Evaluating the Effects of I-35W Bridge Collapse on Road-Users in the Twin Cities Metropolitan Region

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Abstract

This study evaluates the effects of I-35W bridge collapse on road-users in the Twin-Cities metropolitan area. We adopted the Twin-Cities (Metropolitan Minneapolis and St. Paul) Seven-County travel demand model developed in previous research, re-calibrated it against July 2007 loop detector traffic data, and used this model to carry out an evaluation of economic loss incurred by increased travel delay in alternative scenarios before and after the bridge collapse. We concluded that the failure of the I-35W bridge resulted in an economic loss of $71,000 to $220,000 a day, depending on how flexible road-users in the system can adjust their trip destinations in response to the bridge closing. We also estimated that the major traffic restoration projects Mn/DOT has implemented in quick response to the bridge collapse can save road-users $9,500 to $17,500 a day. This translates into a benefit-cost ratio of 2.0-9.0, suggesting these projects are highly beneficiary in an economic sense. In this analysis, the use of a simplified, scaled-down travel demand model enabled us to carry out the analysis quickly and accurately, showing its contributions in transportation planning under situations such as emergency relief and comprehensive design.

1 Introduction

On August 1st, 2007 the I-35W Bridge over the Mississippi River in Minneapolis, Minnesota tragically collapsed. Located immediately adjacent to downtown Minneapolis and the University of Minnesota, and only one mile (1.6 km) northeast of the junction with I-94, the eight-lane bridge had served as a corridor for commuters and drivers region wide to get to and from area businesses and north suburban destinations. As of 2004 record, the bridge was crossed by 141,000 vehicles on an average day. In addition to the immediate costs incurred

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by casualties and property damage, the collapse of the bridge has significantly impacted the surrounding transportation system in the Twin Cities region (metropolitan Minneapolis and St. Paul).

The bridge failure has dramatically changed the traffic conditions region wide. The traffic that previously used this bridge had to divert onto alternate routes, leading to increased congestion in the nearby area, and may have switched departure times, modes, or destinations to avoid traffic. The increased driving distance and travel time, on the other hand, caused economic loss to road-users. Minnesota Department of Transportation (Mn/DOT)'s initial study concluded that road-user costs due to the unavailability of the river crossing would total $400,000 per day (Minnesota Department of Transportation, 2007)[1]. In response to a request from Mn/DOT Office Investment Management Office (OIM), we carried out a quick evaluation of the effect of the I-35W bridge removal five days after the tragedy. We estimated the traffic patterns before and after the bridge collapse using an established Twin-Cities region travel demand and investment model, and evaluated the economic loss imposed on road-users in terms of increased travel time delay. This estimate had more than intellectual importance; it is used to value the payment to contractors for early completion of a replacement bridge.

This study, extending our preliminary analysis, revisits the question regarding the effect of the I-35W bridge collapse on the regional transportation system. The reminder of this paper proceeds as follows: the next section introduces the Twin Cities region travel demand model we constructed for previous research purposes, which was improved for this study through re-calibration against peak hour traffic counts in July 2007. Scenarios are then tested to predict the traffic pattern before and after the bridge collapse, and road-users' economic loss evaluated based on different assumptions. The conclusion highlights our findings and indicates their implications.

2 Model

The travel demand and investment model SONG 2.0 was developed for Mn/DOT supported project "Beyond Business As Usual" to forecast the future Twin Cities Seven-County road network with the assumption that travel demand will behave according to the same factors that have affected it in the past (Levinson et al., 2007), though still a function of population, employment, and accessibility. To be consistent throughout the periods of 1990 to 2030, the base 1990 transportation planning network structure is adopted, which consists of 20,380 links, 7,723 nodes, 1,165 Transportation Analysis Zones (TAZs) in the Seven County Metro Area, and 35 external stations, which make a total of 1,200 zones for analysis. Link capacities and other attributes are updated in different years. The travel demand model in SONG 2.0 predicts traffic in the AM Peak Hour, calibrating against real traffic data in 2005, and then using peak hour to daily expansion factors where required to obtain AADT (which is required in some of the investment models). This model simplifies the traditional four-step

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[1] Road-user cost computations are available at `http://www.dot.state.mn.us/i35wbridge/rebuild/pdfs/road-user-cost-computations.pdf`

travel demand forecasting process by dropping mode choice, and instead directly estimates vehicle trips. We also do not model freight trips directly, and instead inflate passenger car trips to account for missing trucks. The assumptions that enter into the SONG model are fully documented in in the technical report for the "Beyond Business as Usual" project (Levinson et al., 2006). The three major components of the model are discussed as follows:

