

1 A Review of Research on Planned and
2 Unplanned Disruptions to Transportation
3 Networks

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6 **Abstract**

7 Travel decisions may be very stable in an environment with which
8 they are familiar. Major network disruptions such as the I-35W bridge
9 collapse disrupt habitual behavior. Such “natural” experiments provide
10 unique opportunities for behavioral studies, but the time window
11 for such studies is limited. A well-developed methodology is crucial
12 for both data collection and analysis, and thus the soundness of be-
13 havioral models, especially in such a limited time window. Therefore,
14 this paper reviews both theoretical and empirical studies on traffic
15 and behavioral impacts of network disruptions. Findings from this
16 paper offers prospective ideas about capturing the impacts of network
17 disruption.

18 *Keywords: Network disruption; Travel survey; Travel behavior*

19 **1 Introduction**

20 The collapse, on August 1, 2007, of the I-35W bridge over the Mississippi
21 River in Minneapolis, abruptly interrupted the usual route of about 140,000

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1 daily vehicle trips and substantially disturbed the flow pattern of the network.
2 In addition to the heavy losses in life and injury, the network disruption has
3 also significantly impacted road-users and reshaped travel patterns in the
4 Twin Cities area, which could generate significant cost due to longer travel
5 distance, higher levels of congestion, and the resulting opportunity losses.
6 According to Minnesota Department of Transportation (MnDOT), rerouting
7 alone could cost individual travelers and commercial vehicles \$400,000 daily
8 based on Metropolitan Council planning model. Xie and Levinson (2008)
9 find a lower, but still large, estimate of expected costs to road users, between
10 \$71,000 and \$220,000 per day. As a result, a significant financial incentive was
11 given to the contractor for the early completion of the replacement bridge. A
12 similar financial incentive was employed after the Northridge Earthquake in
13 California (the transportation-related costs due to network disruption in Los
14 Angeles basin exceeded \$1.6 million per day (Wesemann et al., 1996)) and a
15 contractor earned \$ 14.8 million (\$200,000 per day) for completing work on
16 freeway I-10 66 days ahead of initial schedule. Most of these decisions were
17 based on planning models and conclusions were drawn through travel demand
18 assignments on degraded networks, using User Equilibrium (UE) assumptions
19 (assuming “the journey times in all routes actually used are equal and less
20 than those which would be experienced by a single vehicle on any unused
21 route” according to Wardrop (1952)). However, behavioral responses to the
22 network disruption are much richer than what could be predicted by planning
23 models. The network disruption forced travelers to explore the network and

1 adjust their travel behavior according to their travel experience and external
2 information resources. Immediately after the network disruption, travelers
3 may:

- 4 • change their normal route because of road and ramp closure or conges-
5 tion caused by traffic re-allocation,
- 6 • adjust travel time to avoid congestion,
- 7 • satisfy needs at other destinations,
- 8 • consolidate trips and travel less frequently,
- 9 • switch to alternative travel modes,
- 10 • share travel duties among family members.

11 In the long term, travelers may also adjust their residential and work lo-
12 cations (Goodwin, 1977; Cairnes S. and Goodwin, 2002) . Until a new equi-
13 librium is found (a period sometimes referred to as “the transient phase”),
14 traffic may significantly deviate from the results predicted by planning mod-
15 els. For example, Clegg (2007) showed that a capacity reduction due to road
16 construction generated an initial “over-reaction” effect followed by a “settling
17 down” effect, using license plate match data from the city of York, England.
18 Oscillation of overall traffic and individual route choices was reported. Al-
19 though network disruptions are mostly temporary as damage is eventually
20 repaired and capacity restored, travel experience accumulated during this

1 time period could lead to permanent changes in travel patterns. van Exel and
2 Rietveld (2001) indicated new patterns could become habitual once travelers
3 explore and accept the driving experience during transit strikes. Cairnes S.
4 and Goodwin (2002) also argued travel behaviors were conditioned on new
5 experience instead of past history after investigating 70 case studies of road
6 capacity reduction. Most of these day-to-day dynamics in travel demand can-
7 not be captured by aggregate UE models Cairnes S. and Goodwin (2002).
8 A good understanding of the behavioral changes and decision-making mech-
9 anism could not only better assist traffic management and the design of a
10 mitigation plan in response of network disruptions, but also inform future
11 research in travel demand modeling.

