

Table

2.1: Stop percentage based on vehicle delay ................................................................. 10
2.2: Five diurnal coefficients ...................................................................................... 16
3.1: Coefficient of correlation progress for each scenario ........................................ 32
3.2: Delay costs for the five diurnal period for all scenarios ....................................... 35
3.3: Delay costs for the five diurnal period for all scenarios ....................................... 38
3.4: V/C ratio for all diurnal periods before and after lane implementation............... 45
1. INTRODUCTION

Growing congestion makes traffic engineers find new solutions and improve current situations to relieve this congestion. One of the main principles that Utah Department of Transportation (UDOT) is governed by is “Take care of what we have,” which can include, among other things, assessing if the current road capacity is enough, and improving it if necessary. Often capacity increase means re-striping a road or adding more lanes. Whatever the solution is, a work zone exists.

Determining the best alternative to carry out some road reconstruction can have several approaches. Agencies and companies conducting road improvements have different, and often conflicting, interests compared to road users, or even compared to businesses in the work area. An agency that conducts road work knows what it wants to accomplish, so it is straightforward for it to take care of its interests. For example, the agency can minimize total salaries paid to workers by eliminating night work, or undertake the road work at the certain period when the funds are available. As for the businesses in the work area, their goal is clear: decrease the duration of road works as much as possible, so the impact on their revenues will be minimal. On the other hand, the impact of work zones on users is complex and is often neglected. Users can be affected, for instance, by decreased safety, increased delays, or increased pollution.

The work zone decreases safety. Nationwide, in 2005, 1074 fatalities resulted from vehicle crashes in work zones (1). Isolating work zones from road users provides
more safety. However, complete closure of all work zones (especially work zones on major streets) would cause huge traffic delays by lowering available road capacity, thus having another negative impact on users. Additionally, delays occur not only when a certain route is completely closed, but even when a part of the road is closed (because of decreased capacity and lower speeds). Consequentially, with increased delays, emissions also accumulate.

The intensity of impact depends on:

- type of work (pothole patching, minor shoulder repair, or major bridge repair),
- duration of work (one day, a few weeks),
- time of day (off-peak periods, night work, all day),
- type of closure (partial or complete),
- type of the street (residential, minor, major, freeway).

The scope of the research presented here is to determine the best strategy to be implemented to the specific work zone in Murray City, Utah, with the goal of minimizing impact on users in terms of delays and pollution.

**Background of the Research**

**Existing Situation**

One of the major arterial streets in the Murray City, Utah, is 4500 S; see Figure 1.1. It stretches 5 miles in the east-west direction between 700 W and 2300 S, and it has connection to Interstate 15 (I-15).
Figure 1.1: 4500 S in Murray City
The number of lanes varies from two to three along these 5 miles; the number of lanes per direction for each section is shown on Figure 1.2.

4500 S is the street with the highest volume during the day in Murray City, with more than 25,000 vehicles per day on average. Moreover, the part between 300 W and 700 E is the busiest section and carries more than 33,000 vehicles per day on average (2).

Need for 4500 S Widening

Although the majority of 4500 S has enough capacity to support users’ demands, UDOT identified the part between 300 W and State Street as a bottleneck. Besides regular 4500 S users, this part of the street serves vehicles entering from and exiting to I-15. Two lanes cannot carry 33,000 vehicles a day, especially in the peak periods.

Proposed Improvement

When UTOD identified a bottleneck at 4500 S, the following reconstruction plan was developed. The 4500 S reconstruction project comprises widening 4500 S in both directions from 300 W to State St. 4500 S should be widened to accommodate three lanes in each direction. In addition, a median should be reconstructed, and existing

![Figure 1.2: Number of lanes along 4500 S in Murray City](image)
retaining walls, curbs, and gutters replaced along the reconstruction area. The existing Union Pacific Railroad (crosses 4500 S around 200 W) and UTA Light Rail (crosses 4500 S around 100 W) bridges will remain in place during reconstruction and should not be affected. Work was scheduled to begin on July 9, 2007.

Scope of the Research

Considering that road work on 4500 S will have multiple influences on road users, residents and businesses in the area, it was important to carefully examine all possible alternatives how these road works should be conducted. UDOT developed three alternatives with various type of closure (partial or complete), time of day when some or all lanes should be closed (night work, all day closure), duration of the work itself (from 8 weeks to 6 months), and start of work (right away or beginning of next year). Next, UDOT instructed the Utah Traffic Laboratory (UTL) to examine proposed alternatives and determine the one with the least impact on users. Various measures of effectiveness (MOEs), such as costs of users' delays, level of pollution, etc., were defined to compare proposed alternatives.

