Unexpected versus Expected Network Disruption: Empirical Observations on Travel Behavior Changes

Adam Danczyk
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota, Twin Cities

Xuan Di
Department of Civil and Environmental Engineering
University of Michigan Transportation Research Institute
University of Michigan, Ann Arbor

Henry X. Liu*
Department of Civil and Environmental Engineering
University of Michigan Transportation Research Institute
University of Michigan, Ann Arbor
henryliu@umich.edu
(*Corresponding Author)

David M. Levinson
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota, Twin Cities

Submitted to Transport Policy

May 23, 2016

Abstract

This paper discusses the observed evolution of traffic in the Minneapolis-St Paul (Twin Cities) region road network following the unexpected collapse of the I-35W Bridge over the Mississippi River. The observations presented within this paper reveal that traffic dynamics are potentially different when a prolonged and unexpected network disruption occurs rather than a preplanned closure. Following the disruption from the I-35W Bridge's unexpected collapse, we witnessed a unique trend: an avoidance phenomenon after the disruption. More specifically, drivers are observed to drastically avoid areas near the disruption site, but gradually return after a period of time following the collapse. This trend is not observed in preplanned closures studied to date. To model avoidance, it is proposed that the tragedy generated a perceived travel cost that discouraged commuters from using these sections. These perceived costs are estimated for the Twin Cities network and found to be best described as an exponential decay cost curve with respect to time. After reinstituting this calibrated cost curve into a mesoscopic simulator, the simulated traffic into the discouraged areas are found to be within acceptable limits of the observed traffic on a week-by-week basis. The proposed model is applicable to both practitioners and researchers in many traffic-related fields by providing an understanding of how traffic dynamics will evolve after a long-term, unexpected network disruption.

Keywords: Unexpected network disruption; Avoidance phenomenon; Perceived cost evolution; Traffic dynamic, I-35W Bridge Collapse.

1. Introduction
1.1 Motivation

On August 1st, 2007, at 6:05 PM, the I-35W Bridge over the Mississippi River in Minneapolis, Minnesota, unexpectedly collapsed. The sudden tragedy resulted in the deaths of thirteen commuters and the injury of hundreds. In quick response to the disaster, the Minnesota Department of Transportation converted a former arterial, Trunk Highway 280 (TH 280), into a freeway on August 2nd and designated I-94/TH 280 as the alternative route to serve the traffic previously using I-35W.

Large-scale, long-term transportation network disruptions due to unexpected tragedies are fortunately rare events, but their impact on the local environment can often be serious and prolonged. Given the scarcity of data collection devices near these disruptions, most work regarding network disruptions has been on the long-term impacts. The disruption of a transportation network can have substantial consequences on an economy, either at a local, regional, or national level (Kim et al., 2002; Ham et al., 2005a, Ham et al., 2005b, Sohn et al., 2003). Given these impacts, research has been conducted to aid engineers and planners in finding optimized reconstruction schedules following such disruptions (Lee and Kim, 2007; Chen and Tzeng, 1999; Kiyota et al., 1999) or identify network vulnerabilities (Matisziw and Murray, 2009; Ball et al., 1999). While useful for long-term planning, such research fails to address transient traffic dynamics in the short term. The collapse of the Tasman Bridge in Hobart, Australia, prompted an investigation into traffic change, but the work provides only long-term results (Hunt et al., 2002). Similarly, Cairnes et al. (2002) outlined case studies where road reduction, such as for conversion to pedestrian pathways, did not have the negative impacts on traffic as traditionally believed. While this work does mention some short-term effects on traffic from anticipated closures, it quantifies only the long-term effects. Some research has looked into the consequences on a network following an earthquake, but the focus of this work is either on transportation system performance (Chang and Nojima, 2001), the success of a car-sharing program to reduce commuting traffic following a disaster (Tsuchida and Wilshusen, 1991), or single-point medium and long-term results (Giuliano and Golob, 1998; Wesemann et al., 1996). A more complete review is available in Zhu and Levinson (2011). To date, the evolution of traffic immediately following an unexpected disruption in network infrastructure remains largely unexplored.

With the tragic collapse of the I-35W Bridge, a research opportunity to study traffic dynamics on a day-by-day basis became available, as the loop detector infrastructure around the Twin Cities network could provide traffic data on a continuous basis.

1.2 Literature Review

Traditionally, traveler’s route choice behavior has been modeled using the user equilibrium concept, in which travelers make their route choice decision by selecting the path with the lowest travel cost (Wardrop, 1952). Using this concept, Beckman et al. (1956) formulated a mathematical model to solve deterministic user equilibrium, assuming that drivers had perfect network knowledge, were rational, and were homogeneous. However, given the improbability of these assumptions (Zhang 2011), a variety of equilibrium models have been proposed: stochastic user equilibrium (SUE) (Daganzo and Sheffi, 1977; Sheffi and Powell, 1982), Probabilistic UE (Lo et al., 2006), late arrival penalized UE (LAPUE) (Watling, 2006), mean-excess traffic equilibrium (METE) (Chen and Zhou, 2010; Chen et al., 2011), stochastic bicriterion user-optimal (Dial, 1996; Dial, 1997), bi-objective UE (BUE) (Wang and Ehrgott, 2013), and boundedly rational user equilibrium (BRUE) (Lou et al., 2010; Di et al., 2013; Di et al., 2014; Di et al., 2015; Di et al., 2016a; Di and Liu, 2016b; Di et al., 2016c). These models assume route costs were expanded with an additional term due to driver perception error or indifference towards alternatives with similar utilities.

The conventional approach has been to solve route choice by assuming the network achieves equilibrium, but some work has revealed a network to be a constantly evolving entity based on drivers' daily experiences and perceptions. To understand the evolution of traffic dynamics on a day-to-day basis, dynamical systems have been proposed (e.g. Smith, 1984; Friesz et al., 1994). Horowitz (1984) showed that a two-link network, given a set of learning mechanism assumptions, may never achieve stability under stochastic user equilibrium. Existing traveler learning mechanisms can be classified into three categories (Jotisankasa and Polak, 2006): weighted average approaches (e.g., Watling, 1999; Nakayama and Kitamura, 2000), adaptive expectation approaches (e.g., Cascetta and Cantarella, 1991), and Bayesian approaches (e.g., Jha et al. 1998; Chen and Mahmassani, 2004). In addition to the theoretical modeling of drivers' learning mechanism, the day-to-day traffic dynamic model has also been tested empirically, such as in simulation (Mahmassani and Chang, 1986, Jotisankasa and Polakm, 2005), or against empirical data (Cascetta, 1989).

These models, however, only focus on the evolution of traffic dynamics on a network with unchanging infrastructure. He and Liu (2012) proposed for the first time a day-to-day prediction-correction model to describe traffic dynamic evolution following unexpected network topology change. This model successfully captures the behavioral change in route choice after the I-35W Bridge collapsed and the replacement opened.

There also exist several studies by the research team investigating the bridge collapse and replacement (Xie and Levinson 2011, Zhu et al. 2010, Zhu et al. 2011, Zhu et al. 2012). Zhu et al. (2010) and Zhu et al. (2012) studied the impact of the I-35W Bridge collapse on travel behavior by inspecting aggregate traffic flow equilibrium before and after in the Twin Cities network. Zhu et al. (2011) further proposed an econometric model to identify factors contributing to individual's choices in a disrupted network. Xie and Levinson (2011) evaluated the economic effect of the bridge collapse and major traffic restoration projects using a travel demand simulation model. Though these studies provide a comprehensive modeling framework of travel behavioral change in response to the I-35W Bridge, they are mainly focused on the I-35W Bridge alone without comparing its influence with other scenarios. This paper discusses observations made of traffic evolution following the collapse of the I-35W Bridge, complementing previous work by identifying an avoidance behavior for unplanned network disruption while it remains almost unchanged after planned road closures.

1.3 Contributions

This paper analyzes the traffic dynamics after unexpected long-term link closures. Through the observations made in this work, one unique trend is witnessed following these prolonged and unexpected disruptions: an avoidance phenomenon after the disruption. For purposes of this work, the "avoidance phenomenon" is an observational behavior found in data, where traffic volumes into a particular area on the freeway system decreases near an area of unexpected network disruption. Theoretically, the avoidance phenomenon results from a significantly increase in travelers' perceived cost that discourages route use at equilibrium where the road network carries a different traffic load. Given the constant travel demand levels, the routes passing through the neighborhood of disruption areas carry significantly reduced traffic loads than others. Rather than assign a metric threshold to identify this phenomenon—such as "a 10% decrease in traffic", which may not be a good measure for all roadway networks or disruption events—this phenomenon will be identified as an uncharacteristic, but observationally apparent departure from normal traffic volumes when an unexpected disruption occurs. Following that departure, the expectation is that the avoidance desire decreases and the network returns to an equilibrated volume, which may be the same or different as the volume prior to the disruption. It is important to reiterate that this phenomenon is expected only during unexpected disruptions, which suggests an unreasonable increase in perceived user cost due to the suddenness of the event.

Contrasting observations made at the I-35W Bridge site against a preplanned road construction closure at a different site with similar network topology, it is shown that traffic appears to react differently on a day-to-day basis following unexpected and expected closure. Expected closures have usually been preceded by a public campaign effort by the local transportation agency to raise awareness, to minimize any unexpectedness and allow commuters time to find alternate routes, and are defined as a closure where forewarning exists, such as preplanned closures for major road repair or bridge rehabilitation. An unexpected closure here is defined as one that occurs without forewarning, such as a bridge collapse or other infrastructure disaster,

The aforementioned observation is interesting because, despite the two sites having a similar impact on the network pending long-term closure, the response is much different. Such disparity asks the question: Does traffic behave differently when a network disruption is sudden and unforeseen? If so, traffic models proposing to predict evolutionary dynamics following a network disruption may need to account for these differences, depending on the type of disruption.