2.1 Trip Generation

Trip generation estimates the number of personal motor vehicle trips that originate from or are destined to each zone. The production and attraction models were separately estimated by regressing the composite 2005 vehicle trip rates by traffic analysis zones obtained from Metropolitan Council on a series of zonal characteristics variables. The model that provided the highest goodness- of-fit and had the most significant variables includes the following explanatory variables:

- Population
- Retail Employment
- Non-retail employment
- Residential density
- Shortest distance from centroid zone to either downtown Minneapolis or St. Paul
- Shortest previous distance squared

As zonal demographic information is not directly available for 2007, we used the 2005 data and the 2010 forecasts both obtained from Metropolitan Council to produce trip generation estimates for 2007 by interpolation.

2.2 Trip Distribution

Trip distribution procedures matches the trips produced with the trips attracted. In this research the trip distribution is made for all trip purposes combined, since the trip generation model above does not distinguish trips by purpose. This study includes a doubly constrained gravity-based trip distribution model. The gravity model shows the interaction between zones as below, which decreases with travel cost but increases with the number of trips produced by or attracted to each zone.

$$T_{ij} = K_i K_j T_i T_j e^{-\theta C_{ij}}$$

Where:
K_i, K_j = balancing coefficients

T_i = the production of zone i
T_j = the attraction of zone j
C_{ij} = the travel cost between i and j.

The gravity model assumes that the effect of distance or “separation” can be modeled by a decreasing function, in this case, the negative exponential function of the travel cost between the zones. The friction factor theta (θ) is a parameter in this function for calibration. A friction factor is an inverse function of travel time, which indicates whether people prefer longer or shorter trips. With the decline function specified, an iterative algorithm is executed to find the balancing coefficients (Ks).

2.3 Traffic Assignment

Traffic assignment describes how trips between an origin and a destination are allocated to different routes. In this research the traveler chooses the route with the lowest perceived travel time, which is referred to as a Stochastic User Equilibrium (SUE)(Sheffi, 1985). As elaborated by Sheffi (1985), Dials algorithm is used to perform network loading and Method of Successive Averages (MSA) to find the stochastic user equilibrium. Coding work implementing Dials Algorithm was used by Davis and Sanderson (2002) for the traffic assignment phase, though the code has been translated by the authors from Fortran to Java and optimized. This codebase generates good results on smaller test networks such as Sioux Falls and Waseca. The algorithm adopts the Bureau of Public Roads (BPR) link performance function by which the congested link travel time increases with the volume to capacity ratio to the fourth power (Bureau of Public Roads, 1964). The scaling coefficient used in the discrete choice model is 0.2 following Leurent (1995). The convergence for MSA is defined by a maximal allowable link flow change below a threshold of 100 vehicles [2].

2.4 Calibration

The travel demand model in SONG2.0 was originally calibrated with 2005 AM peak hour volumes. In order to improve the level of accuracy of our analysis, the model was re-calibrated against the real traffic data in July 2007 extracted from loop detector counts. Mn/DOT maintains around a thousand traffic count detector stations on freeways and major highways throughout the Twin Cities Metro area. Measured volume and occupancy data are made public via XML files updated every 30 seconds. As much as the authors would like to calibrate the model with all the stations, the complexity of matching every station with the correspond link in the planning network involves immense amount of time. To date, there is no correlation table for all the traffic count stations and the node and link structure of the Twin Cities planning model [3]. Instead, we randomly picked 10% of the full set of detector stations, removed malfunctioning detectors, and matched 63 out of the remaining stations

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[2] Clearly the lower the threshold is, the closer the resulted traffic pattern is to the equilibrium. The selection of this threshold is again a tradeoff between accuracy and running time.

[3] Xie and Levinson (2008) has a thorough discussion of this issue.

with the planning network, which consist of a total of 166 detectors located around the Metro Area on I-35W, I-35E, I-94, I-394, I-494, I-694, TH 5, TH 36, TH 62, TH 77, TH 100, TH 169 and TH 212 as shown in Figure 1. The morning peak hour volumes were then produced using the average of real count data from 7:00 a.m. to 9:00 a.m. on Monday, Wednesday and Friday in the last full week of July 2007.