The goal of this research was to determine the best reconstruction alternative for the 4500 S widening project considering user costs. This goal was supported by three objectives; each objective compared the following measurements among alternatives:

- User costs based on traffic delays for the whole study area,
- User costs based on traffic delays for I-15, and
- Air quality impacts for the whole study area.
Research Tasks

The following tasks were developed to support achievement of the project’s goal and objectives:

1. Improve VISUM model
2. Divide calibrated model into five diurnal models
3. Obtain signal timings
4. Update SYNCHRO signal timings
5. Transfer signal timings data to VISUM
6. Calibrate basic VISUM model
7. Create VISUM models for predefined scenarios for each diurnal period
8. Run traffic assignment for each scenario
9. Extract delays, vehicle miles traveled, vehicle volume, and speeds from VISUM models
10. Calculate user costs and emissions
11. Compare scenarios and determine the best alternative.
2. METHODOLOGY

The first step toward finding the best alternative for widening 4500 S is defining the Measures of Effectiveness (MOEs) that should be used. Further on, it was necessary to find a way to collect these MOEs. We used traffic simulation for that purpose since simulation is a low-cost and effective way to test various alternatives. More precisely, macro-simulation was chosen (over micro-simulation) because it provides the possibility to observe bigger areas in a timely manner. The macroscopic approach considers all vehicles at once and is commonly used for transportation planning; whereas, microsimulation models simulate the movement and the behavior of a single vehicle based on car-following and lane changing theory (such a level of detail was not necessary for this study). Some data adjustments and model improvements had to be done before the model was calibrated to reflect existing conditions. The following section provides details of the methodology used for this project.

**Measures of Effectiveness**

MOEs are used to compare and select among alternatives. Since our major focus is the impact on users, the following MOEs were used:

- **User costs**: Users’ costs represent monetary value of travel delays. The US Department of Transportation suggests the monetary value of time savings depending on the trip purpose and conditions under which the trip
is made (3). We used average hourly value of travel time savings for local travel (4). The hourly value of travel time savings per passenger is $11.20, and conservative average vehicle occupancy is 1.16. So, multiplication of these numbers gives $13.00 as time value per vehicle. All other costs such as vehicle operating costs, accident costs, etc. were not considered in this study. Furthermore, user costs were calculated (a) for users in the whole study area and (b) for 1-15 users.

- **Volume/Capacity ratio (V/C ratio):** The ratio is a measure of lane capacity efficiency (5). For example, a road with a V/C ratio value of one is identified as a bottleneck. Segments operating close to capacity have a V/C value greater than 0.9. Congested portions of the roads are identified as negative V/C ratios. Volume and capacity were extracted from VISUM, and then the V/C ratio was calculated using spreadsheets.

- **Level of emissions:** People are becoming more conscious about environmental issues that modern society has imposed, and air quality is one of the mandatory components of every traffic study. For that reason, three major emissions were considered and compared:
  - Carbon Monoxide (CO),
  - Nitrogen Oxides (NOx), and
  - Volatile Oxygen Compounds (VOC).

Emissions are not directly available from VISUM, so they were calculated using the following formula (6):
\[ CO = F \times 69.9 \text{ g/gal (g)} \]

\[ NO_x = F \times 13.6 \text{ g/gal (g)} \]

\[ VOC = F \times 16.2 \text{ g/gal (g)} \]

where \( F \) is fuel consumption (in gallons) and is calculated using the following formula:

\[
F = TotalTravel \times k_1 + TotalDelay \times k_2 + Stops \times k_3
\]

where:

\[ k_1 = 0.075283 - 0.0015892 \times \text{Speed} + 0.000015066 \times \text{Speed}^2 \]

\[ k_2 = 0.7329 \]

\[ k_3 = 0.0000061411 \times \text{Speed}^2 \]

\( F \) – fuel consumed (gallons)

\( TotalTravel \) – vehicle miles traveled (mi)

\( TotalDelay \) – total signal delay (hour)

\( Stops \) – total stops (vehicles per hour)

Fuel consumption is a function of speed, total delay, vehicle miles traveled (VMT), and number of stops. All measures, except number of stops, were extracted from VISUM. For number of stops Table 2.1 was used. For example, if the vehicle was delayed 2 seconds, it
Table 2.1: Stop percentage based on vehicle delay

<table>
<thead>
<tr>
<th>Vehicle Delay (sec)</th>
<th>Percent of Stops (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>77</td>
</tr>
<tr>
<td>5</td>
<td>84</td>
</tr>
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<td>6</td>
<td>91</td>
</tr>
<tr>
<td>7</td>
<td>94</td>
</tr>
<tr>
<td>8</td>
<td>97</td>
</tr>
<tr>
<td>9</td>
<td>99</td>
</tr>
</tbody>
</table>

would count as 58% of a stop. All vehicles delayed more than 10 seconds were counted as a complete stop.

Scenarios

Traditionally, the agency that wanted to conduct some road reconstruction would provide a single model showing how that reconstruction should be done. Just a decade ago, traffic simulation was not so widely available, and even various simulation software programs that were available required too much computer time and power. Thus, it was not effective to use simulation for testing various alternatives how road work could be done. With development of more sophisticated computer packages and with an increase in computer power, it has become almost an imperative to test possible alternatives before starting work in the field.
UDOT predefined three alternatives that they considered for reconstruction work. These three alternatives, in addition to no-build, and after-implementation scenarios were considered in this study, are as follows:

- **No-build scenario** assumes no reconstruction work in the terms of improved road capacity. It is used as a base model for comparison with proposed alternatives: to quantify the improvement each alternative would bring compared to the existing condition.

- **First scenario (Scenario 1):** Complete closure for 8 weeks (all lanes are closed all the time with no traffic allowed). This scenario provides the shortest impact on residents, but the biggest and the strongest impact on travelers, not only on 4500 S, but also on surrounding streets. Work would have started on July 9, 2007.

- **Second scenario (Scenario 2):** All lanes are open during the day, with complete closure during the night; duration is 6 months. This scenario provides the lowest impact on travelers because the highest traffic load is during the day. Work would have started on March 15, 2008 because construction season in this year would not be long enough to finish work.