12 However, it is not easy to capture such a day-to-day learning and decision-
13 making process. In an environment with which they are familiar, travelers'
14 route choice decisions may be very stable. Goodwin (1977) argued trav-
15 elers do not carefully and deliberately evaluate their choices because of “a
16 reluctance to upset an ordered and well-understood routine”. As the travel
17 pattern remains unchanged, the role of habit increases and rational factors
18 become less dominant, preventing relevant information from reaching deci-
19 sion makers and rational choices. Major network disruptions such as the
20 I-35W bridge collapse could disrupt habitual behavior . Evidence suggests it
21 took several weeks for the network to re-equilibrate (Zhu et al., 2009), during
22 which period, travelers continued to learn and adjust their travel decisions.
23 These natural experiments provide unique opportunities to investigate how

1 travelers valued different alternatives and made travel decisions over time.

2 Network disruptions, both planned and unplanned, are unusual but not
3 unknown. Unplanned disruptions could be caused by natural disasters (e.g.
4 earthquakes, floods, landslides, hurricanes), terrorist attacks (e.g 9/11), in-
5 frastructure failures (e.g. I-35W bridge collapse), severe accidents, etc. Ex-
6 amples of planned disruptions include road or ramp closure due to mainte-
7 nance or construction work, transit strikes (e.g. 2005 transit strike at the
8 New York City), major events such as Olympic Games and political con-
9 ventions. These disruptions vary significant in both spatial and temporal
10 dimensions. A strike by local transit workers may end in several days and
11 its impacts are limited to the area they served. A severe earthquake may
12 damage many links simultaneously, which may take years to rebuild. Be-
13 cause of inertia in travel behavior and inherent fluctuations in travel pat-
14 terns due to ever-evolving network conditions, only significant disruptions
15 to the network exhibit detectable changes on travel behavior, and thus on
16 the aggregate traffic pattern. “Natural” experiments such as I-35W bridge
17 collapse provide unique opportunities for behavioral studies, and but cies; 2)
18 the economic and social background may change significantly over a longer
19 time, preventing us from establishing any convincing causal effects. A well-
20 developed methodology is crucial for both data collection and analysis, and
21 thus the soundness of behavioral models , especially in such a limited time
22 window.

1 Therefore, this paper reviews both theoretical and empirical studies on
2 traffic and behavioral impacts of network disruptions. This paper begins
3 by summarizing types of transportation-related impacts observed and con-
4 clusions drawn regarding demand responses and behavioral changes. Then
5 this paper focuses on the methods of data collection and analysis employed,
6 which are crucial for a well-founded study. Comparisons are made regarding
7 the advantage and disadvantage of different research approaches in capturing
8 various facets of travel behavior. The final section summarizes the previous
9 discussion and offers some prospective ideas about capturing the impacts of
10 network disruption.

11 **2 Literature review**

12 Although there is a vast literature on travel behavior, previous research on
13 behavioral responses to major network disruptions is limited (Giuliano and
14 Golob, 1998). However, large-scale network disruptions are unusual but not
15 unknown. For bridge failure alone, we have in recent years seen the collapse of
16 the I-80 San Francisco-Oakland Bay Bridge and I-880 Cypress Street Viaduct
17 in Loma Prieta Earthquake, the Hatchie River Bridge in Tennessee, and the
18 I-40 bridge at Webbers Falls, Oklahoma, among others. The lack of behav-
19 ioral studies may partly due to the difficulty of large-scale data collection
20 after major incidents, especially when traffic monitoring devices such as loop
21 detectors and cameras were not widely deployed. For example, the collapse,

1 in 1975, of Tasman bridge in Hobart, Australia, significantly disrupted the
2 network because the nearest alternative, the Bridgewater bridge, required 50
3 kilometers extra drive and there was little vehicular ferry service available.
4 During the 14 months of reconstruction, 60% of the 44,000 daily trips before
5 the bridge collapse disappeared (Hunt et al., 2002), creating a major pattern
6 shift. However, no detailed analysis on behavioral changes has been provided
7 in the literature. As individual-based travel demand modeling received more
8 research interest and more data collection initiatives were implemented, there
9 have been increasing literature focusing on behavioral responses after major
10 network disruptions.