The goal of this calibration is to minimize the difference between the AM peak hour volumes estimated by the model and actual AM peak hour volumes on the selected set of links. As trip generation models have been separately calibrated, the only parameter that was adjusted in this calibration is the distribution model friction factor. The final model has a friction factor of 0.14/min, resulting in an overall 0.71 percent error between the average volumes that go by the forecasts and the average real counts given by the detectors. The $R - Squared$, estimated by regressing forecast peak hour volumes on observed volume for selected stations is 0.91. The root mean square error (RMSE), defined by the formula below, is about 33.6%.

$$RMSE = \sqrt{\frac{(V_n^M - V_n^O)^2}{N-1}} \Big/ \bar{V}_n^M$$

Where:
V_n^M = Model estimated traffic volume on link n
V_n^O = Observed traffic volume on link n
N = Number of detector stations for calibration

3 Evaluation

Using the calibrated travel demand model, we estimated traffic patterns across the Twin Cities road network with and without the I-35W bridge. Alternative after-bridge-collapse scenarios were tested under different assumptions. The first kept the trip table fixed as it was before the bridge collapsed. This means that people did not change the number of trips, or destinations, in response to the bridge failure. This should give an upper bound to the effects of the bridge failure. The second allowed destinations of all trips to vary (though keeping the number of trips fixed) [4]. This provides more of a lower bound of the effects. We believe that the reality lies somewhere between the two extreme scenarios: clearly some people can switch destinations, change departure time to avoid peak hour traffic, or avoid trips altogether, if the cost of reaching their previous destinations are now too high; not everyone, on the other hand, has the flexibility to do so. Examples include commuting workers and college students. Scenarios 1 and 2 are tested on the crippled road network, which is created by directly removing the two directional I-35W bridge links from the base-scenario planning network, while ignoring Mn/DOT's efforts to restore traffic after bridge

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[4] The assumption that all trip destinations can vary does not mean all trips actually change their destinations. As the gravity-type model predicts trip distribution on an aggregate level according to travel costs between origins and destinations, how many trips will change destinations depends on the extent to which travel cost increases to reach previous destinations.

collapse though infrastructure upgrades[5]. Scenarios 3 and 4 included these upgrades in a updated planning network [6] and re-ran the model with a variable trip table and a fixed trip table, respectively. Table 1 summarizes tested scenarios based on alternative assumptions.

At an aggregate level, the model computes daily vehicle hours of travel (VHT) [7] and vehicle kilometers of travel (VKT) as direct outputs. A peak hour to daily factor of 0.08 is adopted from our previous research, estimated using the average peak hour and daily traffic counts from 2005 detector data. The model also computes average trip length and average trip time during the AM peak hour.

The economic loss incurred by the bridge collapse is evaluated by road-users' increased vehicle hours of travel due to the closed river crossing, monetized using values of time from Minnesota Department of Transportation (2005). Automobiles and trucks have different values of time of \$12.63/hour and \$20.41/hour, respectively. As our model does not break out cars and trucks, we instead generated a composite value of time of \$14.19 by assuming 80% auto and 20% truck.

The model also computes a series of accessibility measures which indicate the relative ease of reaching valued destinations. The isochronic or cumulative opportunity measure is one of the basic accessibility measures. This approach counts the number of potential opportunities that can be reached within a predetermined travel time (or distance). In this case, we calculated the average number of job opportunities that can be reached in 10 minutes, 20 minutes, and 30 minutes from a zone.

We also calculated the point accessibility from workers to jobs and from jobs to workers for each zone using the following mathematical relation:

$$A_i^E = W_i \sum_j E_j f(C_{ij})$$

$$A_i^W = E_i \sum_j W_j f(C_{ij})$$

where:

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[5] A list of I-35W traffic restoration projects and their budgets proposed by Mn/DOT can be viewed at `http://www.dot.state.mn.us/i35wbridge/pdfs/35WTrafficRestoration_Projects.pdf`. Major projects that have been implemented by the end of August 2007 include converting the substandard interchange on TH280 at Hennepin/Larpenteur from cloverleaf to diamond with two temporary signals of ramps, widening the north ramp of TH280 to two lanes, widening the south ramp from I-94 to TH 280 to two lanes, and adding the fourth lanes in each direction of I-94 between TH 280 and I-35W.

[6] We incorporated the change to the interchange at Hennepin/Larpenteur by increasing the capacity of upstream links on Hennepin Avenue and Larpenteur Avenue to 3500 vehicles per hour, the same as it is downstream on TH280; we estimated the capacity of links with added lanes assuming link capacity increases proportionally with the number of lanes.