- **Third scenario (Scenario 3):** Complete closure of one direction at the time. One direction would be closed for 6 weeks, thus making the total work duration 12 weeks. For the modeling purposes, it was easier to divide the third scenario into two subscenarios:
  - 3.1 Closing the eastbound (EB) direction for 6 weeks
  - 3.2 Closing the westbound (WB) direction for 6 weeks
After-implementation scenario: This scenario represents the new, improved condition (with three lanes in each direction).

Figure 2.1 provides a Gantt chart for each alternative (beginning and end of each scenario).

In order to make scenarios comparable with each other, all scenarios were adjusted to the same time frame, which is 18 months (from the beginning of July 2007 till the end of December 2008). For instance, reconstruction work for scenario 1 would last 8 weeks, so delays caused by complete closure during this period of 8 weeks were used. For the other 16 months (18 months minus 8 weeks), delays from the after-build scenario were used. The sum of these two delays provided total delays for scenario 1. An equivalent technique was applied to calculate delays for scenarios 2 and 3.

Study Area

Initially, the idea was to investigate the impact of the 4500 S reconstruction on the biggest possible region. So, the initial study area consisted of a planning model for Salt Lake, Utah, Weber, and Davis Counties. This model was comprised of 14,000 links. However, the time required for the calibration and running assignment for such a big

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
<th>Duration</th>
<th>Q3 07</th>
<th>Q4 07</th>
<th>Q1 08</th>
<th>Q2 08</th>
<th>Q3 08</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alternative 1</td>
<td>6/22/2007</td>
<td>9/28/2007</td>
<td>8w</td>
<td>[student's data]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Alternative 2</td>
<td>3/15/2008</td>
<td>6/15/2008</td>
<td>25.43w</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.1: Visual representation of scenario occurrences in period
network is not justified for this particular project. Thus, it was important to find an adequate network size that would provide an area large enough to enable allocation of trips from the construction area and to measure users’ delays in the region surrounding 4500 S, and small enough to be sufficient for modeling purposes. Several trial calibration runs were conducted, each time reducing the size of network.

The final study area represented the road network in Salt Lake County. The area, shown in Figure 2.2, is bounded by 3300 S on the north, 5900 S on the south, 900 W on the west, and 2000 E on the east. The area is 4 by 5 miles.

Figure 2.2: Work area (bounded by ellipsoid) within study area (bounded by square)
Figure 2.2 also shows that the work area (rounded by ellipsoid) is much smaller than the actual study area (bounded by square), which is important because the 4500 S closure would have an influence on the surrounding streets. It is important to note that the study area included the I-15 part, from 3300 S to 5900 S, which enabled us to measure the impact on I-15 users.

Data Gathering and Data Adjusting

Ideally, necessary data for model calibration would be collected in the field because that would provide the most recent data to work with. However, that was not possible for a few reasons: (1) the project time frame did not allow additional time to be spent on data collection, and (2) as a general rule, it is expensive to collect data, especially 24 hours a day. Therefore, we had to work with data that were already available.

The Average Annual Daily Traffic (AADT) for May 2005 was used (2). The main challenge was converting available daily traffic to hourly volumes. In order to assign hourly volumes from daily volumes, we used results from the May 1996 data collection (7). Data collected in 1996 were the most recent hourly volumes collected for the whole day. These data were found to be out of date, but were used to calculate hourly coefficients. Since data were collected on only 21 stations in Salt Lake County (8), we used the station that was the closest to the study area (Station number 406, SR 71, 700 E, milepoint 13.26).

For example, the hourly coefficient for the period from 7 to 8 AM is:

\[ \text{Hourly coefficient } 7-8 = \frac{\text{Volume } 7-8}{\text{Volume } 0-24} \]
Additionally, volumes used for hourly coefficient calculations are average volumes for all days in the week, because the reconstruction is scheduled for all days in a week. The result of the calculation was a list of 24 hourly coefficients (for every hour). However, this study did not require such a level of detail, so instead of using hourly coefficients, diurnal coefficients were used.

Diurnal periods are defined in such a way that morning and afternoon peaks are distinguished from the rest of day. Additionally, the hours after the afternoon peak are split into evening and night periods since there is a scenario with night work. The diurnal periods for this study were defined as follows:

- From 6:00 AM to 9:00 AM – Morning peak period (3 hours)
- From 9:00 AM to 3:00 PM – Midday period (6 hours)
- From 3:00 PM to 6:00 PM – Afternoon peak period (3 hours)
- From 6:00 PM to 10:00 PM – Evening period (4 hours)
- From 10:00 PM to 6:00 AM – Night period (8 hours)

To get diurnal coefficient from hourly coefficients, hourly coefficients for a certain period were summed. Table 2.2 provides values of diurnal coefficients for each diurnal period. By multiplying those coefficients with AADT for a particular day, we were able to produce periodic volumes used for modeling purposes.