11 Table 1 summarizes 16 existing studies on behavioral responses after net-
12 work disruptions in the literature. Some of them focused on one specific
13 aspect of behavioral changes (e.g. Ferguson (1992) focused on transit rid-
14 ers), while others were more comprehensive and addressed a wide spectrum
15 of issues in travel demand (e.g. Giuliano and Golob (1998)). Network disrup-
16 tions caused by different types of incidents exhibited very different effects in
17 travel demand (e.g. route switching may be the most universal after a bridge
18 closure (Hunt et al., 2002; Zhu et al., 2009), while responses to earthquakes
19 have been more diverse), while the underlying behavioral pattern may be
20 quite similar. Therefore, this section will provide a brief review of existing
21 studies on network disruptions by their causes: 1) transit strikes (summa-
22 rized in Table 2), 2) bridge closures (summarized in Table 3), 3) special
23 events, and 4) earthquakes summarized in Table 3). More discussions about

1 behavioral patterns emerging from these events will be provided in the next
2 section.

3 **2.1 Transit strike**

4 Public transit strikes disrupted the normal travel of transit riders and dis-
5 turbed the network by increasing use of personal vehicles. Transit strikes
6 also provide a unique opportunity to understand alternatives transit riders
7 have and how travel decisions are made, both of which are crucial for draft-
8 ing future transportation policies. Although news coverage and qualitative
9 descriptions about transit strikes are widely seen in the media, quantitative
10 analysis of traffic and behavioral responses are limited.

11 The 1966 transit strike in New York City (lasting 13 days) significantly
12 affected the network because public transit represented 60% of total trips in
13 New York City. According to a study by the New York City Transit Au-
14 thority (NYCTA) based on home interviews of 8000 transit users, 67% of
15 commuters switched to private vehicles, 75% as drivers and 25% as passen-
16 gers. On the first day 50% travelers cancelled their trips but this number
17 reduced to 10% in following days, showing the effects of initial shock and
18 subsequent adaptations among travelers. With more cars on route, the peak
19 period spread from 2 hours to 4 hours. More interestingly, estimates from
20 subsequent studies indicated permanent losses in transit ridership (2.1% for
21 work trips, 2.6% for shopping trips, and 2.4% for other trip purposes) af-
22 ter service was restored. Similarly, the 1981 and 1986 Orange County transit

1 strike in California reduced 15% to 20% of transit trips after the strike accord-
2 ing to Ferguson (1992). However, the importance of these numbers should
3 not be exaggerated because public transit only represented 2% of total trips
4 in Orange County. Lo and Hall (2006) investigated the effects of the Los
5 Angeles transit strike based on loop-detector data. They revealed that al-
6 though overall traffic flow remained almost the same due to the small number
7 of bus riders, the speed scheme clearly showed a spread of the morning peak
8 hour and a higher level of congestion during the strike period. Individual
9 behavior, however, was not discussed in this paper due to lack to data.

10 A more detailed study was provided by Blumstein and Miller (1983),
11 focusing on the 1976 transit strike in Pittsburgh, where 60% of the commuters
12 to the CBD use transit. Both traffic counts and survey data were employed
13 in the analysis. A surge in total traffic (up about 40% on the first day
14 and 20% after), vehicle occupancy (up 50%), downtown garage usage (up
15 about 10%), and taxi revenue (up 9.9%) were observed and there was a
16 spread of the peak period. Two subsequent telephone surveys indicated that
17 most previous transit users were dropped off by a non-commuter (presumably
18 a spouse), while 10% and 28% of previous transit riders decided to drive
19 alone and carpool, respectively. respectively. The authors argued that the
20 “dropped-off” trips explained most of the increases in total traffic and vehicle
21 occupancy, and vehicle ownership played a key role in choosing alternative
22 mode (households with no car or only one car were more likely to use “drop-
23 off” compared to households with two or more cars). Impacts on travel

1 patterns of previous single drivers were also reported, including switching
2 route (18%), departure earlier (65%), and changing parking place (31%).
3 However, no modeling work was reported despite the abundance in data.