[7] Our model estimates AM peak hour traffic, expands it into daily traffic, and computes daily VHT using peak hour travel time, which may exaggerate the actual vehicle travel time as trips that occur in non-peak periods experience a shorter travel time as opposed to those in peak periods. Given the fact that nearly half of all daily trips (45.7%) in 2000 occur during the AM and PM peak periods (Metropolitan Council, 2003), however, we believe our estimates constitute a close approximation without introducing too much error.

E_i = employment (jobs) at zone i
W_i = resident workers at zone i
C_{ij}= the cost to travel between i and j

The cost function $f(C_{ij})$ is determined using a gravity model, which states that the cost of traveling from origin i to destination j is inversely related to the distance between them.

$$f(C_{ij}) = e^{-\theta C_{ij}}$$

Note that the friction factor (θ) takes the same value as in the trip distribution model.

4 Results

The failure of I-35W bridge has resulted in significant changes in traffic conditions in the surrounding area. Figure 2 and Figure 3 display the estimated Volume-Capacity (V/C) ratios on individual links before (Scenario 0) and after (Scenario 2) the bridge collapse, respectively. They together illustrate how the removal of the bridge connection has impacted the traffic pattern across the network. As we can see in Figure 2, before the bridge collapsed, the interchange between I-35W and I-94, as well as the junction of I-94 and I-394 represent the most congested spots around downtown Minneapolis. After the bridge collapsed, as shown in Figure 3, severe congestion occurred at I-94 around the I-394 junction, and at TH280 around the I-94 junction, two major detour routes designated by Mn/DOT after August 1st. All the remaining bridges across the Mississippi river became more congested, especially the 10th Ave bridge, the one immediately to the right of the I-35W bridge. In contrast, the I-35W section north of Mississippi River to the TH36 junction saw a significant drop in traffic after the bridge closing.

Table 2 reports MOEs and accessibility measures in alternative scenarios. Note that these are direct model outputs, so while the precision is high, the accuracy is not nearly as high as implied by the precision.

As can be seen in Scenario 1 under which all people are free to change their trip destinations, the bridge failure has resulted in a 0.35% increase of daily vehicle hours of travel from 1.427 million to 1.432 million due to increased congestion. The increase in total vehicle travel time translates into an monetary loss of about $71,000 a day, which represents the lower bound of economic loss as in this case people enjoy the highest flexibility among all the after-bridge-collapse scenarios in terms of adjusting trip destinations in response to the bridge failure. Total vehicle kilometers of travel in Scenario 1, on the other hand, decreased by 0.31%. This is not surprising because some people switched to nearer destinations with a higher cost to reach their previous destinations. This can be corroborated by the results of a shorter average trip length but longer trip time as compared to the base scenario. Although people can switch to closer destinations, the job opportunities that can be reached during a specific duration have unavoidably decreased on the crippled network, so have the gravity-type measures of accessibility to jobs and workers in the metropolitan area. Scenario 2 represents the “worst-case” scenario as nobody can change their destinations despite increased travel cost after the bridge collapse. Consequently, both VHT and VKT have increased due to longer driving time and distance. Accordingly, accessibility to jobs and workers have significantly decreased after the bridge collapse. The increased vehicle time of travel with the fixed trip table amounts to about \$220,000 a day, which suggests the upper bound of economic loss. Thus it is estimated that the economic loss incurred by the I-35W bridge collapse on road-users in the Twin Cities metro area is \$71,000 to \$220,000 a day, depending on how flexible people can switch their destinations. As the exact number of people who change their destinations is not something we can easily know, we re-ran our model assuming that after the bridge collapse one third and two thirds of all trips are destined to their previous destinations, respectively[8]. Not surprisingly results produced with one-third and two-thirds assumptions lie between those in Scenario 1 and in Scenario 2. With one-third of all trips being fixed, the economic loss amounts to about \$120,000 a day, and if it is two-thirds, the loss increases to about \$170,000 a day. Scenarios 3 and 4 that incorporate a updated planning network have resulted in a lower economic loss as compared to their counterparts Scenarios 1 and 2.

The calculated reduction in economic loss suggests that the major upgrades Mn/DOT has implemented on road infrastructure in response to the bridge failure can save road-users \$9,500 (with a variable trip table) to \$17,500 (with a fixed trip table) a day, which translates into a direct economic benefit of approximately 4.8-21.3 million dollars, as the new I-35W bridge may open as late as December $24^{th}, 2008$ (511 days after the bridge collapse). Given the total budget of the restoration projects we have included in this analysis amounts to no more than \$2.4 million , the estimated benefit-cost ratio of these upgrades ranges from 2.0-9.0, indicating the restoration projects are highly beneficiary in an economic sense.