Improving VISUM Model

The model of the Utah region (Salt Lake, Utah, Weber, and Davis Counties) was available from the local Metropolitan Planning Organization (MPO) Wasatch Front Regional Council (WFRC), and was used as a starting point. However, since this was a
Table 2.2: Five diurnal coefficients

<table>
<thead>
<tr>
<th>Period of the day</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>6am-9am</td>
<td>0.120</td>
</tr>
<tr>
<td>9am-3pm</td>
<td>0.337</td>
</tr>
<tr>
<td>3pm-6pm</td>
<td>0.211</td>
</tr>
<tr>
<td>6pm-10pm</td>
<td>0.247</td>
</tr>
<tr>
<td>10pm-6am</td>
<td>0.084</td>
</tr>
</tbody>
</table>

planning model, the network did not have sufficient details needed for this project. Geometry for the study area had to be checked and updated if necessary, both links and intersections. Google Earth (9) and TerraServer (10) were used for updating geometry. The study area model consisted of more than 800 links and 60 signalized intersections. Figure 2.3 gives an example of the intersection 4500 S and State Street before and after geometry update and signal timings implementation.

Figure 2.3: Intersection before and after updated geometry
Once the geometry was accurate, the next step was making five networks (one for each diurnal period) from the base model. For each diurnal period and for the whole study area, different volumes, based on calculated diurnal coefficients, were added. Volumes were added as a user defined attribute, so that they can be used later on in the calibration procedure.

Next, traffic signal timings for all 60 signalized intersections were uploaded. UDOT provided current signal timings in SYNCHRO format. In this project, SYNCHRO was used only as a tool to transfer signal timings—not as an optimization tool (which is its most common application). Because it is not possible to directly transfer signal timings from SYNCHRO to VISUM, micro-simulation software VISSIM was used as an intermediate step. That means that for all five diurnal periods, all 60 signal timings had to be manually transferred. With this step, the five models for five diurnal periods were ready for further steps.

Previously available Origin-Destination (OD) matrices for each diurnal period (11) were imported into VISUM models. Creating new matrices from the beginning is a time consuming process, so we used these previously available matrices as a starting point for calibration.

The calibration procedure of the VISUM model is complex and uses a built-in module TFlowFuzzy. This procedure is explained in more detail in the following sections.

The final step was making five scenarios for each diurnal period, as shown in Figure 2.4. This made a total of 25 models that had to be analyzed.
Calibration

Calibration is a process of adjusting the simulation model so it represents real-world conditions. In traffic simulation models, the goal is to match measurements from the model with the observed measurements from the field, usually by adjusting available parameters in a model. In this study, the aim was to obtain vehicle volume from the model (modeled volume) equivalent to field vehicle volume (field volume) for each link and for each diurnal period.

The coefficient of determination ($R^2$) expresses the amount of common variation between the two variables. If the regression line is $x=y$, $R^2$ can be used to determine how
closely the model predicts given data. As the aim is to produce in VISUM the same volume for every link as field volume, the regression line must have an $x=y$ formulation. The $R^2$ values lie between 0 and 1. If a model has perfect predictability, $R^2$ will be 1; by contrast, if a model has no predictive capability, $R^2$ will be 0. The rule of a thumb (12) says that when $R^2$ is greater than 0.65, the correlation is strong. Thus, $R^2$ was calculated to compare the model and field volumes.

VISUM uses the TFlowFuzzy module to adjust OD matrices to field volumes and traffic assignment to distribute volumes to links according to the newly adjusted OD matrices. Thus, these two modules (TFlowFuzzy and Traffic Assignment) were used in the model calibration.

TFlowFuzzy

TFlowFuzzy is a VISUM built-in module that updates the OD matrix based on user defined attributes such as volume, OD travel demand by zone, turning movements on nodes, etc. (13). These values can be obtained from various sources: surveys for origin and destination trips, traffic counts for turning movements, etc. In this study, attributes (targeted values) are diurnal volumes obtained from 2005 AADT volumes (field volumes). The goal was to make new matrices for all five diurnal periods so that the modeled volumes were as close as possible to the field volumes.

TFlowFuzzy uses matrix correction techniques to update the existing OD matrix in such a way that results from assignment closely match targeted field values. The following section describes how TFlowFuzzy works (13).

The old, starting OD matrix is presented as a vector, containing just nonzero trips:
OD trips that are made contribute to the volume on links as a sum of all OD trips traveling on that link.

There is a linear relation between the demand on the OD pairs and the traffic counts, as represented by the following equation:

\[
\begin{pmatrix}
0 & t_{12} & t_{13} & \cdots & t_{1n} \\
t_{21} & 0 & t_{23} & \cdots & t_{2n} \\
t_{31} & t_{12} & 0 & \cdots & t_{12} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
t_{n1} & t_{n2} & t_{n3} & \cdots & 0
\end{pmatrix}
\begin{pmatrix}
t_{12} \\
t_{13} \\
\vdots \\
t_{1n} \\
t_{21} \\
t_{22} \\
\vdots \\
t_{2n} \\
t_{31} \\
\vdots \\
t_{3n}
\end{pmatrix}
= \begin{pmatrix}
V_{11} \\
V_{12} \\
\vdots \\
V_{1n}
\end{pmatrix}
\]

A is called the share-matrix. The number of columns of this share-matrix refers to the number of nonzero OD pairs; the number of rows corresponds to the number of traffic counts. Each element \(a_{ik}\) of this share-matrix expresses the share of trips of one OD pair \(k\), which uses link \(l\). In order to select the best possible matrices, an evaluation function \(q\) is applied as an objective function: Maximize \(q(t)\) so that \(A^*t=v\).

Maximizing \(q\) in the following function favors the matrices that differ least from the base matrix:

\[
q(t) = \sum_{k=1}^{p} t_k \cdot \ln \frac{t_k}{l_k} - t_k
\]
where

\[ \hat{t}_k \] travel demand on one OD pair in the base matrix

\[ t_k \] travel demand on one OD pair in the new matrix.

