ASSESSING THE MARGINAL COST OF FREEWAY CONGESTION FOR VEHICLE FLEETS USING PASSIVE GPS SPEED DATA

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Nicholas Stephen Wood

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Approved by:

Dr. Randall Guensler, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Michael Meyer
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Frank Southworth
School of Civil and Environmental Engineering
Georgia Institute of Technology

Date Approved: July 6, 2010

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LIST OF SYMBOLS AND ABBREVIATIONS

ARC	Atlanta Regional Commission
ATRI	American Transportation Research Institute
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GCT	Gwinnett County Transit
GDOT	Georgia Department of Transportation
GPS	Global Positioning System
GRTA	Georgia Regional Transportation Authority
GSM	Global System for Mobile Communications
GT	Georgia Tech
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
IRB	Institutional Review Board
JIT	Just-in-Time
min/mile	Minutes per Mile
mph	Miles per Hour
mph/sec	Miles per Hour per Second
MSA	Metropolitan Statistical Area
NAFA	National Association of Fleet Administrators
NAICS	North American Industry Classification System
PDOP	Positional Dilution of Precision

SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Act: A Legacy for Users
TOT	Truck-Only Toll

SUMMARY

Assessing the marginal costs of urban congestion is an essential component of transportation policy analysis. Businesses and organizations are impacted by limited mobility and have to account for an additional burden within their operation to meet an expectation of efficiency. Previous literature on the subject is broad in scope because each user of the system interprets delay and unreliability in separate contexts and considers lateness differently.

This thesis examines the marginal cost of congested travel to a variety of businesses by observing time spent in congestion and estimating excess labor costs based upon the relevant value of time. The fleets in the scoping study represented commercial deliveries of goods and services, government agencies, and transit systems. Observations on limited-access expressways within the 13-county Atlanta metropolitan region were used in the analysis. Vehicles were monitored by using a passive GPS assembly that transmitted speed and location data in real-time to an off-site location. Installation and operation during the observation period required no interaction from the driver. Over 217 hours of good freeway movement during 354 vehicle-days was recorded.

Rates of delay, expressed as a unit of lost minutes per mile traveled, were calculated by taking the difference in speeds observed during congestion from an optimal free-flow speed of 45 mph and dividing that by the distance traveled per segment. The difference between the 50th and 95th percentile delay rates was used as the measure for travel unreliability. Daily average values of extra time needed per fleet vehicle to ensure on-time arrivals were derived, and the median buffer across all fleets was 1.65 hours of added time per vehicle.

Weekly marginal costs per fleet vehicle were estimated by factoring in the corresponding driver wages or hourly operation costs (for transit fleets). Equivalent toll rates were calculated by multiplying the 95th percentile delay rate by the hourly costs. The equivalent toll per mile traveled was representative of an equal relationship between the marginal costs of congestion experienced and a hypothetical state of free-flow travel (under first-best rules of marginal cost pricing). The median equivalent toll rates across all fleets was $0.43 per mile for weekday mornings, $0.13 per mile for midday weekdays, $0.53 per mile for afternoon weekdays and $0.01 per mile for weekday nights and weekends.

CHAPTER 1

INTRODUCTION

1.1 Framing the Costs of Urban Transportation

Understanding how urban congestion affects mobility is an important component of transportation policy analysis and assessing how a transportation system impacts regional productivity. In 2007, the Texas Transportation Institute estimated that urban congestion costs $87.2 billion in lost productivity throughout 439 urban areas in the United States [1]. The Metro Atlanta Chamber of Commerce had listed transportation and congestion as one of its main regional public policy concerns context is conducting a vigorous campaign to change statewide policy [2]. The Governor of the State of Georgia even proposed confronting the problem by conducting referendums in 12 local regions to increase the sales tax to finance future transportation programs. The referendum proposal was brought about as a method to inform the public as to why a tax increase was needed and to let voters directly approve funding for a list of transportation programs [3]. The reason for the proposed change in policy is the shortfall in state transportation financing and the reluctance to generate revenue through traditional means, such as increasing the motor fuel taxes.