4 van Exel and Rietveld (2001) provided a comprehensive review of 13
5 major strikes in the public transit sector. Their impacts on traffic vary
6 significantly, primarily depending on the importance of public transit among
7 other modes. However, individual travel choices, constrained by long-term
8 factors such as car ownership, working and residential location, seems more
9 sensitive to the length and extent of such strikes.

10 **2.2 Bridge closure**

11 Bridge closure damages the network by completely shutting down one im-
12 portant link. Its impacts on traffic and travel behavior varies significantly,
13 depending on alternatives available. The aforementioned case of Tasman
14 bridge represents one extreme where alternatives are almost non-existent,
15 causing severe disruption in normal travel. However, network redundancy is
16 more common in metropolitan area, where impacts of bridge closure could
17 be moderate.

18 Hunt et al. (2002) evaluated travelers' responses to a 14 month long clo-
19 sure (from August, 1999) of the Center Street Bridge in the city of Calgary,
20 Alberta, Canada, based on both traffic counts and results from a telephone
21 survey. Traffic observations indicated a minor drop (4.4%) in total daily trips
22 and a 15-minute forward shift of the morning peak period. Public transit rid-

1 ership increased by 6.6%, while vehicle occupancy declined 1.5%. The traffic
2 count data, however, only included observations of two days, in May 1999
3 and May 2000, respectively. The limited data prevented them from drawing
4 statistically significant conclusions. Moreover, background conditions may
5 have changed significantly over a year, preventing them from establishing
6 any convincing causal effects. Therefore, a telephone interview survey was
7 conducted to supplement the study, which generally confirmed previous find-
8 ings. Although route switching effects were reported (15% to 30% of users
9 of five parallel bridges before the bridge closure used a different bridge), no
10 robust analysis was provided.

11 Clegg (2007) showed that a partial bridge closure (capacity significantly
12 reduced) due to road construction generated an initial “over-reaction” effect
13 followed by a “settling down” effect, using license plate match data from
14 the city of York, England. Oscillation of overall traffic and individual route
15 choice were reported.

16 Zhu et al. (2009) provided a comprehensive review of traffic and behav-
17 ioral effects of the collapse of the I-35W Mississippi River Bridge in Min-
18 neapolis, Minnesota. Both the survey data and traffic counts suggested that
19 total travel demand did not significantly reduce after the network collapse,
20 possibly because of redundant capacity provided by alternatives. However,
21 the results suggest about 50,000 fewer vehicles were crossing the Mississippi
22 River in total on a daily basis in the Twin Cities. The average total travel
23 time is clearly longer on average for those commuting to downtown or the

1 nearby University of Minnesota, two areas close to the I-35W bridge. The
2 peak period on the I-94 bridge, a major freeway alternative, clearly spread.
3 The bridge collapse generate a small increase in public transit ridership,
4 which is consistent with observations in previous research (Giuliano and
5 Golob, 1998)

6 **2.3 Special events**

7 Special events such as Olympic Games also significantly disrupt normal traf-
8 fic by introducing a highly concentrated travel demand. However, trans-
9 portation agencies usually have a greater authority in these circumstances
10 and travelers are generally more willing to follow instructions. For exam-
11 ple, although promoting public transit is difficult, 74% trips were carried by
12 public transit during 2004 Athens Olympics according to Dimitriou et al.
13 (2006). High transit ridership was also observed during the 2000 Sydney
14 Olympics according to(Hensher and Brewer, 2002) (no detailed percentage
15 number provided), although bus riders had to wait as long as 45 minutes. As
16 a result, background traffic dropped 2% to 4.5% depending on the location,
17 and travel speed doubled. These events show great potential for public tran-
18 sit. Although questions on how to achieve similar transit usage in day-to-day
19 dynamics have been frequently asked, no detailed studies on decision-making
20 mechanism under these circumstances have been provided.

1 **2.4 Earthquakes**

2 Natural disaster such as earthquake could create extensive damage to the
3 network and it generally takes a long time to restore capacity.