To have an idea of how accurately our model under alternative assumptions predicted the real traffic pattern after bridge collapse, we extracted the peak hour detector data for the selected stations in the last full week of August, 2007 and in that of October, respectively, and compared model forecasts to the real traffic counts. The percentage off of average forecast traffic counts on selected links as compared to the observations was computed, as well as the $RMSE$ for all after-bridge-collapse scenarios. As can be seen in Table 2, our model achieves an average error below 2% and a $RMSE$ of around 38% in all the scenarios when using the detector traffic counts in August. $RMSE$ has significantly dropped to about 32% in October, over two months after the shock of bridge collapse, when the traffic was restored order and a new equilibrium was reached. Although no significant difference is observed, Scenarios 1 and 3 assuming a variable trip table seem to outperform their counterparts with a fixed trip table in August in terms of producing smaller average error and $RMSE$, but this situation is reversed in October. This could be explained by the fact that in August people still searching for a new equilibrium, and before all of the road upgrades were in place, adjust their destinations to avoid crossing the river; while in October when a new equilibrium was established, most people switched back to their previous destinations.

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[8] According to Metropolitan Council (2003), home-based work trips account for 34.3% of all trips that occur during AM peak hour. Thus one-third assumption would be close to the reality if all the home-based work trips had fixed their destinations but other trips not; the two-thirds assumption would be meaningful if we assume all the home-based work trips and half of other trips fix their destinations.

5 Conclusions

This study evaluates the effects of I-35W bridge collapse on road-users in the Twin-Cities metropolitan area. We adopted the Twin-Cities Seven-County travel demand model we developed in a previous research, re-calibrated it against July 2007 loop detector traffic data, and used this model to carry out an evaluation of economic loss incurred by increased travel delay in alternative scenarios before and after the bridge collapse. We conclude that the failure of the I-35W bridge resulted in an economic loss of \$71,000 to \$220,000 a day, depending on how flexible road-users in the system can adjust their trip destinations in response to the bridge closing. The evaluation of road-users' daily economic loss provided some general guidance and insight for decision-makers in incident response and traffic restoration, in addressing issues like bonus-setting for contractors associated with the construction period of the replacement bridge. According to Kaszuba and Foti (2007), Mn/DOT set a \$200,000 a day bonus (up to 100 days) for an early finish of the I-35W new bridge, which falls on the high side of the range of estimated users' economic loss between \$71,000 and \$220,000 a day. Based on the economic loss calculation, we also estimated that the major traffic restoration projects Mn/DOT has implemented in quick response to the bridge collapse can save road-users \$9,500 to \$17,500 a day. This translates into a benefit-cost ratio of 2.0-9.0, suggesting these projects are highly beneficiary in an economic sense.

This analysis could be treated as a "back of the envelope" calculation in order to capture the magnitudes of the economic impact of the bridge closure. The use of a simplified, scaled-down travel demand model enabled us to carry out the analysis quickly and accurately. On the one hand, the duration of one scenario test was limited within a hour, which is pretty fast considering the magnitude of the Twin-Cities transportation system; on the other hand, the travel demand model achieved a $R - Squared$ of 0.91 and a $RMSE$ of 0.33 in calibration, and was able to predict the changes in traffic conditions after the bridge collapse. One needs to realize our model has achieved the short running time at the cost of sacrificing some realism in the analysis. A longer time of period allowed, improvements on modeling techniques and assumptions may generate more accurate results. This analysis, though, could see its contributions in transportation planning under situations such as emergency relief and comprehensive design.

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Scenario	**Time**	**Trip Table after Aug 1st**	**Planning Network**
0 (Base)	Before bridge collapse	N.A.	Complete network
1	After bridge collapse	Variable	Crippled network
2	After bridge collapse	Fixed	Crippled network
3	After bridge collapse	Variable	Crippled network with upgrades
4	After bridge collapse	Fixed	Crippled network with upgrades