Because the new matrix cannot differ significantly from the original matrix, TFlowFuzzy had to be run several times; every time with slightly changed parameters in order to get closer to the targeted values.

The targeted value is always one, fixed number. Deriving a new matrix that would represent that one number would be impossible, and even incorrect, because one, fixed number could only be an average of multiple counts. That is why PTV implemented Fuzzy Sets Theory into matrix correction (so that input can be represented as Fuzzy sets number). In addition, TFlowFuzzy uses bandwidth, which allows a new matrix to be created more efficiently. The old matrix is used as a weight for the OD relationships and new matrix, and using these weights, tries to fit its values into the prespecified bandwidth, usually to the mean value.

The TFlowFuzzy module contains many parameters (see Figure 2.5), making the calibration procedure complex and time consuming, because each of these parameters influences results.

These are the TFlowFuzzy parameters and their explanation:

- **Max. correct. factor**: The factor limits any change in a trip relation from the old to the new matrix to the factor \( e^{\pm \Delta} \).

- **Cancel if change <**: The calculation is cancelled if the OD matrix has not changed from one to the next iteration in any trip relation by more than the specified number of trips. Usually it is one.
Figure 2.5: TFlowFuzzy parameters
• No. of iterations: The calculation stops when the specified number of iterations has been reached.

• Estimated No. of trips: By default, the number of trips in the new matrix is the same as the number of trips in the old matrix.

• Alpha-Level: This factor is used to scale the bandwidth.

Calibration Process

In order to create the new matrix for each of the five diurnal periods, TFlowFuzzy had to be run several times using parameters within the module. Figure 2.6 shows input parameters for the TFlowFuzzy module.

As shown in Figure 2.6, link volumes were used as targeted values. “AddValue1” represents measured (and targeted) volumes and is previously entered on each link as the volume from 2005. “AddValue2” is an allowable variation from the measured “AddValue1”. This bandwidth allows results for the new matrix to fluctuate around the mean value (“AddValue1”). For instance, if “AddValue1” is 500 and “AddValue2” is 80% (or 400), the final matrix results will fluctuate between 100 and 900 during the iteration steps, trying to reach the mean value (500). “AddValue2”, ideally, should not fluctuate considerably from the mean value, but because of the nature of TFlowFuzzy, it does not allow for the new matrix to differ considerably from the original or an error message will appear. “AddValue2” should be gradually decreased after each TFlowFuzzy run, in order to reach the final target value. The start value for “AddValue2” differed from matrix to matrix and is set by a trial and error process.
After each TFlowFuzzy run, measurements from the VISUM were extracted and compared to the field data for correlation. If the increase in coefficient of determination was considerable, the next TFlowFuzzy, with a smaller “AddValue2”, was run. So, every next TFlowFuzzy was run with a smaller “AddValue2” in order to get the final matrix as close as possible to the targeted “AddValuel”. Several TFlowFuzzy runs had to be executed for each diurnal period, and the number of times differ from matrix to matrix (some matrices needed less correction than others).
Assignment procedures are based on search algorithms that determine routes between origin and destination. The search procedure is followed by a choice procedure, which distributes the travel demand of an OD pair onto links.

Traffic assignment is an important part for two steps of this study. First, it has to be run after each TFlowFuzzy procedure in order to assign new volumes to links, so these volumes can be compared with field volumes. Second, after dividing the base model into diurnal models, traffic assignment has to be run again to reroute traffic from the closed links.

The traffic assignment result (assigned volumes on links) depends on the capacity of the link, free flow speed and impedance that can be defined ahead. The user has to choose a traffic assignment procedure that VISUM will use to calculate volumes. There are few possible traffic assignment procedures available within VISUM software package. However, for this study, equilibrium assignment was used.

During equilibrium assignment, volumes are assigned to the links based on a volume-delay function (impedance) that is predefined. Volumes are distributed to all links based on Wardrop's first principle (14); often called user-optimized equilibrium because it hypothesizes that no driver can improve his/her travel time by switching routes. In other words, a user-optimized equilibrium is reached when no user may lower his or her transportation costs by switching routes.

An important factor for a traffic assignment is the volume-delay function. As traffic volumes increase, travel speed decreases due to increased congestion. The Bureau of Public Roads (BPR) function is the most commonly used function for relating changes
in travel speed to increases in travel volume. The BPR function is specified \((6)\) as follows:

\[
T_f = T_0 \times \left(1 + a \left[ \frac{V}{C} \right]^\beta \right)
\]

where:

- \(T_f\) – final link travel time
- \(T_0\) – original (free-flow) link travel time
- \(a\) – coefficient (often set at 0.15)
- \(V\) – assigned traffic volume
- \(C\) – link capacity
- \(\beta\) – exponent (often set at 4.0).

For different types of links (arterial, freeway, connector or residential), different BPR coefficients were used:

- Freeway: \(a=1.2, b=7.0\)
- Multilane highway, or rural freeway: \(a=0.3, b=4.0\)
- Arterial street: \(a=0.5, b=4.0\)
- Collector: \(a=0.3, b=4.0\)
- Off-on ramp: \(a=2.0, b=2.0\)

These BPR functions, which were conducted by the WFRC, are also shown in Figure 2.7.
Figure 2.7: VISUM dialog showing BPR function applied to link types
3. RESULTS

First, the model had to be calibrated so it represents real traffic conditions; thus, the first part of the results section consists of calibration results. The second subsection contains results from the scenario analysis showing observed MOEs.