The National Surface Transportation Policy and Revenue Study Commission stated that gas taxes would need to be raised nationally by $0.79 per gallon by 2020 to meet the investment gap for supporting sustainable infrastructure [4]. However, receiving the support of Congress and state legislatures in raising the motor fuel tax has been difficult, and it is likely that the current legislation of SAFETEA-LU will be extended for years, despite the political will to support any surface transportation bill [5].

The 2000 edition of the Highway Capacity Manual states that travel delay is "the additional travel time experienced by a driver, passenger, or pedestrian [6]." A recent Federal Highway Administration (FHWA) report defines travel time reliability as the "variability in congestion, or how reliable travel conditions are on a day-to day basis [7]." Users of the system respond to delay and uncertainty in travel time by allocating additional time for travel to give an element of assurance toward arriving on-time at a destination. Regular and repetitive instances of delay are usually perceived by drivers to be reliable; however, travelers tend to recall the few bad occurrences of unexpected delay and adjust their schedules accordingly with extra time to account for unreliability.

The dimensions of congestion can be exhibited through values of intensity, duration, and extent [8]. For example, the Atlanta Regional Commission (ARC) defines intensity as how frequently delay is experienced by a traveler, duration as the number of hours of delay, and extent as the number of travelers impacted by congestion. ARC planners and modelers look at all three variables when evaluating which programs should be implemented [8]. Travelers typically consider intensity and duration to be important because those are the two conditions that influence their mobility the most. In confronting the concerns of congestion, one method has been to showcase econometric models that explain the problems of delay and unreliability in the transportation system.

Highway automobile travelers bear costs to use transportation facilities, which can include: operating and maintenance, vehicle capital, travel time, and schedule delay and unreliability. These are specifically borne by the users themselves, as opposed to the externalities of incidents and crashes, government services, and environmental impacts borne by all of society. In transportation economics, all of the expenses on the travelers themselves are represented as the short-run average variable user costs under the first-best rules of marginal-cost pricing. When congestion occurs, the output on the facility is slowed and the delay per vehicle increases, causing the unit costs to also rise. The short-run marginal costs are representative of increasing traffic volumes and congestion. Marginal costs represent the expense that each additional user places on themselves and the burden they place on all users of that facility at the same time. The difference between marginal and average traffic costs is known as the marginal external cost of congestion, which can be viewed as being equivalent to a hypothetical optimal congestion toll [9].

1.2 A Regional Proposition

The Georgia Department of Transportation (GDOT), in their most recent strategic plan [10], identified congestion as being a major factor toward company location decisions. GDOT identified congestion as being a key influence in making Georgia attractive to prospective employers and encouraging economic growth and competitiveness. Some of the metrics for defining success were outlined in the plan as the annual congestion costs, travel times, and the average number of workers reaching major employment centers by car or transit in 45 minutes. One of the principal areas of concern changes in these characteristics is the Metropolitan Atlanta Region, with particular focus paid to the local expressway system as maintained by GDOT [10].

GDOT has proposed a regional system of high-occupancy toll (HOT) lanes to give users a choice in bypassing typically congested facilities at a total capital cost of $16.2 billion [11]. As currently proposed, the toll lanes would be open to passenger vehicles with single drivers and those carrying an additional passenger for a toll. These lanes would be free to use for carpools and vehicles carrying three or more people. Buses are also exempt from paying a toll. Heavy-duty trucks and vehicles with more than three axels would be prohibited from using the HOT lanes. GDOT is aiming to have HOT lane facilities on nearly every limited-use expressway in the Atlanta region. By instituting a HOT lane network, GDOT expects the cost of delay to be reduced by $37 billion over the next 35 years [10]. Figure 1 graphically shows the expected increase in employment-sheds once the regional HOT lane system is implemented, with a 196% increase in workers within 45 minutes of Downtown [11].