4 Chang and Nojima (2001) investigated the post-disaster transportation
5 system performance after the 1995 Kobe, 1989 Loma Prieta, and 1994 Northridge
6 earthquakes, using measures based on length of network open, total and
7 areal accessibility. No analysis on behavioral responses were provided. In-
8 stead, Tsuchida and Wilshusen (1991) investigated the car-sharing program
9 in Santa Cruz County, California, which was mandated immediately after
10 the Lima Prieta Earthquake and was removed after capacity was restored.
11 Traffic changes, however, were not included.

12 Giuliano and Golob (1998) and Wesemann et al. (1996) provided a com-
13 prehensive study of traffic and behavioral responses after the 1994 Northridge
14 Earthquake in Los Angeles basin, California. Caltrans systematically doc-
15 umented the freeway traffic volume and Los Angeles Department of Trans-
16 portation (LADOT) counted arterial traffic on a randomly chosen weekday
17 each month. Metrolink collected all passenger counts by station and different
18 bus operators had monthly passenger ridership by route. Vehicle occupancy
19 was roughly estimated by the level of High Occupancy Vehicle (HOV) lane
20 usage. Total demand (in person-trips) and shares of different modes were
21 evaluated by the trips crossing the I-5 corridor screen line drawn between
22 south of I-5/SR-14 junction and Balboa Blvd. The traffic on I-5 (the bridge
23 at Gavin Canyon and the interchange between I-5 and State Route 14 col-

1 lapsed) dropped 59% immediately due to lack of alternative. However, after
2 restoring 70% of pre-earthquake capacity by implementing a series of mitiga-
3 tion project, traffic volumes increased to 88% of pre-earthquake level. After
4 full capacity was restored in May 1994, total traffic increased quickly and
5 went beyond the 1993 level in June by 1%. Arterials still sustained signifi-
6 cantly higher traffic compared to the pre-earthquake levels (carrying 10.85%
7 of all daily trips crossing the screen line on I-5 corridor compared to the
8 3.62% before earthquake). The rail ridership (Metrolink) surged (carrying
9 9.64% of all daily trips on the I-5 corridor) immediate after the earthquake,
10 and then gradually reduced (0.83% of total trips, compared to 0.21% before
11 the earthquake). Bus ridership remained flat (0.29% of all trips on the same
12 corridor) during this period. Transit trips only accounted for 1.1% of total
13 trips once pre-earthquake capacity was restored. Meanwhile, a telephone
14 survey was conducted to sample 1000 workers in February 1994. Significant
15 changes were reported in all aspects of travel decisions, though with differ-
16 ent magnitude. Changing route (31.2%) and changing schedule (21.7% of
17 respondents left earlier while 7.9% left later) were the most dominant, while
18 changing mode had a smaller but detectable proportion (5.8% from drive
19 alone to carpool/vanpool and 0.3% to transit). Similar trends were revealed
20 on I-10 where the Fairfax Avenue bridge collapsed. Systematic data col-
21 lection efforts from different transportation agencies allowed this study to
22 evaluate changes in traffic patterns over time.

23 However, the traffic shares of freeway, arterials, and transit one month

1 after full capacity were restored were still significantly different from the
2 market shares one year before. And no arguments have been provided about
3 whether traffic patterns had re-equilibrated, which is crucial for travel de-
4 mand analysis. Duration of this re-equilibration process may extend from
5 several days (Clegg, 2007) to one year (Hunt et al., 2002) depending on con-
6 text, and in models this has usually been assumed without solid justification.
7 Robust statistics have to be introduced to evaluate the equilibration process
8 and longitudinal observations are required.

9 **3 Behavioral effects**

10 Behavioral responses after network disruptions are the key research question
11 in all these studies, each of which had specific focuses depending on the
12 context and data availability. Table 3 summarizes primary findings from the
13 literature. Instead of chronologically reviewing these studies, this section only
14 presents important findings and unanswered questions where future research
15 is needed.