Calibration Results

Once the network was updated to have the appropriate geometry and signal timings needed for this study, calibration was done using the TFlowFuzzy procedure. This procedure had been repeated several times; the number of times depended on the quality of the starting model. More iterations were necessary if the model did not represent reality well. Calibration for each model was stopped after the TFlowFuzzy module was not able to make any progress (the module gives an error message informing a user that progress cannot be made).

The coefficient of determination ($R^2$) was used to compare modeled with field vehicle volumes. Figures 3.1 to 3.6 show how $R^2$ is increased with each iteration for one of the diurnal models (from 6 AM to 9 AM).

During the calibration process, graphs were created after each TFlowFuzzy run. Figure 3.1 presents the initial correlation between modeled and field volumes for the base model 6 AM to 9 AM.
Figure 3.1 shows that the model did not present the current situation very well, which was expected because this comparison was done before any model calibration.

Figures 3.2 to 3.5 show the increase in coefficients of determination after each calibration run.

Figure 3.6 shows that modeled volumes are close to field volumes for the final calibration run; the coefficient of determination is as high as 0.958.

Table 3.1 provides coefficients of determination for all scenarios. This table represents coefficients for each scenario after every calibration run.
Figure 3.2: Correlation for base model 6 AM – 9 AM after first calibration run

Figure 3.3: Correlation for base model 6 AM – 9 AM after second calibration run
Figure 3.4: Correlation for base model 6 AM – 9 AM after third calibration run

Figure 3.5: Correlation for base model 6 AM – 9 AM after fourth calibration run
Figure 3.6: Correlation for base model 6 AM – 9 AM after fifth calibration run

Table 3.1: Coefficient of correlation progress for each scenario

<table>
<thead>
<tr>
<th>Run</th>
<th>Diurnal Period</th>
<th>Run 6 AM-9 AM</th>
<th>9 AM-3 PM</th>
<th>3 PM-6 PM</th>
<th>6 PM-10 PM</th>
<th>10 PM-6 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6 AM-9 AM</td>
<td>0.544</td>
<td>0.737</td>
<td>0.692</td>
<td>0.715</td>
<td>0.522</td>
</tr>
<tr>
<td>1</td>
<td>9 AM-3 PM</td>
<td>0.805</td>
<td>0.762</td>
<td>0.814</td>
<td>0.815</td>
<td>0.815</td>
</tr>
<tr>
<td>2</td>
<td>3 PM-6 PM</td>
<td>0.939</td>
<td>0.778</td>
<td>0.839</td>
<td>0.834</td>
<td>0.853</td>
</tr>
<tr>
<td>3</td>
<td>6 PM-10 PM</td>
<td>0.948</td>
<td>0.786</td>
<td>0.959</td>
<td>0.844</td>
<td>0.869</td>
</tr>
<tr>
<td>4</td>
<td>10 PM-6 AM</td>
<td>0.952</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.875</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.958</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.878</td>
</tr>
</tbody>
</table>
As Table 3.1 shows, every subsequent calibration run made smaller improvements than the previous one. The number of possible runs varied among models (from 3 to 5), because TflowFuzzy could not make any progress in creating a new matrix, and the module would send an error message. All models had a high (above 0.65) coefficient of determination between modeled and field volumes.

**Study Results**

The traffic assignment procedure in VISUM is used to get traffic measurements for each observed scenario. Delays were converted to costs using value of time. Further, these costs were projected to the period from July 9, 2007 until December 31, 2008, so alternatives can be comparable.

**Users’ Delay Costs**

The costs of user delays were calculated (1) for users in the whole study area, and (2) for the 1-15 users.

**Whole Study Area**

From numerous traffic assignments, user delays were extracted from VISUM, and then summarized and converted to users’ costs using spreadsheets (MS Excel). This MOE is used as a major comparison factor for all alternatives.

Figure 3.7 presents the users’ costs among different alternatives. In order to make scenarios comparable with each other, all scenarios were adjusted to the same time frame, which is 18 months (from the beginning of July 2007 until the end of December 2008).
For instance, reconstruction works for scenario 1 last 8 weeks, so delays caused by complete closure during this period of 8 weeks were used. For the other 16 months (18 months minus 8 weeks), delays from the after-build scenario were used. The sum of these two delays provided total delays for scenario 1.

Costs after reconstruction is done are lower than before. This is because the capacity of the road has been increased, so there are fewer delays. According to users’ delay costs, scenario 2 is the least expensive alternative.

Table 3.2 shows user delays for the whole study area for the period from July 2007 to December 2008, divided by diurnal periods and scenarios.
This table can be used to address some periods of the day when costs of users' delays are highest, that is, to determine when users are most impacted by reconstruction.

Figure 3.8 shows when users’ costs (based on traffic delays) occur in time for the whole study area. No-build line represents costs to users if nothing would be changed in the analyzed period.

Figure 3.8 shows that users encounter more than a million dollars worth of delays for scenario 1, but in a very short period of time. In contrast, scenario 2 has the lowest impact on users, but it would require much more time to be finished. Scenario 3 has a mixed impact on users.

Figure 3.9 represents cumulative user delay costs. It shows how much the delays cost users during a given period. Figure 3.9 also shows how costs accumulate over time for each scenario.