In summary, the purpose of this work is to illustrate the observations from two case studies where long-term, unexpected network disruptions have occurred and compare them against observations from case studies of expected closures. It contributes to existing research in three ways:

1. It provides observable data on a day-to-day basis and discusses potential uses for this information. It provides an opportunity for additional research questions into the motivations and perceptions of drivers following such disruptions and offers guidance to the development of theoretical day-to-day models designed specifically for post-disruption scenarios.
2. It also establishes a perceived-cost based model to explain the traffic dynamics after such a long-term, unexpected network disruption. It provides an opportunity to further understand the impact of unexpected disruption on drivers' perception, and offers an applicable approach in the development of day-to-day traffic models that utilize perceived cost evolution as the underlying factor of drivers' decision making.
3. With knowledge of how traffic evolves in the short term following a disruption, network operators can better allocate traffic management resources, such as infrastructure

enhancements, law enforcement presence, or incident management vehicles, to improve operational efficiency and commuter safety.

The remainder of the paper is organized as follows: In Section 2, we discuss the I-35W Bridge collapse event and illustrate the traffic dynamics following the tragedy. The effects of unexpected disruption are shown not to be unique to just the I-35W Bridge scenario, based on another similar disaster: San Francisco Bay Area network disruption. To further inspect whether traffic dynamics observed at preplanned closures display similar patterns, in Section 3, behaviors after partial closure of Trunk Highway 36 in the Twin Cities, Minnesota is investigated, showing starkly contrasted trends compared to unexpected disruption. In Section 4, the avoidance phenomenon we identified from the I-35W Bridge collapse event is modeled, assuming traffic are influenced by perceived travel costs as a result of the tragedy. We reveal the evolution of perceived travel cost is best described as an exponential decay function. The applicability of the proposed model by using a calibrated mesoscopic traffic simulation model is validated. The mesoscopic simulator is able to reproduce traffic flows that are similar to real-world cordon traffic on a week-by-week basis. Concluding remarks are provided in Section 5.

2. Unexpected Network Disruption

To analyze the impact of network disruption, this work examined volumetric flows entering an area of the network that fell within varying degrees the disruption's influence. To best ascertain these varying degrees, a "cordon zone" methodology was followed, where cordon circles were drawn at varying lengths from the disruption site and all inbound freeway traffic volumes were measured as they crossed the circles. Each cordon circle was drawn to encompass certain key roadway topology, as opposed to strict Euclidian distances that may not capture all features on an asymmetric network. The rationale for each cordon line will be explained later for each case, but tended to examine the same types of areas:

- Immediate area near the disruption site – purpose is to evaluate how many vehicles came near the disruption area, but were forced off the network after the disruption occurred.
- Nearest Available Alternate Route – purpose is to evaluate how many vehicles continuing using the same route, but by using the nearest available freeway alternate route after the disruption occurred.
- Within Major Ring Road – purpose is to evaluate how many vehicles continued to come within the region's major "ring" road, when an alternative route would be to use the ring road to bypass the disruption.
- Outside Major Ring Road – purpose is to evaluate whether the disruption affected traffic volumes coming to the region, such as cross-country trips.

2.1 I-35W Bridge Collapse

The I-35W Mississippi River Bridge plays a critical role in transporting commuters to downtown Minneapolis and the University of Minnesota. Its collapse in 2007 forced 140,000 daily users (Zhu et al. 2010) to switch to other parallel bridges or to cancel their trips. Despite the tragedy, the majority of loop detector infrastructure around the Twin Cities freeway network remained fully operational. Using loop detectors on all Twin Cities on-ramps to capture traffic counts, the total traffic to the freeway was assessed on a daily basis during a three-hour period in the AM Peak.

Data was collected between July 23rd, 2007, and August 31st, 2007, to determine if the bridge collapse caused a significant change in freeway flows. These daily total counts are provided in Figure 1.

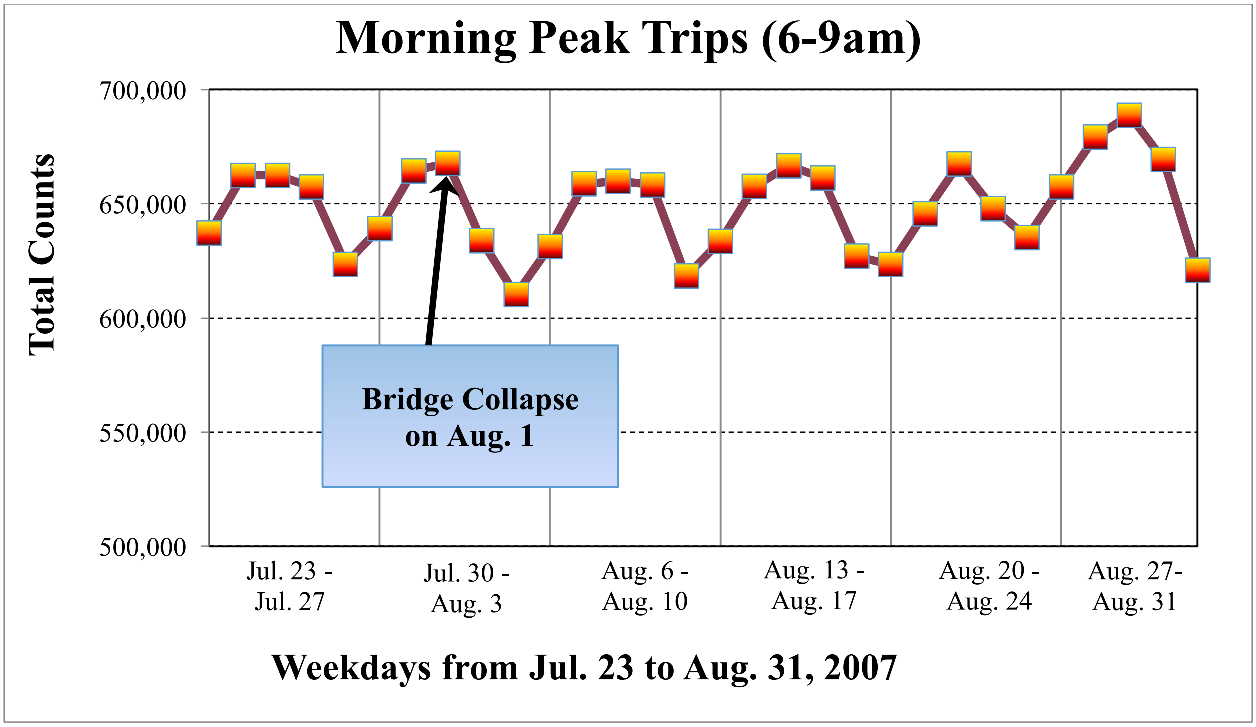

Figure 1: Daily trips entering the Twin Cities freeway network via on-ramps

As revealed by the on-ramp data, freeway flows in the days and weeks following the bridge collapse do not experience drastic changes, instead fluctuating within the bounds of weekly variation. The exception is on August 2nd, which is the first day following the collapse, where a noticeable decrease occurs when compared to other Thursdays. Otherwise, traffic levels remain consistent with previous weeks. This shows that the bridge collapse did not influence freeway traffic during the morning Peak on the system as a whole. Given this, the next question is how, if at all, the bridge collapse influenced traffic within the network.

This work will focus on the evolution of traffic patterns on freeway and major instrumented arterial routes heading toward the bridge. To do this, several zonal regions will be defined around the bridge collapse site. These zonal regions do not necessarily have a Euclidean radius, as such a radius would collect biased infrastructure features (e.g. accounting for a major interchange on one side of the zone, but not the other). Instead, the boundaries of these zones are defined by cordon lines, which are drawn to uniformly capture similar network topology. For example, a cordon may be drawn to cross all routes bound for downtown Minneapolis, as to study if traffic avoided the central business district after the collapse. These lines serve as counting points, where all traffic entering the cordon is tallied and aggregated over the analysis period. Cordon lines have been used in the past to study traffic patterns for different purposes (Roess et al., 2004), such as traffic planning around activity centers.

Counts will be provided by the existing loop detector infrastructure on the freeways and most major arterials. Minor arterials and city streets, which had no daily counts occurring at the time of the collapse, will not be included in the total count. This excluded traffic represents a small minority of commuting traffic, as traffic in the Twin Cities generally uses the freeways and major arterials due to the limited capacity available on these smaller routes.

Five cordons are tested, shown in Figure 2. The network topologic features intended to be captured are discussed in Table 1. For reference, Cordon 1 refers to the smallest cordoned area near bridge while Cordon 5 refers to the largest cordoned area around the metropolitan area.