Table 1: Descriptions of scenarios

	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Daily VHT (10^6 veh.hrs)	1.427	1.432 (0.35%)	1.442 (1.09%)	1.431 (0.31%)	1.441 (1.00%)
Daily VKT (10^6 veh.kms)	86.53	86.27 (-0.31%)	86.58 (0.05%)	86.27 (-0.30%)	86.58 (0.06%)
Daily Economic loss ($)	N.A.	71,466	220,198	62,408	203,409
Aver trip length (kms)	18.82	18.76 (-0.31%)	18.83 (0.05%)	18.76 (-0.30%)	18.83 (0.06%)
Aver trip time (mins)	18.61	18.68 (0.35%)	18.82 (1.09%)	18.67 (0.31%)	18.8 (1.00%)
Jobs reached in 10 mins	110,072	108,036 (-1.85%)	107,692 (-2.16%)	108,255 (-1.65%)	107,931 (-1.95%)
Jobs reached in 20 mins	557,514	545,791 (-2.10%)	543,669 (-2.48%)	546,751 (-1.93%)	545,230 (-2.20%)
Jobs reached in 30 mins	1,105,462	1,089,406 (-1.45%)	1,087,226 (-1.65%)	1,090,994 (-1.31%)	1,089,424 (-1.45%)
Accessilibty to jobs	3.23E+11	3.17E+11 (-1.70%)	3.17E+11 (-2.00%)	3.18E+11 (-1.58%)	3.17E+11 (-1.83%)
Accessilibty to workers	3.30E+11	3.25E+11 (-1.55%)	3.24E+11 (-1.79%)	3.25E+11 (-1.41%)	3.25E+11 (-1.60%)
Aug 2007, % off average	N.A.	0.52%	1.57%	0.61%	1.66%
Aug 2007, RMSE oct	N.A.	37.98%	38.35%	38.03%	38.44%
Oct 2007, % off average	N.A.	-5.81%	-4.82%	-5.73%	-4.74%
Oct 2007, RMSE oct	N.A.	32.18%	32.00%	32.17%	32.01%

Table 2: MOEs and accessibility measures in alternative scenarios. Number in parenthesis indicate the percentage change of a measure as compared to its counterpart in the base scenario.