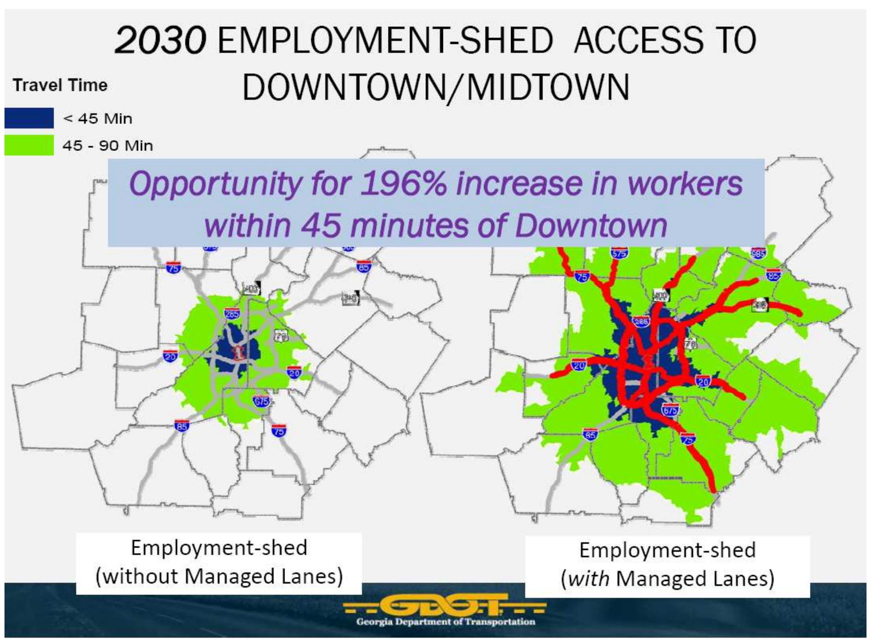

Figure 1 Slide of Presentation Given to GDOT Board, 9/17/2009 [11]

1.3 Scope of Research

When HOT lanes are implemented, it is likely that some commercial fleets will take advantage of the opportunity to buy their way out of congestion. In analyzing the outcomes of implementing a region-wide managed lane network, the affects of congestion and unreliability were considered on a microscopic level for 12 fleets based in the Atlanta area. However, under the proposed HOT lane concept, only passenger-class vehicles would be allowed to use the facility, thus, only 8 of the 12 fleets analyzed would be permitted to use the lane. These fleets represented a small cross section of the variety of commercial and government activities that currently utilize the system.

From February to August 2009 (except for one fleet monitored in 2005), for a period of two weeks for each fleet, second-by-second data was collected using a passive GPS assembly that monitored all roadway activity. The data were then summarized to determine the extent and duration of delay experienced on each expressway corridor. In the analysis presented in this thesis, congestion was defined to be all occurrences of travel below 45 mph, typically a speed with maximum throughput of vehicles per hour per lane [12]. The trip segments were then examined to determine the frequency of delay by time period. The final segment of the thesis examines the percent of fleet activity lost to delay and unreliability and estimates the equivalent toll rates based on reliability for the fleets based on monitored travel. The percentage of fleet activity loss can be thought of as having to operate additional vehicles in the fleet. In reality, the number of extra vehicles and workers depends on the commercial enterprise and how much time they spend driving versus working. Toll values were derived by only considering the marginal cost of congestion and the how much more delay per mile was borne by each fleet vehicle. Environmental and social externalities outside of the principal labor expenses were not considered in this thesis.

CHAPTER 2

LITERATURE REVIEW

The literature on value of time and reliability varies considerably in focus and conclusions. Most of the value of time estimates was dependent upon how its investigators approached the methodology and reviewed the results. The authors may have considered particular aspects of commercial and freight movement delay to be more inhibitive to specific fleets as opposed to others. Research into detailed reliability metrics for commercial operations was extremely limited, and research on unreliability primarily looked into personal travel. Additional literature was reviewed to consider as a whole at the lost economic opportunity due to congestion. One study [13] utilized semi-passive GPS data to collect vehicle tour data and derived trip summary statistics with information regarding travel distances, stops per tour, and vehicle speeds.