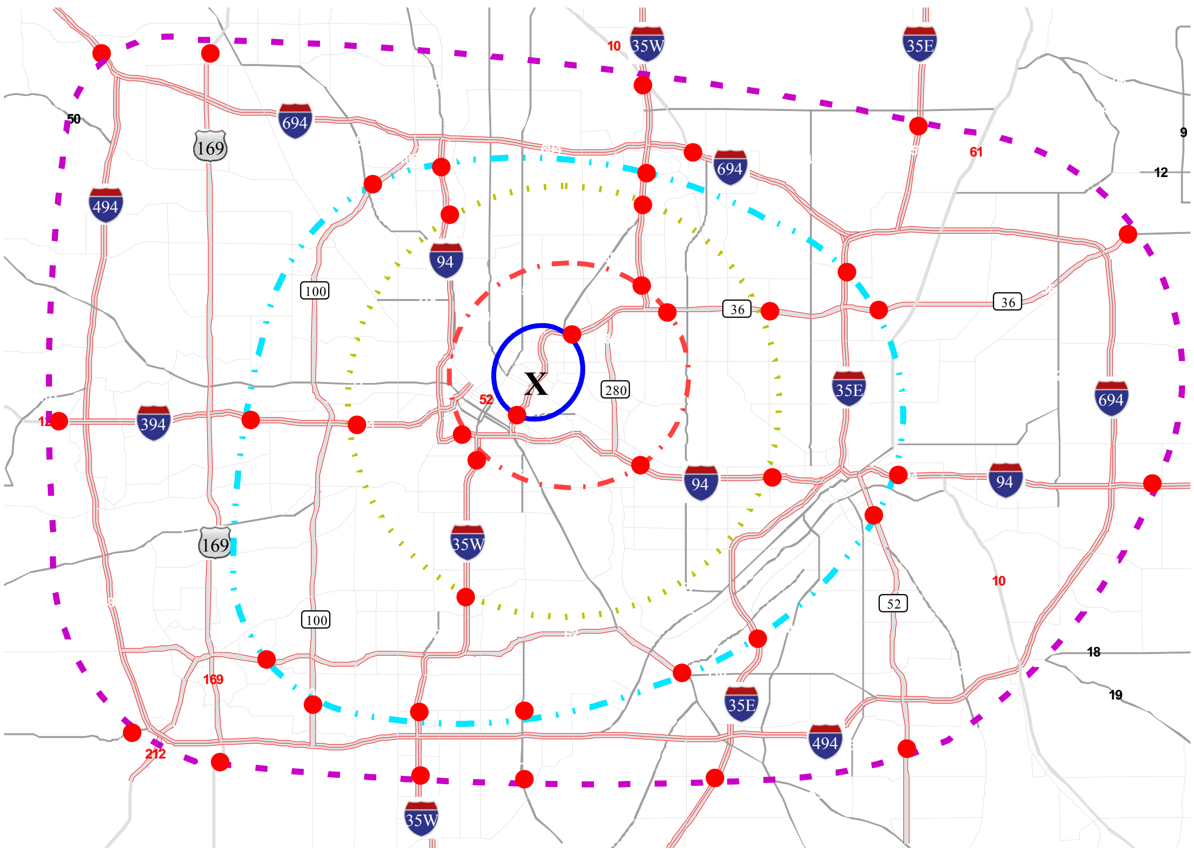

Figure 2: Five cordon circles around the Twin Cities for the I-35W Bridge, where the closed bridge is marked with an 'x' (Cordon 1 is the innermost cordon line, increasing to Cordon 5 as the outermost cordon line)

As described earlier, the cordon circles were selected to encompass similar roadway topology features, such as entirely capturing an alternate route that is available to the route that experienced the disruption. The cordon circles attempted to capture varying degrees of network features to demonstrate impacts to traffic at varying locations relative to the disruption. For the Twin Cities network, the cordons were selected based on criteria outlined in Table 1.

Table 1: Network topologic features of cordoned areas in Twin Cities

Cordon Number	Region within Cordon	Network Topology Features	Approximated Cordon Radius (miles)

1	Immediate Area of I-35W Bridge	No alternative routes within cordon. No freeway connectivity within cordon. Traffic approaching bridge is forced to exit.	0.5
2	I-35W/I-94 Corridor Interchange	Includes I-94 corridor and I-35W (using TH 280 detour) corridor. No other freeway-based alternative routes within cordon.	2.5
3	City of Minneapolis and Minneapolis Central Business District	Includes all routes bound for Minneapolis. Some freeway-based alternative routes.	5.5
4	Minneapolis and St. Paul Central Business District	Includes all routes heading toward central business district in either city. Many freeway-based alternative routes.	8.5
5	Twin Cities Metropolitan Area	Includes all routes approaching the I-494/I-694 beltway. Many freeway-based alternative routes.	15

The aggregated freeway counts entering these cordons are analyzed for each non-holiday weekday between Monday, July 9th, 2007, and Friday, November 16th, 2007. The period in which traffic is counted is during the morning peak, as most trips in this time period historically are inflexible ones, such as journeys to work or school. To avoid issues of peak spreading, the morning peak period is designated between 6 a.m. and 10 a.m. local time, which is consistent with the accepted morning peak period for this area. Thus, the aggregated total for each day consists of four hours of traffic counts.

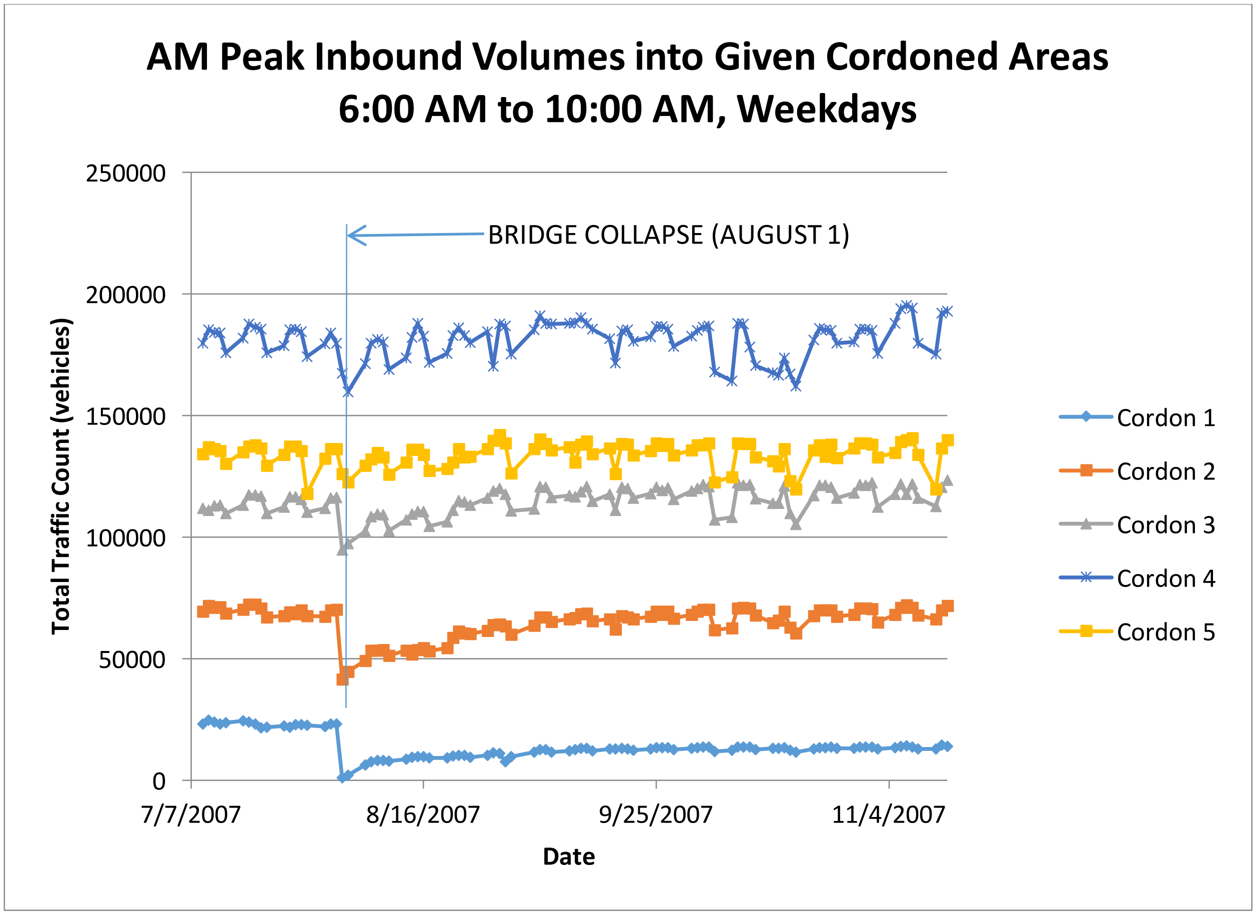

Figure 3: Total Traffic Counts for Each Cordon Circle for Twin Cities Network in 2007

Figure 3 illustrates the evolution of daily four-hour traffic counts over the analysis time frame. Prior to the bridge collapse, traffic counts are mostly stable for all five cordons. However, after the collapse, these counts dramatically change. The traffic at Cordon 1 drops to nearly zero while traffic at Cordons 2 and 3 decrease as well. In the weeks following the collapse, the traffic at these three cordons recovers to a certain stabilizing point in the long term. These traffic changes are not observed at Cordons 4 or 5, where total traffic stays relatively stable across the entire time period.

We want to point out that although total traffic stays relatively stable after avoidance behavior stabilizes, there still exist traffic fluctuations. In Figure 3, there are several relatively pronounced dips in the traffic counts. However, these drops are not as significant as the drop right after the bridge collapse and caused by either weekly, seasonal, or holiday fluctuations. First, there is a natural gravitation toward higher traffic between Tuesday and Thursday and lower traffic on Monday and Friday. A noticeable variance can be seen between weekend traffic and weekday traffic, which is to be expected. Second, traffic oscillates on certain days for Cordons 2-5 due to special events:

- 8/31/2007 – This is the Friday before Labor Weekend. Most people in the region would traditionally take that day off. Consequently, there are dips on Cordons 3, 4, and 5. The similar trend was also observed in the year of 2006 (not shown in Figure 3) but to a lesser extent.

- 10/5/2007 and 10/8/2007 – This is Columbus Day (on October 8, 2007). Most government services and schools are off on that day. As a consequence, some people in the region would traditionally take the previous Friday off (10/5) to have a four-day weekend. The similar trend was also observed in the year of 2006 (not shown in Figure 3) but to a lesser extent.
- 10/19/2007 –Schools in the region traditionally have an academic holiday around this time (the date differs each year), where children would have a day off of school and parents would work from home. A similar dip was also observed in the year of 2006 (not shown in Figure 3) that echoes roughly the same.
- 11/10/2006 – Veterans Day. Traffic drop is observed typically because most government offices and schools are closed. Some people in the region would have a paid holiday off work.

Taking a closer look at the cordons, it is seen that these dramatic traffic decreases, or “shocks”, diminish in intensity as alternatives become available, generally corresponding to an increase in distance from the bridge. Between pre- and post-collapse traffic, Cordons 1, 2, and 3 experience shocks of 67 percent, 25 percent, and 6.5 percent, respectively, while Cordons 4 and 5 experience no notable shocks. Similarly, aside from Cordon 1, the recovery rate to pre-collapse traffic is faster with more alternatives, as Cordons 2 and 3 recover by September 28th and August 24th, respectively, and Cordons 4 and 5 recover seemingly instantaneously. Cordon 1 can be considered a unique case as, given a severed corridor and no alternative freeway or major arterial routes within the cordon, the long-term post-collapse traffic is more than 40 percent lower than pre-collapse traffic. Thus, recovery to this substandard traffic occurs in a relatively short time, achieving stability on around August 24th. Stability, for this work, was considered present for a given cordon when week-by-week traffic vary by less than 5 percent.