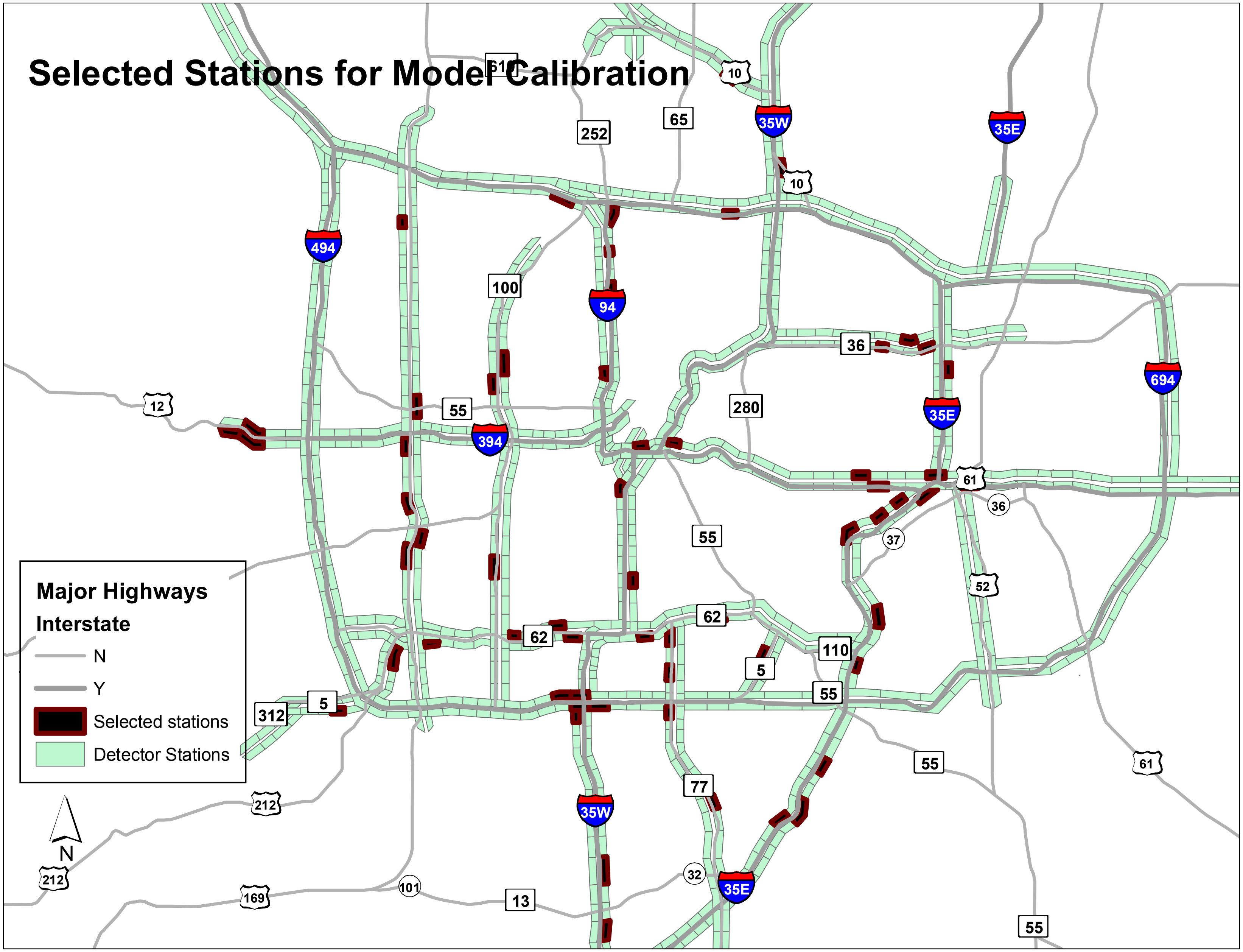

Figure 1: Selected 63 detector stations for calibration

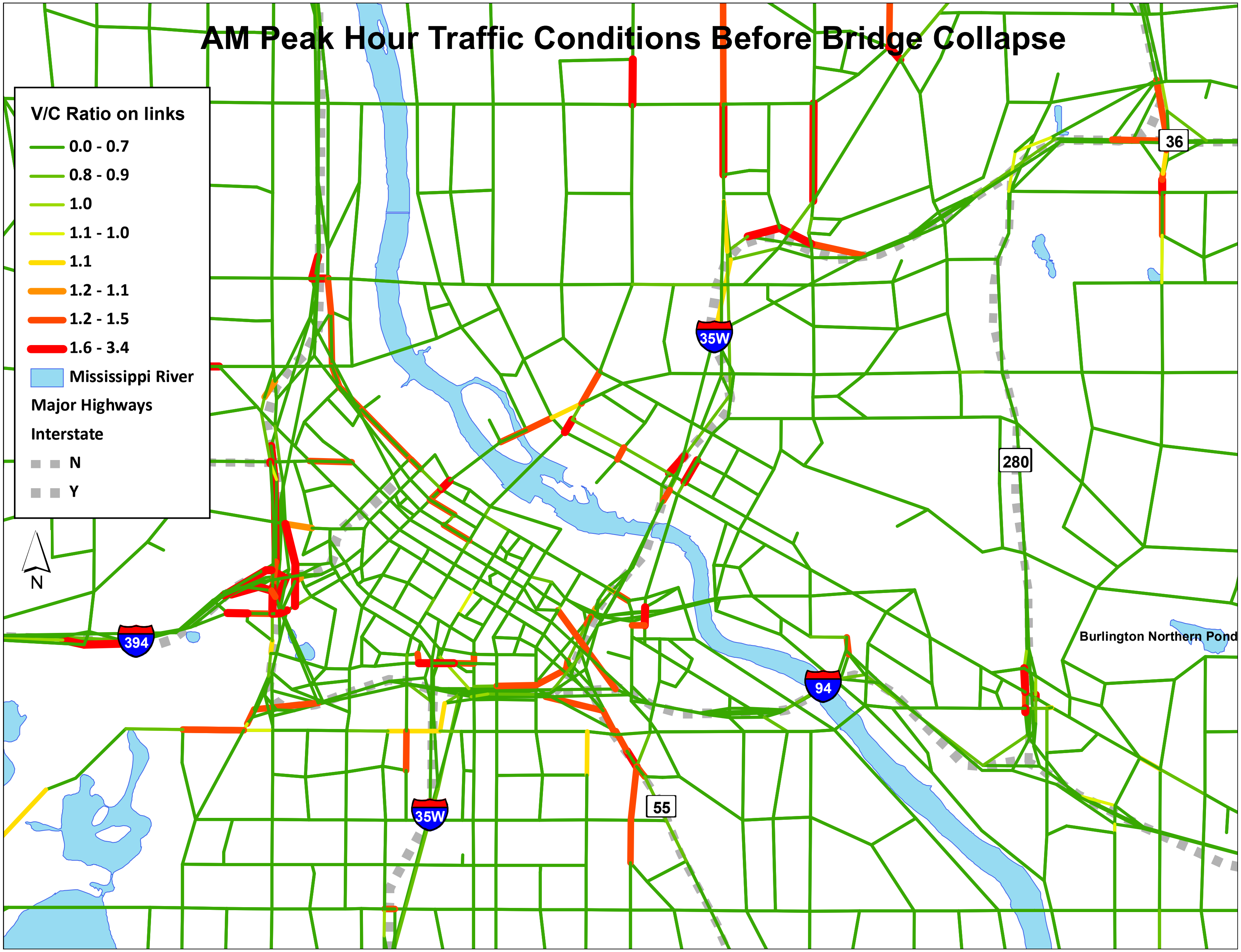

Figure 2: Traffic conditions before I-35W bridge collapse (Scenario 0)