16 **3.1 Route choice and departure time**

17 Cairnes S. and Goodwin (2002) investigated 70 case studies of road capacity
18 reduction and concluded that although people changed mode, consolidated
19 trips for different purposes and visited alternative destinations in response
20 to network degradation, “changing route and changing journey time seem

1 to be the most universal". Findings in the literature generally confirm this
2 conclusion, while the magnitude of changes varies depending on the context.
3 However, no research efforts have been dedicated to building individual based
4 models, using data collected from these studies. Although route switching
5 effects were reported in these studies(Hunt et al., 2002), the details of actual
6 routes used by respondents were ignored most of the time, preventing further
7 theoretical studies. The survey methods used, including both telephone in-
8 terview and mail-in questionnaires, cannot easily record and compare routes
9 used, especially for car drivers. Ideally, automatic route recording devices
10 such as GPS recorders should be employed in future research.

11 Replicating travel route using questionnaires is easier for transit users.
12 Dimitriou et al. (2006) evaluated the travel pattern during 2004 Athens
13 Olympics , using a survey of 14,000 Olympic Games passengers. The travel
14 chains were analyzed, showing although visitors might drive a significant por-
15 tion of entire trip, the mode for final stage was predominantly public transit.
16 However, their study focused more on public transit planning during such
17 one-time major events, while its implications for modeling individual travel
18 decisions are limited.

19 **3.2 Preference for driving**

20 Travelers have a strong preference for driving. According to the stated pref-
21 erence survey conducted after reopening of I-880, 9% of respondents stated
22 that they would considering moving further from work and 11% reported

1 that they would consider taking a job further from home as a result of travel
2 time savings. A small share (7%) of respondents indicated that they would
3 otherwise take transit if the bridge had not opened, which is surprisingly
4 high.

5 Strong preference for driving alone is consistent with the difficulty of
6 persuading travelers using public transit. In the case of I-5 in California, 88%
7 of traffic returned with only 70% of capacity restored. Therefore, travelers
8 must search for extra capacity available in the previously off-peak period, and
9 thus create new congestion. However, travelers still prefer to drive, even with
10 an 11.7 to 21.7 minutes increase in delay. In the modern metropolitan area,
11 network redundancy is very high. A tolerance as large as 20 minutes before
12 switching mode implies that very few travelers would switch mode because
13 of delay. Giuliano and Golob (1998) indicated that the parking shortages,
14 crowdedness on trains, and delays due to frequently aftershock might drive
15 many riders back to car. Also, accessibility provided by public transit is
16 very low in decentralized Los Angeles. Therefore, we should be cautious in
17 generalizing this conclusion.

18 **3.3 Travel experience**

19 Many researchers have argued travelers make travel decisions based on pre-
20 vious experience (Goodwin, 1977), which may introduce non-linearity and
21 generate travel patterns in dis-equilibrium. van Exel and Rietveld (2001) in-
22 dicated that strikes undermine the perceived reliability of public transit and

1 encourage some transit riders to switch to driving alone or carpooling. More-
2 over, new patterns could become habitual once travelers consider the driving
3 experience. Their conclusions are supported by evidence from the permanent
4 losses in public transit ridership after major transit strikes, including 1966
5 New York City (2.1%-2.6%), 1977 Knoxville (7%-16%), 1981,1986 Orange
6 County, CA (15%-20%), and 1995 Netherlands (0.3%-2%).

7 Tsuchida and Wilshusen (1991) drew a similar conclusion after investi-
8 gating the car-sharing program in Santa Cruz County, CA. Commuters were
9 required to share vehicles during the reconstruction period after the Lima Pri-
10 eta Earthquake. After the damage was repaired and ride-sharing mandate
11 removed, 57% of survey respondents continued with ride-sharing. More inter-
12 estingly, the primary reason convincing them to continue was cost-savings of
13 ride-sharing experienced during this mandate (42%), followed by the people
14 they shared rides with (22%), enjoyment of the trip (12%), environmental
15 preservation (12%), and finally, less stress (10%).

16 Hensher and Brewer (2002) noticed people were willing to change their
17 behavior for a one-time “single largest major event” (background vehicle
18 trips dropped and transit ridership was high) when evaluating performance of
19 public transportation in 2000 Sydney Olympics. Priority measures during the
20 2004 Athens Olympics increased the average speed of buses from 15-17 km/h
21 to 30-40 km/h, creating significant incentives for riding buses (Dimitriou
22 et al., 2006). Both studies argued that travel experience and performance of
23 public transportation during the Games could promote a permanent shift in

1 travel pattern.