2.1 Larger Components of Assessing Economic Impacts

In assessing the economic costs of a transportation system, Weisbrod et. al. [14] attempted to conceptualize how congestion affects the business market by shrinking the area for operating capacity. If a region experiences heavy congestion that reduces travel time, then the spatial market would be reduced as opposed to a free-flowing system that enables trips to be made on-time. Weisbrod et. al. considered a holistic approach that took into account factors of accessibility, location, and economic productivity costs. Part of the methodology involved scrutinizing data by evaluating productivity measurements associated with travel time variability, freight inventory, worker availability, scheduling, and markets of scale. For the business delivery sub-model, Weisbrod et. al. utilized regional demand models and segmented travel behavior based on the type of commodity served; either agriculture, mining, or manufacturing [14]. Weisbrod et. al. concluded that fleets with higher portions of truck shipping tended to be more affected by congestion as opposed to non-specialized firms that cannot easily change locations by alternating to closer suppliers [14]. Another significant finding demonstrated that if the labor market doubled in size, an average increase of 6.5% could be expected in business productivity [14].

2.2 Value of Time

Mackie et. al. critiqued the assumption that all travel time saved is a direct benefit to the employer [15]. It can only be true if: "100% of the savings is allocated for other productive purposes, travel time is entirely unproductive, and the wage rate is directly equivalent to the marginal product of labor." Mackie et. al. came to the conclusion that marginal product value may in fact exceed the wage rate when arriving at social costs. However, for working travel time savings, the yield to the employer can be defended as a cost savings value [15].

Five of six dimensions identified by Mackie et. al are known to influence the perception of travel time savings for vehicle fleets. The factors were the (1) time of the trip, (2) travel conditions (whether congested or free-flow), (3) trip purpose, (4) trip length, (5) the extent of time saved. Mackie et. al. recommended conducting choice experiments if the values of time did vary along all those dimensions. When looking at the variables, correlations between them must be considered and separated out in the analysis. Generally, Mackie et. al. did not find any reason to distinguish the values of time among any of the first four dimensions because of the lack of empirical evidence and its complexity, except the extent of time saved [15].

One of the first efforts to place a value on commercial vehicle travel time was undertaken by Haning and Wootan [16] in 1965. The extent of travel was derived from a previous study of truck traffic, where volume counts were collected and segmented by number of axles. It was then assumed for the value of savings that each additional amount of time that became available would be taken and used for additional freight volume. However, Haning and Wootan also questioned the practicality of that statement, because fleet operators may not use all the savings for practical business purposes. In explaining the distance-based cost of vehicular travel, the authors segmented the expenses into: driver wages, employees' welfare, workman's compensation, license and registration fees, real estate and property taxes, and social security taxes. Haning and Wootan gave a range of $2.91 to $3.89 per hour (in $1959 dollars, $21.45 to $28.68 in $2010 dollars using the average urban consumer price index) of travel time saved and given that 60-80% of savings was utilized for carriers. Haning and Wootan also hypothesized that travel time savings would enable corporate entities to extend the geographical reach of distribution and manufacturing centers. This in turn would enable a company to build fewer centers and expand operations at reduced costs [16].

The United States Department of Transportation (USDOT) suggested values of time in a 1997 policy memorandum for use in evaluating regulatory actions and infrastructure investments [17]. USDOT consulted a number of individuals who preformed research in this area and considered mode choice, trip purpose and household income to be contingent variables in the valuation of travel time. Travel distance was the largest source of variation, with considerable difference between local and intercity trips. The USDOT also concluded that both large and small time savings were valued at the same rate. Therefore, the use of a constant value of time was deemed appropriate. The memorandum adopted the value of local and intercity commercial travel to be 100% of the wage rate (inclusive of all fringe benefits) involved in transporting the good or service [17].