When analyzing Year 2006 data for the same time period, these shocks and recoveries are not observed, revealing that they are a likely consequence of the bridge collapse rather than seasonal variation. Traffic counts entering the cordons during the same seasonal time period in Year 2006 are shown in Figure 4 to reveal these absences.

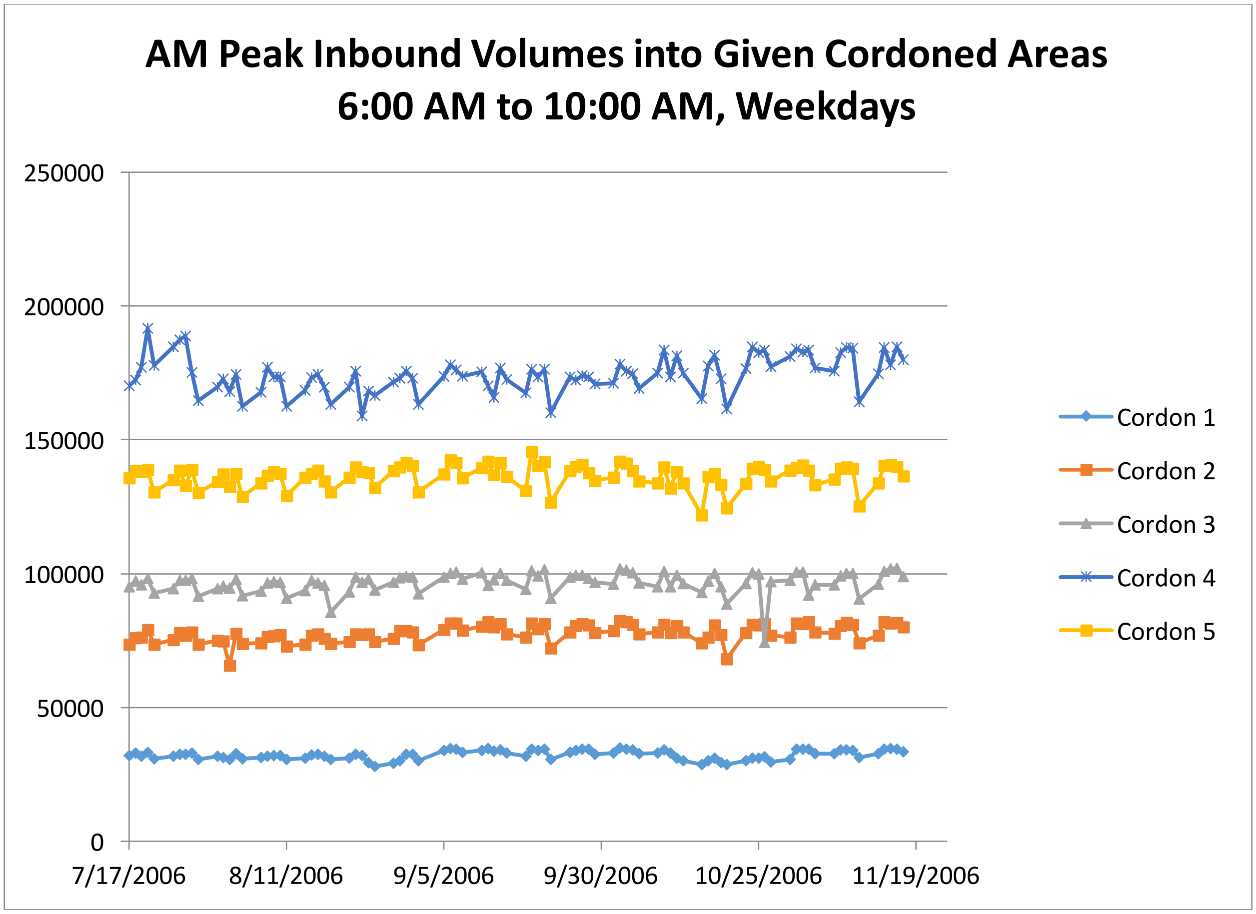

Figure 4: Total Traffic Counts for Each Cordon Circle for Twin Cities Network in 2006

Moreover, as shown by the daily traffic for the freeway in Figure 1, the magnitude of morning commuters over this time period remains largely unchanged, suggesting that the decreases in traffic corresponds with a desire to avoid these cordons because of the collapse. This is particularly interesting because this avoidance results in spare capacity within the cordoned areas. Is this avoidance phenomenon a characteristic of unexpected network disruptions or is it unique only to the Twin Cities network? To answer this question, another network with an unexpected disruption event will be analyzed to observe the presence of this phenomenon.

2.2 MacArthur Interchange Collapse

In the early morning hours of Sunday, April 29th, 2007, a tanker truck carrying flammable fuel overturned on the MacArthur Interchange near Oakland, California, which is a busy interchange serving major routes including Interstate 80, Interstate 580, Interstate 880, and the Bay Bridge into San Francisco. The resulting fire from the tanker truck structurally weakened a ramp overpass, causing it to collapse and effectively closed two freeway-to-freeway ramps. The extent of the damage required a construction effort that, as initially stated to the public, would likely take several months. While not a full closure for the interchange, the absence of the ramps significantly reduced accessibility for certain highways. Between the periods before and after the collapse, we calculate the total traffic flows entering the freeway system in the Bay Area network and did not find out any significant change in freeway flow. In other words, the total travel demand did not vary substantially due to the collapse.

To explore the impact on traffic distribution, the same cordon-line methodology is applied to the Bay Area network, using California Department of Transportation Freeway Performance Measurement System (PeMS) data to provide traffic counts. Four cordons are proposed, shown in Figure 5. The network topologic features intended to be captured are discussed in Table 2. For reference, Cordon 1 refers to the smallest cordoned area near bridge while Cordon 4 refers to the largest cordoned area around the metropolitan area.

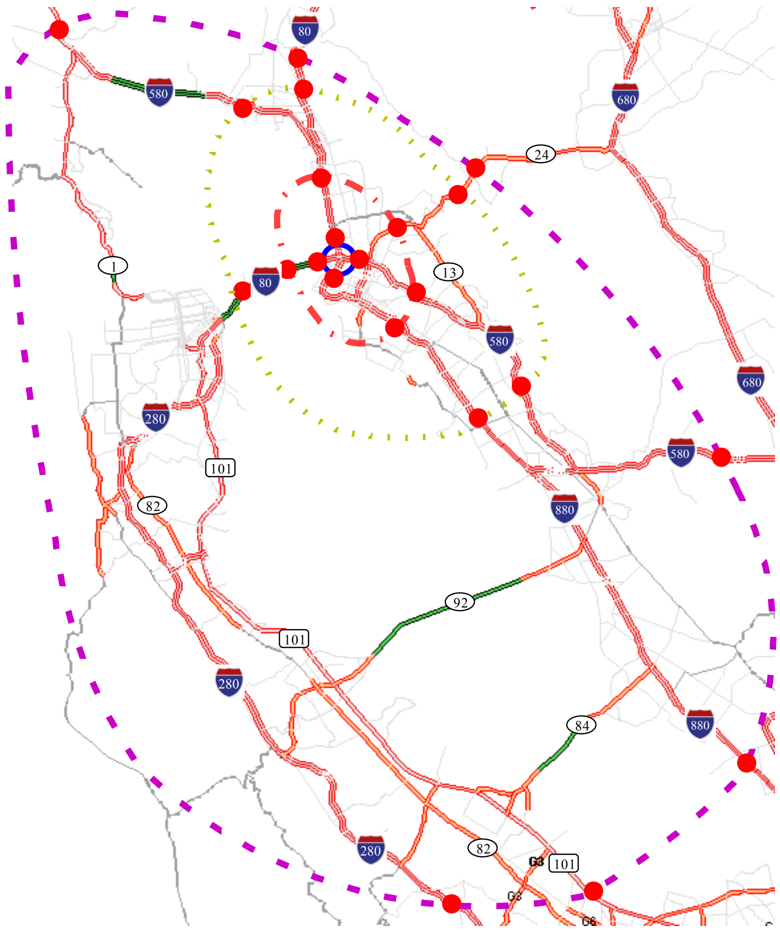

Figure 5: Four cordons around the MacArthur Interchange in the Bay Area, where the closed ramps are located within the innermost cordon (Cordon 1 is the innermost cordon line, increasing to Cordon 4 as the outermost cordon line)

Table 2: Network topologic features of cordoned areas in Bay Area

Cordon Number	Region within Cordon	Network Topology Features	Approximated Cordon Radius (miles)

1	Immediate Area of MacArthur Interchange	No alternative routes within cordon. No freeway connectivity within cordon for corridors with severed connections. Unsevered routes operate at full capacity	0.5
2	I-80/I-580/I-880/I-980 Corridor	Includes interchange-bound corridors. Some freeway-based alternative routes available within cordon.	2
3	Greater Oakland/Berkeley Area	Includes all freeway routes to the Oakland/Berkeley Areas. Some freeway-based alternative routes available within cordon.	5
4	Bay Area Metropolitan Area	Includes all freeway routes to San Francisco/Oakland Area. Many alternative routes within cordon.	8~24

The aggregated counts entering these cordons are analyzed for each non-holiday weekday between Monday, April 2nd, 2007, and Friday, June 29th, 2007. Like the Twin Cities, the morning peak period is the analysis time frame, but instead using four-hour counts between 5 a.m. and 9 a.m. local time. This shift in time frame was due to observed differences in the times of the peak period in the San Francisco Bay area. The four-hour counting period was kept the same to compare with the observations of the I-35W Bridge.