<table>
<thead>
<tr>
<th>Total Delay Costs (mil.$)</th>
<th>No-Build</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>After implemented changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM-9 AM</td>
<td>14.93</td>
<td>15.46</td>
<td>14.97</td>
<td>15.22</td>
<td>15.03</td>
</tr>
<tr>
<td>9 AM-3 PM</td>
<td>104.60</td>
<td>107.08</td>
<td>104.30</td>
<td>105.01</td>
<td>103.75</td>
</tr>
<tr>
<td>3 PM-6 PM</td>
<td>245.87</td>
<td>250.86</td>
<td>246.37</td>
<td>246.69</td>
<td>244.93</td>
</tr>
<tr>
<td>6 PM-10 PM</td>
<td>98.75</td>
<td>100.67</td>
<td>99.34</td>
<td>98.24</td>
<td>96.33</td>
</tr>
<tr>
<td>10 PM-6 AM</td>
<td>0.15</td>
<td>0.16</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 3.2: Delay costs for the five diurnal period for all scenarios
Figure 3.8: Users' daily costs for period July 2007 - December 2008

Figure 3.9: Cumulative users' costs for period July 2007-December 2008
I-15 Area

Beside user costs for the whole study area, impact on I-15 users was calculated. For that purpose, just part of I-15 was used: from 3900 S to 5600 S with all off- and on-ramps and the close surrounding streets (one or two links after ramps, so possible congestion on ramps could be captured and analyzed).

Figure 3.10 represents impact of reconstruction on I-15 users. Figure 3.10 shows a pattern equivalent to that shown in Figure 3.3, which shows users' costs for the whole study area. Again, scenario 2 has the lowest costs to users.

![Graph showing user costs for different scenarios](image-url)
Table 3.3 presents costs of 1-15 users’ delays for the period from July 2007 to December 2008 divided by diurnal periods and scenarios. This table can be used to address some periods of the day when costs of 1-15 users’ delays are highest, that is, to determine when users are most impacted by reconstruction.

Figure 3.11 represents users’ cost based on traffic delay for the 1-15 study area represented through time. Figure 3.11 shows that users encounter almost 200,000 dollars worth of delays for scenario 1, but for a very short period of time. In contrast, scenario 2 has the lowest impact on users, but it would require much more time to be finished.

Scenario 3 has a mixed impact on users.

Figure 3.12 represents cumulative user delay costs. It shows how the cost of delays for users during a given period. Figure 3.12 shows how costs accumulate over time for each scenario. It also shows little distinction among scenarios.

Table 3.3: Delay costs for the five diurnal period for all scenarios

<table>
<thead>
<tr>
<th>Delay Costs for 1-15 users (mil. $)</th>
<th>No Build</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>After implemented changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM-9 AM</td>
<td>1.81</td>
<td>1.79</td>
<td>1.81</td>
<td>1.78</td>
<td>1.78</td>
</tr>
<tr>
<td>9 AM-3 PM</td>
<td>14.45</td>
<td>15.24</td>
<td>14.39</td>
<td>14.72</td>
<td>14.31</td>
</tr>
<tr>
<td>3 PM-6 PM</td>
<td>43.11</td>
<td>43.52</td>
<td>43.20</td>
<td>43.06</td>
<td>42.78</td>
</tr>
<tr>
<td>6 PM-10 PM</td>
<td>15.37</td>
<td>15.92</td>
<td>15.50</td>
<td>15.27</td>
<td>14.70</td>
</tr>
<tr>
<td>10 PM-6 AM</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Figure 3.11: Users’ daily costs-impact on I-15 for period July 2007-December 2008

Figure 3.12: Cumulative users’ costs-impact on I-15 for period July 2007-December 2008
Emissions

Levels of calculated emissions are shown in this section. Figure 3.13 shows the level of CO for the whole region from July 2007 to December 2008.

Figure 3.13 shows that although the level of CO is lower after adding a lane (compared to before or during reconstruction), there is no sufficient difference among alternatives.

Figure 3.14 represents the level of NOx for the whole region from July 2007 to December 2008. Figure 3.14 shows that levels of NOx do not differ among alternatives.

Figure 3.15 represents level of VOC for the whole region from July 2007 to December 2008. Figure 3.15 shows that levels of VOC do not differ among alternatives.

![Figure 3.13: Calculated level of CO for period July 2007 - December 2008](image)
Figure 3.14: Calculated level of NOx for period July 2007 - December 2008

Figure 3.15: Calculated level of VOC for period July 2007 - December 2008
Volume-to-Capacity Ratio

Volume/Capacity (V/C) ratio for the part of 4500 S that was under construction (260 W and State St.) was calculated before and after improvement (lane implementation) in order to address any possible improvements in traffic conditions.

Figure 3.16 represents V/C ratio for the 6 AM – 9 AM period for the eastbound (EB) direction. Capacities and volumes shown in this figure represent capacity and volumes for all lanes (2 for before and 3 for after implementation) multiplied by the number of hours (3 hours). Figure 3.16 shows that with adding one more lane, the capacity increased (as expected), whereas volume stayed on the same level. Overall, the V/C decreased.

![Figure 3.16: Volume/capacity ratio for the period 6 AM – 9 AM EB](image-url)
In order to better understand V/C for the part that was reconstructed, the same data (as in Figure 3.16) are represented in different ways. Here, data are shown through traffic flow—vehicle volume per hour per lane. Figure 3.17 shows capacity and flow per hour per lane on the reconstructed section before and after lane implementation.