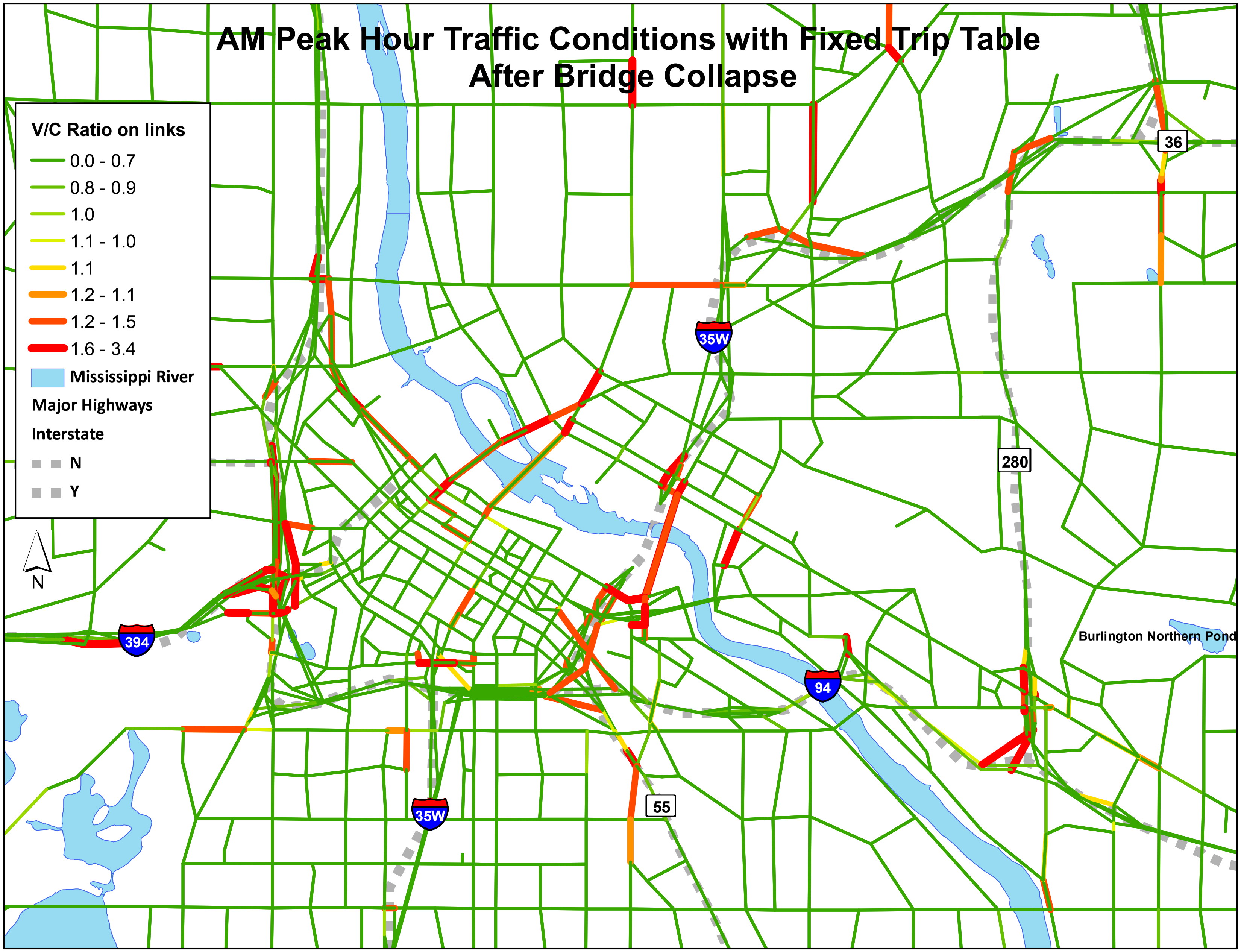

Figure 3: Traffic conditions with a fixed trip table after I-35W bridge collapse (Scenario 2)