2 Evidence from these studies provides strong arguments for introducing
3 travel experience in demand modeling, which could not only improve accu-
4 racy of demand forecasting, but also capture day-to-day traffic dynamics.
5 More research is required to model travel experience and empirical studies
6 after network disruptions could provide valuable guidance.

7 **4 Data collection**

8 High-quality data is crucial for empirical studies and it is a big challenge to
9 design and implement data collection schemes within the limited time after
10 network disruptions. Automatic data collection devices enable 24/7 traffic
11 monitoring with higher accuracy, which could greatly expand the depth and
12 extent of analysis. For example, longitudinal analyses were only implemented
13 in the case of I-5 corridor after the Northridge Earthquake because Caltrans
14 systematically documented freeway traffic data collected by loop-detectors,
15 which was not available in many other studies. Data collection on arterials
16 still depended on manual counts in all these studies, representing a major
17 barrier for traffic analysis in the metropolitan area. This barrier could be
18 overcome by retrieving traffic data from signal control systems, which has
19 been widely deployed in major cities. HOV and HOT lanes provide good data
20 resources for vehicle occupancy. However, we could not accurately estimate
21 the vehicle occupancy on the entire network without supplementing typically

1 collected data. Similarly, ridership statistics from transit operators provide
2 good estimates of total trips. However, it tells little about the boarding stops,
3 boarding time and duration of those trips, all of which are crucial to fit a
4 transit model.

5 Traffic observations alone cannot support a well-founded analysis of be-
6 havioral changes. Well-administered surveys are need. In the literature,
7 three types of surveys, telephone survey, home interview, and mail-in ques-
8 tionnaires, have been employed. Home-interview and telephone survey have
9 higher response rate ($\geq 80\%$ in studies listed), they are, however, also gener-
10 ally more expensive. Mail-in surveys have a much lower response rate in the
11 literature. Moreover, concerns about self-selection biases should be addressed
12 before using such data.

13 Plate matching was employed by Clegg (2007). By identifying vehicles
14 at different survey points, trip travel time could be estimated. Based on the
15 same approach, route choice could be systematically estimated. However, col-
16 lecting license plate number is labor-intensive, and cannot be implemented
17 on a large-scale without a major new infrastructure investment. Moreover,
18 Clegg (2007) also reported that plate-matching is error-prone and more re-
19 search is required to generate convincing results.

1 **5 Conclusion**

2 Although network disruptions occur from time to time and provide unique
3 opportunities to explore travel behavior, existing studies in the literature are
4 limited. Traffic data were limited in time and locations before loop-detectors
5 were widely deployed, preventing continuous traffic observation. As a result,
6 no statistical analysis have been provided to empirically measure the re-
7 equilibration of traffic flow, a key concept in travel demand modeling. A
8 practical measure of network equilibrium could not only advance theoretical
9 research in travel demand modeling, but also guides the efforts in survey and
10 behavioral study.

11 Although surveys based on questionnaires, telephone calls, and home in-
12 terviews have been routinely conducted and generated significant findings,
13 they are not sufficient to assist recent research efforts in individual-based
14 travel demand modeling. For example, none of the three survey tools cur-
15 rently used could provide a good description of route choices, which is crucial
16 in large metropolitan areas because of the complexity in network and thus
17 the large number of alternative routes. Moreover, although changes in de-
18 parture time and route choices are frequently reported in the survey, they
19 are seldom combined, preventing us from investigating these two choices as
20 a whole. This combined model is attracting increasing interest in theoretical
21 research.

22 Existing studies clearly showed the important role of experience in travel

1 decisions, which has been frequently discussed in theoretical studies. How-
2 ever, the barriers to empirically capture its role are two-fold. First, it is
3 difficult to observe travel decisions over time with current survey approaches
4 (respondents describe their travel pattern either on one day, or generally dur-
5 ing a period). Second, it is very hard to integrate survey data with traffic
6 information (predominantly from loop-detectors), which reveals the traffic
7 environment travelers experienced.