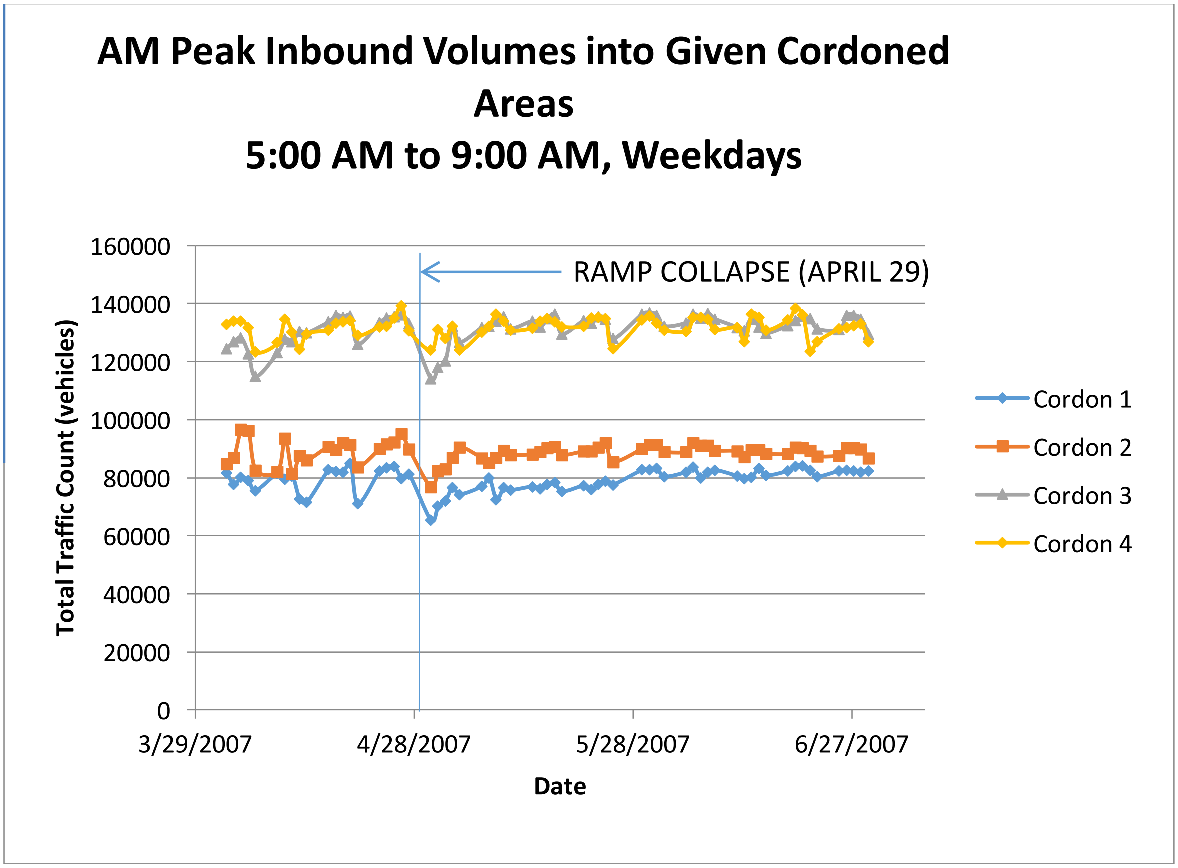

Figure 6: Total Traffic Counts for each Cordon Circle for Bay Area Network

Figure 6 illustrates the evolution of daily four-hour traffic counts from before to after the interchange disaster. Prior to the ramp collapse, traffic counts are fluctuating at gradual rates. However, after the collapse, the counts in the three innermost cordons experience sudden decreases and a recovery period. While not nearly as dramatic as seen in the Twin Cities, their presence is still notable. At Cordon 4, traffic counts remain relatively stable.

Note that, other than the sizeable decrease in traffic after the interchange disaster, several smaller drops in traffic counts occur due to weekly fluctuations. We want to point out one relatively significant traffic count drop on May 25, 2007, which is the Friday before Memorial Day weekend. Most people in that region would traditionally take that day off, which explains the traffic reduction across most cordons.

It is important to note that the Bay Area freeway network has some differences compared with the Twin Cities network. First and foremost, the MacArthur Interchange collapse was only a partial closure. Additionally, the Bay Area transportation network is generally closer to capacity and the availability of alternatives overall is much more limited due to the proximity of the San Francisco Bay. Nonetheless, the avoidance phenomenon, while not nearly as pronounced, is still observed with this event.

Two cases of long-term unexpected network disruption have revealed the presence of this avoidance phenomenon. Now, the question becomes whether this phenomenon is something potentially unique to unexpected disruptions or if it is applicable to all long-term disruptions, including preplanned closures such as road construction.

3. Planned Network Disruption

On May 1st, 2007, a two-mile length of Trunk Highway 36 (TH 36) in the Twin Cities, Minnesota, was fully closed for a construction project intended to upgrade the road to freeway standards. TH 36 was originally a suburban arterial that served as a major thoroughfare for suburban commuters in the northeastern metropolitan area that were heading to the urban center. This construction project was slated to keep the TH 36 corridor closed for several months. In the preceding months, the Minnesota Department of Transportation informed the public of the closure and suggested detour routes on the adjacent Interstate 694 (I-694). While not as busy as the I-35W Bridge, this route was still considered a major link in the Twin Cities regional network. As such, its closure could be considered to have a major impact on the region.

Again, the total traffic flows entering the freeway system in the Twin Cities network did not change significantly before and after the closure. In other words, the total travel demand did not vary substantially. Keeping with the previous cases, the cordon-line methodology will be applied around the TH 36 construction site, analyzing the time periods before and after the closure. Four cordons are proposed, shown in Figure 7. The captured network topologic features are discussed in Table 3. For reference, Cordon 1 refers to the smallest cordoned area near the construction closure while Cordon 4 refers to the largest cordoned area around the metropolitan area.

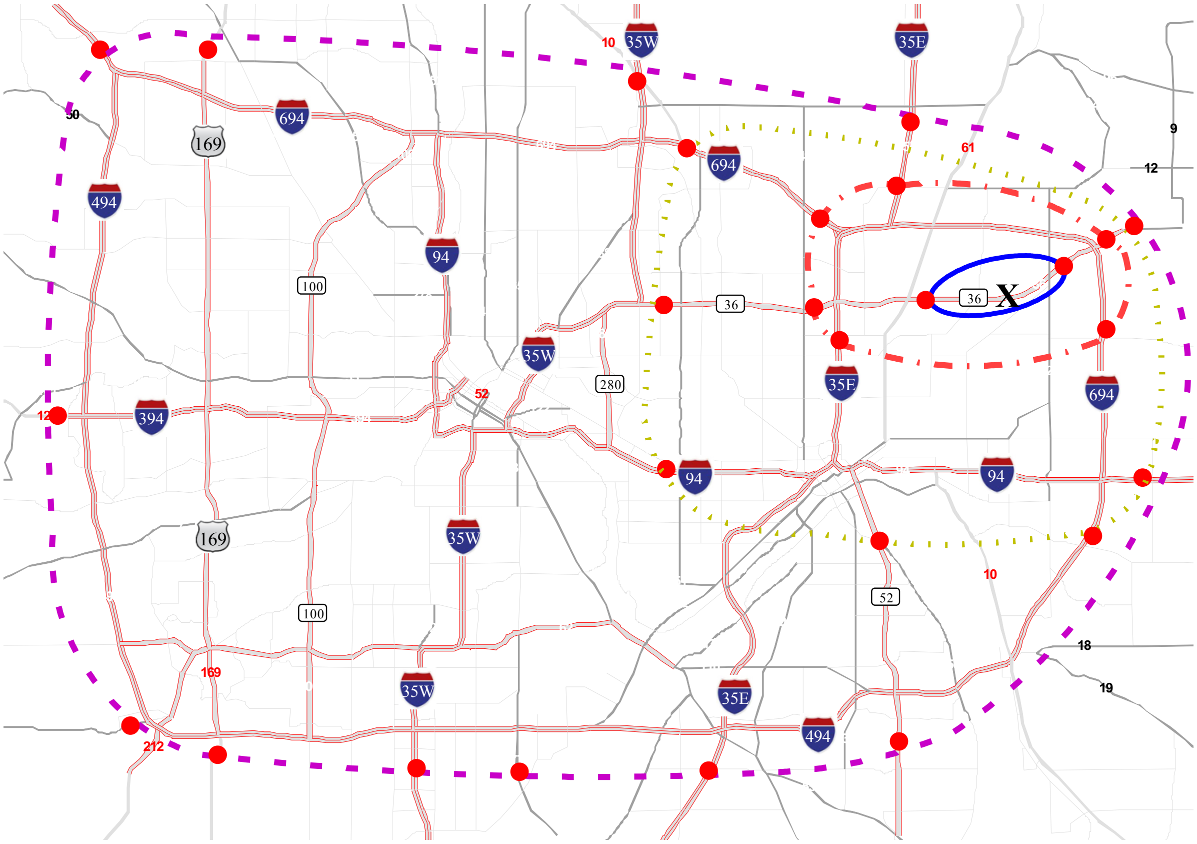

Figure 7: Four cordon lines around the TH 36 construction site, where the preplanned construction closure is marked with an 'x'

Table 3: Network topologic features of cordoned areas in Twin Cities for TH 36 closure

Cordon Number	Region within Cordon	Network Topology Features	Approximated Cordon Radius (miles)
1	Immediate Area of TH 36 Construction Area	No freeway or arterial-based alternative routes within cordon. No corridor connectivity within cordon.	0.5
2	I-694 Detour	Includes I-694 alternative route, the defined detour suggested by the Minnesota Department of Transportation. No other freeway-based alternative routes within cordon.	3.5
3	I-94 corridor, I-694 corridor, and St. Paul Central Business District	Includes all routes bound for downtown St. Paul, as well as I-94 and I-694 corridors. Some freeway-based alternative routes.	5.5

4	Twin Cities Metropolitan Area	Includes all routes approaching the I-494/I-694 beltway. Many freeway-based alternative routes.	15

The aggregated counts entering these cordons are analyzed for each non-holiday weekday between Monday, March 26th, 2007, and Tuesday, July 31st, 2007. The period in which traffic is counted will be the morning peak period, keeping a four-hour count between 6 a.m. and 10 a.m. local time. This is consistent with the time period used for the I-35W Bridge collapse and is considered to be the morning peak for the region.