Figure 3.17 shows that capacity per lane stayed the same, but volume has been reduced because all traffic was divided across three instead of two lanes. Thus, the V/C ratio is decreased.

Figures 3.18 and 3.19 use the same approach as Figures 3.16 and 3.17, except for the westbound (WB) direction.

Figure 3.17: Traffic flow for the period 6 AM – 9 AM EB
Figure 3.18: Volume/capacity ratio for the period 6 AM – 9 AM WB

Figure 3.19: Traffic flow for the period 6 AM – 9 AM WB
Figures 3.18 and 3.19 show that V/C ratio for the WB direction was decreased when observing both vehicle volume (traffic on all lanes) and flow (traffic per lane).

Table 3.4 provides diurnal V/C ratios before and after implementation for both EB and WB directions.

V/C ratio was decreased for all diurnal periods.

Table 3.4: V/C ratio for all diurnal periods before and after lane implementation

<table>
<thead>
<tr>
<th>Time</th>
<th>Direction</th>
<th>Before Implementation</th>
<th>After Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM-9 AM</td>
<td>EB</td>
<td>0.63</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>0.56</td>
<td>0.38</td>
</tr>
<tr>
<td>9 AM-3 PM</td>
<td>EB</td>
<td>0.89</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>1.04</td>
<td>0.67</td>
</tr>
<tr>
<td>3 PM-6 PM</td>
<td>EB</td>
<td>0.78</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>0.80</td>
<td>0.43</td>
</tr>
<tr>
<td>6 PM-10 PM</td>
<td>EB</td>
<td>1.23</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>1.30</td>
<td>0.98</td>
</tr>
<tr>
<td>10 PM-6 AM</td>
<td>EB</td>
<td>0.23</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>0.16</td>
<td>0.11</td>
</tr>
</tbody>
</table>
4. DISCUSSION

The number of calibration runs varied among models because the TFlowFuzzy module, used in the calibration procedure, was not able to make any improvements at any particular time. The underlying reason was the limited field data. If there were more field volumes (targeted values), TFlowFuzzy would be able to make more accurate OD matrices.

The monetary value of the time savings of $13 per hour was used to calculate users' costs. Users' costs calculated for both the whole study area and I-15 showed that scenario 2 (night work during 8 weeks) would impose the lowest costs for users. This result is expected since only users' delays are used to calculate costs, and there are the least number of users in the night hours when the reconstruction would take place. However, all other costs, such as accidents, fuel consumption, etc. were not included. These other costs could possibly have an impact on the overall results.

Additionally, although this study did project all costs until the end of 2008 (so that results can be comparable among alternatives), it did not include traffic growth for that period. By not considering traffic growth, the current results—more precisely, the difference between costs among alternatives—might be inflated. For instance, scenario 1 (complete 24-hour closure during summer 2007) would not have much higher costs than scenario 2 (night work in the spring and summer 2008), because reconstruction would
have been finished sooner, and an additional lane would be available to accommodate growing demand in the region.

Users’ costs, when plotted for the whole study area and for I-15 users, have a similar relationship among alternatives. A possible explanation can be found in the fact that vehicles (on I-15 and surrounding streets used for calculating I-15 users’ costs) account for the largest portion of users for the whole study area (traffic flow on one freeway lane can be as much as four times higher than the flow on an arterial street).

This study did not find substantial variation in pollution (CO, NOx or VOC) among alternatives. Pollution is calculated based on fuel consumption, and fuel consumption depends on total travel, total delays, number of stops, and speeds in the region. Thus, the pollution insensitivity among alternatives indicates that total number of trips did not change much in the region. Simply put, the road users who were planning to make a certain trip will make it regardless of some road construction—they will find an alternative way to reach their destination.

Utah Division of Air Quality (DAQ) historical data (15) for the 2005 triennial inventory show that the level for the On-Road Mobile (primarily consists of cars and trucks and represents 56% of the total CO level) in Salt Lake County is around 127,675 tons per year. Considering the size of the study area, in comparison to Salt Lake County, we can conclude that CO level computation is accurate and can be used as an indicator for the study area.

The V/C ratio is an indicator of lane efficiency; a usually a lane is considered congested when the V/C ratio is above one. Although the V/C analysis for the before reconstruction condition did not always yield a V/C ratio close to one, it should be
emphasized that our observation periods were five diurnal periods, not every hour. This can underestimate some of the ratios. For instance, the period from 3 PM to 6 PM in the WB direction has a V/C ratio of 0.83. These 3 hours, if observed separately, would potentially give two lower ratios (for the period from 3 PM to 5 PM), and one higher ratio (for the period from 5 PM to 6 PM). However, after adding a lane, the V/C ratio for this 3-hour period is decreased to 0.43, so no hourly period can have a high V/C ratio.
5. CONCLUSIONS

The following conclusions were drawn from this study:

1) Scenario 2 (night work during 6 months in spring and summer 2008) imposes the least costs to users (based on users’ delays).

2) After adding a lane, users’ costs are lower (for both the whole study area users and I-15 users).

3) After adding a lane, emissions are lower.

4) Emissions are insensitive to the road reconstruction methods observed in this study.

5) The volume/capacity ratio is decreased by adding a lane.
REFERENCES