8 Considering these difficulties, more advanced survey approaches such as
9 Global Positioning System (GPS) should be employed. Objective observa-
10 tions of travel decisions and experience such as route selected, departure time,
11 travel speed, and on-route delay from these devices could supplement sub-
12 jective evaluations collected from existing surveys, and thus allowing more
13 sophisticated behavioral analysis. Moreover, devices such as GPS allow ac-
14 curate observations of day-to-day route choices for the first time, and easily
15 combine them with traffic information if clocks from both system are care-
16 fully synchronized. Such research initiatives could be very promising.

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Table 1: Empirical studies of traffic and behavioral response to network disruptions

Event	Year	Focus	Traffic	Transit	Occupancy	Survey Type	Effective Sample	Response Rate
New York City transit strike	1966	Ridership changes	Traffic survey			Home interview of transit users	8000	
Tasman Bridge, Hobart, Australia	1975	Traffic change						
Pittsburgh transit strike	1976	Comprehensive	Traffic counts		Manual counts	Two telephone surveys, 70% on commuters and 30% on non-commute bus users	1000	
Knoxville transit strike	1977	Transit ridership losses		Ridership				
Orange County transit strike	1981, 1986	Transit ridership losses		Ridership				
SR-17, Loma Prieta Earthquake, California	1989	Car-sharing					Two mail-in surveys on carpooling passengers	587 and 187
Northridge Earthquake, California	1994	Comprehensive	Detectors, Caltrans	Ridership	HOV usage	Telephone survey, random	846	29% and 33% 84.60%
Kobe earthquake	1995	System performance	Detector counts					
Center Street Bridge, Calgary, Canada	1999	Comprehensive	Two-day traffic survey	Ridership	Manual counts	Telephone survey, bridge users	1500	
I-880 reopening, California	1999	Comprehensive				Mail-in survey, hypothetical questions	822	13%
Amsterdam transit strike, Netherlands	1999	Transit users				Interview and mail-in survey	166	28.40%
Sydney Olympics	2000	System performance	Revenue at toll roads	Ridership				
Los Angeles transit strike	2003	Traffic impact	Detectors					
Athens Olympics	2004	Public transportation		Ridership		Questionnaire	14000	
Road maintenance, City of York, UK	2005	Traffic	Video record			Plate match	one hour	≈ 50%
I-35W Bridge collapse, Minneapolis, MN	2007	Comprehensive	Detectors, MnDOT	Metro Transit		Mail-in Questionnaire	141	14.1

Table 2: Impacts on traffic and travel behavior of transit strikes

City	Year	Duration	Traffic increase (%)	Peak hours	Leave earlier (%)	Cancel trips (%)	Transit to carpool (%)	Transit to drive (%)	Change route (%)	Long-term losses in ridership (%)
New York City	1967	13 days		2h to 4h		10(50*)	16.7	50		2.1-2.6
Pittsburgh, PA	1976	5 days	20(40*)	Spread	65		28(37**)	10	18	
Knoxville, TN	1977	6 weeks								7-16
Orange County, CA	1981, 1986	21 days, 15 days								15-20
Netherlands	1995	4 weeks				10		30		0.3-2.0
Amsterdam, Netherlands	1999	1 day			10(18***)	10		15		
Los Angeles, CA	2003	35 days		200%						

* On the first day of strike

** Dropped off by a non-commuter, presumably the spouse

*** Percentage for departure later

Table 3: Behavioral changes after bridge closures or bridge collapses after an earthquake

Event	Leave earlier (%)	Leave later (%)	Drive to carpool (%)	Drive to transit (%)	Transit to carpool (%)	Transit to drive (%)	Change route (%)	Cancel trips (%)	Other destinations (%)
Tasman Bridge, Hobart, Australia									60
SR-17*, California			57						
I-10**, California	21.7	7.9	5.8	0.3	2.4	0	31.2		5.4
Center Street Bridge, Calgary, Canada				3.6				2.7	
I-880 reopening*, California		41				7		3	9
I-35W, Minneapolis	17.7	9.9	0	2.63	0	0	39.72	7.8	33.33

* Damaged in Loma Prieta Earthquake, 1989

**Damaged in Northridge Earthquake, 1994