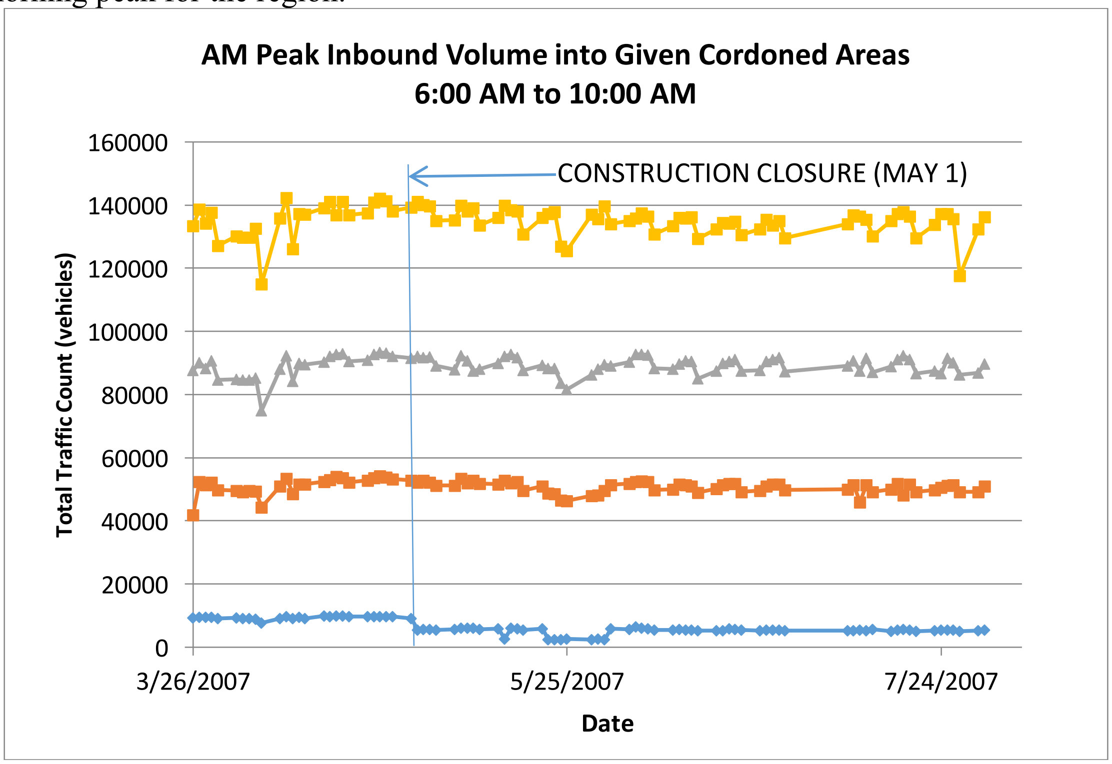

Figure 8: Total Traffic Counts for each Cordon Circle for Twin Cities Network for TH 36 closure

Figure 8 illustrates the evolution of traffic over the four-month time frame. Prior to the road closure, traffic counts are mostly stable at all four cordons. However, when the closure occurs, a different pattern emerges than seen in the unexpected disruption cases. Rather than experiencing a sudden shock and prolonged recovery, the traffic does not change. The lone exception is Cordon 1, where the absence of an open corridor or alternative routes causes a reduction. For all cordons, traffic appears to instantaneously adapt to the new network.

We want to make a note here that, in the instance of the preplanned closure, the analysis of the traffic count evolution starts a few weeks prior to the road closure. In the real world, preplanned road closure activities are usually announced a few months even a year before the actual closure, providing a longer time span for a gradual avoidance phenomenon compared to unexpected network disruption. To be more comparable to unexpected disruption, ideally, the analysis should perhaps start from a few weeks prior to the announcement of the road closure. Unfortunately the date of the first official announcement would be extremely difficult to ascertain. We suspect that the significant drop in traffic count in early April may indicate the first official announcement but this is just our conjecture.

Note also that there exist several smaller drops in traffic counts due to weekly fluctuations. The relatively significant traffic count drop happens on May 25, 2007, the Friday before Memorial Day weekend. Friday and Monday of those periods is traditionally lower due to people taking four-day weekends.

This observation starkly contrasts the avoidance phenomenon observed after the unexpected disruptions. As there did not exist any other big events around that time, we believe that the lack of avoidance phenomenon under planned disruption is a major reason for the unchanged traffic count. It is not the only case, as the absence of a shock and prolonged recovery can be found in other examples of preplanned disruptions. In the literature, Hunt et al. (2002) studied traffic equilibration following the planned construction closure of a bridge in Calgary, stating equilibrium was reached quickly.

This observation suggests that traffic equilibration differs when long-term disruptions are expected versus unexpected. It appears that awareness of an upcoming closure may give drivers a different perception of how the network will be than when a closure abruptly occurs. The awareness of these differences is useful for practitioners seeking to better cope with future disruptions.

In the next section, we will model the avoidance phenomenon from the perceived cost evaluation perspective using data collected from the I-35W Bridge collapse case.

4. Avoidance Phenomenon Modeling After the I-35W Bridge Collapse

Data observations following the I-35W Bridge collapse reveal that drivers drastically avoid the freeway network near the collapse site, despite that portion of network being significantly below capacity (as illustrated in Figure 3). This phenomenon is also observed in MacArthur Interchange collapse. Driver reluctance is often caused by a perceived cost, or risk, that deters their route choice from that route to a more favorable, or less costly, route.

In this section, we propose a perceived cost evolution model to explain the reductions in traffic following the I-35W Bridge collapse. This model will serve as a basis to predict traffic dynamics after network disruption happens. The proposed model separates travelers' perception into an experienced travel time and an additional perceived cost (i.e. additional travel time) due to a perceived impact from unexpected network disruption. The perceived cost can be framed as a cordon-based tolling scheme. Cordon tolling is a technique used in practice for congestion pricing, by charging users entering roads along a cordon line a monetary fee to achieve a desirable traffic into the cordoned area. It has been studied in the literature (e.g., Zhang and Yang, 2004; Ho et al., 2005) and has been deployed in cities such as London, Singapore, and Stockholm. To reproduce the avoidance phenomenon, we imagine a cordon surrounding the portion of the network centered on the disruption. A perceived cost is added to the link travel cost on links that lie on the cordon lines (for entering the cordoned areas). Since it is applicable to only those links, it can be inferred that the perceived cost is a fee for entering the cordoned area, similar to a cordon toll. With the varying levels of route alternatives between cordons, different perceived costs could be inferred at each zone. In the I-35 Bridge collapse case, however, the incurred additional toll costs represent the perceived cost of extra inconvenience (or psychological fear of accessing the impacted area) rather than a monetary payout. Seeing that traffic levels return in the long term following the collapse, these perceived costs would be expected to diminish with time.

4.1 Perceived Cordon-based Cost Modeling

We would like to make one note before delving into modeling. To avoid the debate of whether traffic equilibrium is eventually achieved or if a network is a constantly evolving entity based on drivers' daily experiences and perceptions (e.g., Horowitz, 1984; Smith, 1984; Friesz et al., 1994; Cascetta, 1989), this paper assumes only that traffic on a network is equilibrium-seeking. We propose that the forces pushing the traffic state toward equilibrium are influenced by the existence of this aggregated-level perceived cost. The traffic state evolves around this diminishing cost until, in the long term, such perceived costs disappear and traffic stabilizes to pre-collapse levels, assuming the availability of a detour route with sufficient capacity to "reopen" the disrupted network.

We used a calibrated mesoscopic simulation model (implemented in AIMSUN) of the Twin Cities network to find traffic entering the cordons. This model is comprised of major Twin Cities network features, including all freeways, major arterials, and some minor arterials deemed critical from designer experience. Origin-destination demands in this model were calibrated to average weekday freeway traffic data from the third week of July 2007 during the morning peak. Route choice was determined using C-Logit and traffic calibration was performed against 200 freeway mainline loop detectors that compared simulated traffic counts over an hour against observed traffic counts over the peak hour, using acceptance standards generally used by practitioners (Dowling et al., 2002). To remove the within-week traffic fluctuation, we ran the simulation on a week-by-week basis.

The Twin Cities network was initially simulated without the I-35W Bridge or cordon tolls, which produces a solution that matched the long-term traffic patterns observed in reality. This is not a surprise, as perceived costs are expected to be negligible in the long term as motorists begin to understand the new topology. In the short term, however, perceived costs are likely to be tangible in order to discourage entry in a particular cordon. Each cordon is assessed a perceived "cordon" travel cost to discourage route selection in hopes of matching the observed behavior. A brute-force search procedure was used to estimate the perceived cordon cost that the simulation needed to generate a particular level of traffic. This was done on a week-by-week basis, using averaged traffic over all non-holiday weekdays for that week. The resulting perceived costs for each week through the brute-search procedure are shown in the Table

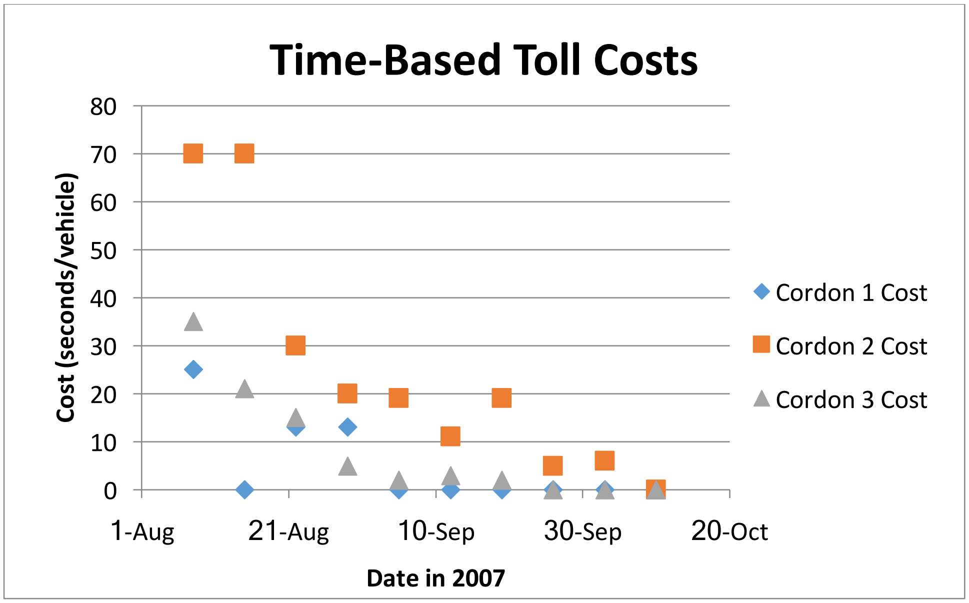

Figure 9: Time-based Toll Costs, as computed in the Twin Cities Model

Initially, the perceived cordon costs are all relatively high, suggesting a strong influence immediately after the bridge collapse. However, with each passing week, these costs decrease at a diminishing rate of return. At the tenth week and beyond, the costs all approach zero, which results in the stabalized pattern witnessed in the long term. Given the characteristics of this data, the trend best fits an exponential decay function, where the decreasing rate of the curve is proportional to its functional value. This is verified by curve-fitting software as the preferred function for all three cordons.

The observed exponential decay function can be specified as a general form of negative exponential function, i.e. $y^i = C_0 \exp(-\lambda i)$, where the perceived cost is denoted as y^i for a given week i. This function is composed of two coefficients, which include the initial cost, C_0, and a decay constant, λ. Using Microsoft Excel optimization Solver, the coefficients are estimated for all three cordons. The recommended values are shown in Table 5.

Table 5: Coefficient Values for Cordon Circles

	Initial Cost (seconds/vehicle)	Decay Constant (1/week)	R-Squared	Correlation Coefficients
Cordon 1	35.94	0.53435	0.604	0.777
Cordon 2	107.75	0.34942	0.916	0.957
Cordon 3	60.767	0.53741	0.986	0.993

Overall, the proposed function fits the data. Cordon 1 is the exception, resulting in a lower R-Squared value. However, given the proximity of Cordon 1 and the construction activities occurring near the site following the collapse, the disparity is likely due to extra trips by construction vehicles that normally are not part of AM peak trips and, thus, not reflected in the calibrated O/D table. For Cordon 2 and Cordon 3, though, the curves fit very accurately.

Some initial observations can be made from the fitted perceived cordon-based cost functions. Ignoring Cordon 1 for now, it can be seen that the initial cost coefficient decreases as distance from the bridge and the number of alternatives increases. Cordon 2 has the fewest alternative routes and has a high initial cost, while Cordon 3 has more alternative routes and a lower initial cost. Cordon 4 and Cordon 5 have initial costs of zero, given the absence of perceived costs, and are the fact that they are the farthest and have the most alternative routes. The same thing is shown by the decay constant, which increases as distance from the bridge and number of alternative routes increases. Cordon 2, which is closest and has fewest alternative routes, has a very low decay constant while Cordon 3 has a higher decay constant.

To understand the differences of Cordon 1 from these trends, it is important to recall that no connecting freeways and no freeway-based alternative routes exist within this cordon. Thus, any drivers that are intent on using the I-35W corridor must use the detour route outside of Cordon 1, resulting in a natural decrease in traffic. This reduced traffic could easily explain the disparity of the coefficients for Cordon 1 with respect to the trends of other cordons. Unfortunately, it prevents a good correlation to determine the initial cost and decay constant from being established.

The actual estimation of these coefficients may, in fact, require more elements than simply alternative routes and relative location to the bridge. Such elements might include available system capacity within the cordon, local driver habits, costs of cordons that are within a given cordon, or psychological significance of the disruption in question. Additionally, initial costs and decay constants may change given the total number of cordons, their proximity to one another, or the traffic management along the borders. For now, the cordons will be kept constant throughout this work, leaving the exploration of different cordon sizes, numbers, and locations to future research.

4.2 Model Validation

How well does the proposed perceive cost model reproduce the traffic flows observed following the I-35W Bridge collapse? Simulation results are shown in Table 4 (in the second column for each cordon) for the ten weeks following the bridge collapse, utilizing estimates for the perceived cost. To ensure that the perceived cost generated traffic levels that matched reality, the GEH statistic (i.e., a formula used in traffic modeling to compare two sets of traffic volumes), used in Dowling et al. (2002), was computed for each cordon (see Table 4). A GEH statistic of less than 5 is considered acceptable for calibration standards.

Table 4 Simulated and observed flows on a week-by-week basis following I-35W bridge collapse, along with the corresponding GEH statistic

	Cordon 1			Cordon 2			Cordon 3		
Week	Real Flow	Simulated Flow	GEH	Real Flow	Simulated Flow	GEH	Real Flow	Simulated Flow	GEH
1	1906	1970	1.45	13044	11945	9.83	26596	26288	1.89
2	2347	2306	0.85	13325	13821	4.26	27083	27250	1.01
3	2451	2452	0.02	14760	14578	1.5	27987	28475	2.9

4	2485	2484	0.02	15637	14949	5.56	29137	29072	0.38
5	3018	2616	7.57	16435	16392	0.33	29305	29219	0.5
6	3156	2624	9.9	16775	16695	0.61	29385	29320	0.38
7	3192	2640	10.22	16456	16915	3.55	29254	29426	1
8	3278	2644	11.65	17021	16942	0.6	29652	29463	1.1
9	3280	2651	11.55	16982	17064	0.63	29414	29526	0.65
10	3283	2649	11.64	17146	17105	0.31	29443	29555	0.65

For Cordon 1, the GEH statistic meets the requirement for the first four weeks. Following that fourth week, the threshold is violated, but this is likely due to the increased construction activities following the bridge collapse that could not be accounted for in the calibrated traffic table in AIMSUN. For Cordon 2, eight of the ten weeks met the GEH statistic requirement, while the other two weeks come within a relative error of ten percent. While not perfect, this result is still favorable. For Cordon 3, all ten weeks met the GEH statistic requirement. Given the low relative errors and satisfactory GEH statistics for Cordon 2 and Cordon 3, it is reasonable to say that this model has accurately proposed perceived costs that reproduce traffic along the cordons.

5. Conclusion

To date, little is known about the transient traffic dynamics following a prolonged, unexpected network disruption, mostly because these events are rare. Nonetheless, it is extremely important for practitioners and researchers to understand driver behavior after the occurrence of such events so that the resulting traffic can be better dealt with. This paper has explored the observed traffic dynamics on the Twin Cities freeway network following the collapse of the I-35W Bridge. The data shows that driver route choice behavior is different for unexpected disruptions than for the common, preplanned disruptions.

Following the unexpected disruption shown in this paper, an avoidance phenomenon is observed, where drivers appear to initially avoid the disruption site and gradually return over an extended period of time. This avoidance phenomenon is observed in the Twin Cities network after the bridge collapse, as well as in the San Francisco Bay Area network after a similar disaster. A simple concept is then proposed to explain the avoidance phenomenon in which drivers dramatically avoid areas near the bridge and gradually return following the collapse of the I-35W Bridge: a perceived travel cost exists as a result of the disruption. This perceived cost can be modeled using an exponential decay function and is found to be relatively lower as the distance from the bridge and number of alternative routes increases. When applied to traffic simulation software along cordoned lines for which it was calibrated, the model influences route choice in such a manner that the simulated traffic falls within an acceptable error range of the real traffic. While the influences behind the coefficients making up the exponential decay function are still unknown and left to future research, this idea of an exponential decay process contributes to the general knowledge by offering a simple hypothesis describing traffic dynamics that is supported by accurately simulated data.

In summary, this work offers potential answers to theoretical questions of traveler behavior following unexpected network disruption. The observations provided in this work benefit transportation policy, operations, and safety. From a policy perspective, this knowledge could aid in better identifying the risks and rewards of network restoration following an unexpected tragedy. From an operations perspective, this knowledge could help traffic managers understand the dynamics of how traffic evolves over the long-term. Lastly, from a safety perspective, this knowledge provides insight of where network congestion may appear, allowing a more effective deployment of incident management resources and infrastructure improvements. Accordingly, this work is useful to both practitioners and researchers. For practitioners, it offers a better understanding of how traffic behaves after an, unplanned disruption and a means to estimate the magnitude of the avoidance phenomenon. Such understandings would allow for more educated resource deployment to improve capacity, efficiency, and safety. For researchers, it offers a simple concept behind the traffic dynamics following this type of network disruption, from which further research about route choice can be conducted.

Future work in this area of study could investigate if the same avoidance phenomenon occurs in more unexpected long-term link closures and whether the proposed perceived cost model is transferrable to other unexpected disruptions. While fortunate to rarely occur, the absence of other large-scale, long-term network disruption scenarios due to an unexpected tragedy makes it impossible to declare trends for the initial costs and decay constant for the cordons. Though MacArthur Interchange collapse in San Francisco provides another avoidance phenomenon, modelling travelers' perceived costs requires simulating the Bay Area network with detailed traffic count and travel demand data, which would be challenging to accommodate in one paper. Therefore, we will leave it for future research. Additionally, further investigation could observe day-to-day traffic behaviors following unexpected network disruptions that involve more than a single link, such as the aftermath of an earthquake or a terrorist attack.

Acknowledgements

This research was partially funded by the National Science Foundation (CMMI 0825768) and the Intelligent Transportation Systems Institute of the University of Minnesota. The views are those of the authors alone.

Bibliography

Ball, M.O., Golden, B.L., and Vohra, R.V. (1999), Finding the most vital arcs in a network, Operations Research Letters, Vol. 8, No. 2, pp. 73-76.

Beckman, M.J., Mcguire, C.B., and Winsten, C.B. (1956), Studies in the Economics of Transportation, Yale University Press, New Haven, Connecticut, USA.

Cascetta, E., Cantarella, G. (1991), A day-to-day and within-day dynamic stochastic assignment model. Transportation research Part A, 25(5), 277–291.

Cascetta, E. (1989), A stochastic process approach to the analysis of temporal dynamics in transportation networks, Transportation Research Part B, Vol. 23, No. 1, pp. 1-17.

Cairnes, S., Atkins, S., and Goodwin, P. (2002), Disappearing traffic? The story so far, Proceedings of the Institution of Civil Engineers, Municipal Engineer 151, Issue 1, pp. 13-22.

Chang, S. and Nojima, N. (2001), Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective, Transportation Research Part A, Vol. 35, pp. 475-494.

Chen, A. and Zhou, Z. (2010), The α-reliable mean-excess traffic equilibrium model with stochastic travel times, Transportation Research Part B, 44 (4): 493-513.

Chen, A. and Zhou, Z. and Lam, W. HK, (2011), Modeling stochastic perception error in the mean-excess traffic equilibrium model, Transportation Research Part B, 45 (10): 1619-1640.

Chen, R., Mahmassani, H., (2004), Travel time perception and learning mechanisms in traffic networks. Transportation Research Record, 1894, 209–221.

Chen, Y.W., and Tzeng, G.H. (1999), A Fuzzy Multi-Objective Model for Reconstructing the Post-Quake Road Network by Genetic Algorithm, International Journal of Fuzzy Systems, Vol. 1, No. 2, pp.85-95.

Daganzo, C. and Sheffi, Y (1977), On stochastic models of traffic assignment, Transportation Research Part B, Volume 14, pp. 243-255.

Di, X., Liu, H.X., Pang, J.S., Ban, X. (2013), Boundedly rational user equilibria (BRUE): mathematical formulation and solution sets. Transportation Research Part B, 57, 300-313.

Di, X. and He, X. and Guo, X. and Liu, H.X. (2014), Braess paradox under the boundedly rational user equilibria. Transportation Research Part B, 67: 86-108.

Di, X., Liu, H.X., Ban, X., Yu, J.W. (2015), On the Stability of a Boundedly Rational Day-to-day Dynamic, Networks and Spatial Economics, 15http://link.springer.com/journal/11067/15/3/page/1 (3): 537-557.

Di, X., Liu, H.X., Ban, X. (2016a), Second Best Toll Pricing Within the Framework of Bounded Rationality, Transportation Research Part B, 83: 74-90.

Di, X., Liu, H.X. (2016b), Boundedly Rational Travel Behavior: A Review of Models and Methodologies, Transportation Research Part B, 85: 142-179.

Di, X., Liu, H.X., Zhu, S.J., Levinson, D.M (2016c), Indifference Band for Route Switching, Transportation, doi: 10.1007/s11116-016-9699-1, 1-26.

Dial, R.B. (1996), Bicriterion traffic assignment: basic theory and elementary algorithms, Transportation Science, 30 (2): 93-111.

Dial, R.B. (1997), Bicriterion traffic assignment: efficient algorithms plus examples, Transportation Research Part B, 31 (5): 357-379.

Dowling, R., Holland, J., and Huang, A. (2002), California Department of Transportation Guidelines for Applying Microsimulation Model Software, Sacramento: Dowling Associates, Inc.

Friesz, T., Bernstein, D., Mehta, N., Tobin, R., and Ganjalizadeh, S. (1994), Day-to-Day Dynamic Disequilibria and Idealized Traveler Information Systems, Operations Research Vol. 42, Issue 6, pp. 1120-1136.

Guiliano, G. and Golob, J. (1998), Impacts of the Northridge Earthquake on Transit and Highway Use, Journal of Transportation and Statistics, Vol. 1, pp. 1-20.

Ham, H., Kim, T.J., and Boyce, D.E. (2005a), Implementation and Estimation of a Combined Model of Interregional, Multimodal Commodity Shipments and Transportation Network Flows, Transportation Research Part B, Vol. 39, No. 1, pp. 65-79.

Ham, H., Kim, T.J., and Boyce, D.E. (2005b), Assessment of Economic Impacts from Unexpected Events Using an Interregional commodity Flow and Multimodal Transportation Network Model, Transportation Research Part A, Vol. 39, No. 10, pp. 849-860.

He, X. and Liu, H.X. (2012), Modeling the day-to-day traffic evolution process after an unexpected network disruption. Transportation Research Part B, 46 (1): 50-71.

Ho, H.W., Wong, S.C., Yang, H., and Loo, B.P.Y. (2005), Cordon-based congestion pricing in a continuum traffic equilibrium system. Transportation Research Part A, 39, pp. 813-834.

Horowitz, J.L. (1984), The stability of stochastic equilibrium in a two-link transportation network, Transportation Research Part B, Vol. 18, pp. 13-28.

Hunt, J.D., Brownlee, A.T., and Stefan, K.J. (2002), Responses to the Centre Street Bridge Closure: Where the 'Disappearing' Traffic Went, Transportation Research Record 1807, pp. 51-58.

Jha, M., Madanat, S., Peeta, S. (1998), Perception updating and day-to-day travel choice dynamics in traffic networks with information provision. Transportation Research Part C 6(3), 189–212.

Jotisankasa, A. and Polak, J.W. (2005), Modeling learning and adaption in route and departure time choice behaviour: Achievements and prospects, In Integrated Land-Use and Transportation Models, M. Lee-Gosselin and S. Doherty, eds., Elsevier, Oxfords, pp. 133-157.

Jotisankasa, A., Polak, J. (2006). Framework for travel time learning and behavioral adaptation in route and departure time choice. Transportation Research Record, 1985, 231–240.

Kim, T.J., Ham, H., and Boyce, D.E. (2002), Economic Impacts of Transportation Network Changes: Implementation of a Combined Transportation Network and Input-Output Model, Papers in Regional Science, Vol. 81, pp. 223-246.

Kiyota, M., Vandebona, U., and Tanoue, H. (1999), Multistage Optimization of Reconstruction Sequence of Highways, Journal of Transportation Engineering, Vol. 125, No. 5, pp. 456-462.

Lee, J.S. and Kim, T.J. (2007), Implementation of Spatiotemporal Model for Infrastructure Reconstruction Strategy Under Large-Scale Disaster, Transportation Research Record: Journal of the Transportation Research Board, No. 2022, pp. 39-46.

Lo, H.K. and Luo, XW and Siu, B.W.Y. (2006), Degradable transport network: travel time budget of travelers with heterogeneous risk aversion, Transportation Research Part B, 40 (9): 792-806.

Lou, Y., Yin, Y., Lawphongpanich, S., 2010. Robust congestion pricing under boundedly rational user equilibrium. Transportation Research Part B 44 (1), 15-28.

Mahmassani, H.S. and Chang, G.L. (1986), Experiments with Departure Time Choice Dynamics of Urban Commuters, Transportation Research Part B, Vol. 20, No. 4, pp. 297-320.

Matisziw, T.C, and Murray, A.T. (2009), Modeling s-t path availability to support disaster vulnerability assessment of network infrastructure, Computers and Operations Research, Vol. 36, pp. 16-26.

Nakayama, S., Kitamura, R. (2000), Route choice model with inductive learning. Transportation Research Record, 1725, 63–70.

Roess, R.P., Prassas, E.S., and McShane, W.R. (2004), Traffic Engineering, 3rd Edition, Pearson Prentice Hall, pp. 196-197.

Sheffi, Y. and Powell, W.B. (1982), An algorithm for the equilibrium assignment problem with random link times, Network, Vol. 12, pp. 191-207.

Smith, M. (1984), The Stability of a Dynamic Model of Traffic Assignment – An Application of a Method of Lyapunov, Transportation Science, Vol. 18, pp. 259-304.

Sohn, J., Kim, T.J., Hewings, G.J.D., Lee, J.S., and Jang, S.G. (2003), Retrofit Priority of Transport Network Links Under an Earthquake, Journal of Urban Planning and Development, Vol. 129, No. 4, pp. 195-210.

Tsuchida, P. and Wilshusen, L. (1991), Effects of the 1989 Loma Prieta Earthquake on Commute Behavior in Santa Cruz County, California, Transportation Research Board.

Wang, Judith YT and Ehrgott, Matthias (2013), Modelling route choice behaviour in a tolled road network with a time surplus maximisation bi-objective user equilibrium model, Transportation Research Part B, 57: 342-360.

Wardrop, J.G. (1952), Some theoretical aspects of road traffic research, In Proceedings of the Institute of Civil Engineers, Part 2, Volume 1, pp. 325-362.

Watling, D. (1999), Stability of the stochastic equilibrium assignment problem: a dynamical systems approach. Transportation Research Part B 33 (4), 281–312.

Watling, D. (2006), User equilibrium traffic network assignment with stochastic travel times and late arrival penalty, European Journal of Operational Research, 175 (3): 1539-1556.

Wesemann, L., Hamilton, T., Tabaie, S., and Bare, G. (1996), Cost-of-Delay Studies for Freeway Closures Caused by Northridge Earthquake, Transportation Research Record, Vol. 1559, pp.67-75.

Xie, F. and Levinson, D.M. (2011) Evaluating the Effects of I-35W Bridge Collapse on Road-Users in the Twin Cities Metropolitan Region. Transportation Planning and Technology 34(7) pp. 691-703.

Zhang, L. (2011). Behavioral foundation of route choice and traffic assignment. Transportation Research Record: Journal of the Transportation Research Board, 2254(1), 1-10.

Zhang, X. and Yang, H. (2004), The optimal cordon-based network congestion pricing problem. Transportation Research Part B 38, pp. 517-537.

Zhu, S. and Levinson, D.M. and Liu, H.X. and Harder, K. (2010), The traffic and behavioral effects of the I-35W Mississippi River bridge collapse. Transportation research part A, 44 (10): 771-784.

Zhu, S. and Levinson, D.M. (2011) Disruptions to Transportation Networks: A Review. Published in Network Reliability in Practice Edited by David Levinson, Henry Liu, and Michael Bell. pp. 5-20.

Zhu, S., Tilahun, N., Levinson, D.M., and He, X. (2011) Travel Impacts and Adjustment Strategies of the Collapse and the Reopening of the I-35W Bridge. Published in Network Reliability in Practice Edited by David Levinson, Henry Liu, and Michael Bell. pp. 21-36.

Zhu, S., Levinson, D.M, and Liu, H.X. (2012) Measuring Winners and Losers from the new I-35W Mississippi River Bridge. Presented at 89th Transportation Research Board Conference, January 2010, Washington, DC. Transportation (in press).