Small, et. al. (1999) [18] also evaluated whether freight carriers and travelers place a value on saving time during trip-making activities. For their experimental approach, they attempted to collect information through a stated preference survey and by conducting telephone interviews. Small et. al. (1999) managed to confirm that saving travel time was an important characteristic in determining freight costs for shipping decisions, but could not significantly explain values for travel reliability. Small et. al. (1999) calculated that fleets valued time savings at $144.22 to $192.83 per hour ($183.95 to $245.96 in $2010 dollars) and valued late schedule delays at $372.33 per hour ($474.91 in $2010 dollars) of the overall operating costs. The average value of time savings was approximately one-third of the flat hourly trucking expense and predictability was about two-thirds of the hourly trucking expense. Small et. al. (1999) believed their analysis was weak because it relied on a small sample of 20 carriers, fleet characteristics were not controlled for and the respondents had difficulty in grasping the concepts of using cost variables and the distribution of schedule delays [18].

In response to the work of Small et. al. (1999), the American Transportation Research Institute (ATRI), an organization that specializes in trucking operations sponsored a recent research effort to quantify the distance and time based costs of operating on the highway [19]. The main concern of ATRI was that value of time was being overestimated for fleet operations in the evaluation of potential congestion mitigation strategies and that corresponding benefits would also be overestimated. The research methodology focused on 43 surveys selected through various State Trucking Associations and the American Trucking Associations' National Accounting and Finance Council carrier membership. ATRI segmented the marginal operating costs into driver and vehicle-based categories, which consisted of: fuel and engine oil, truck leases or purchase payments, repair and maintenance, fuel taxes, insurance premiums, tires, licenses and permits, tolls, wages, benefits, and bonuses. ATRI only considered direct benefits to the trucking operations and not external environmental or social factors. In their model, ATRI arrived at a marginal cost of $1.73 per mile and a value of time of $83.68 per hour in their model and explained that fixed costs were a significant contributor to the variable costs. Late deliveries were not accounted for in the analysis and they assumed that travel time costs were linear. ATRI also concluded that significant differences in marginal costs can be found across the range of fleets, which was likely the result of the diverse range of operations represented in the research [19].

A stated preference survey conducted by Kawamura [20] in 1999 on California-based trucking companies and private fleets measured responses in determining whether to use a tolled facility. Kawamura collected replies through a telephone conversation with 70 corporate fleets, asking 10 stated preference questions that gave travel time savings of 5 to 15 minutes for a hypothetical toll of $1 to $10. A few fleets completed follow-up interviews to ask additional questions tailored specifically for them, based on responses to the first survey. The value of time was derived by observing the switching point in changing travel choice for each fleet. For instance, an operator who would be willing to pay $7 to save 15 minutes but would not pay $8 for the same savings would be classified as having a value of time between $28 and $32 per hour. A modified logit model was used to estimate the coefficients for the utility function with the assumption that value of time was distributed lognormally among the participants. Kawamura concluded that private fleets tended to have lower values of time as compared to for-hire operations and companies that pay their drivers by an hourly rate [20].

Smalkoski and Levinson [21] considered stated preference data in their investigation of value of time for commercial vehicle operators. Smalkoski and Levinson mailed 2,523 surveys to corporate entities, as identified by the Minnesota Trucking Association and local city and county engineer offices, and received 441 good responses. About half of the respondents agreed to participate in a personal interview. The correspondence consisted of an adaptive stated preference survey that altered future questions based on the responses given in previous scenarios. Smalkoski and Levinson determined that by fitting the responses to a Tobit model, a mean of $49.42 per hour ($57.50 in $2010 dollars) was found in travel time savings for commercial operators. This value was bounded from $40.45 to $58.39 per hour ($47.07 to $67.94 in $2010 dollars) using a 95% confidence interval [21].

A survey conducted by truck drivers in the Austin, Texas metropolitan region found a difference in valuation between for-hire and private carriers. In Zhou et. al. [22], over 2,000 respondents indicated their route choice preferences and whether or not certain conditions would influence taking a tolled bypass around a congested toll-free highway that intersected the central business district. Smaller freight carriers were found to prefer the non-tolled route because the cost of paying the fee would be immediately borne on the driver, as opposed to larger firms that had a weighed decision-making process. The incentive shown as most effective toward influencing driver opinion was the use of discounts during the off-peak time periods. In performing their analysis in 2008, Zhou et. al. arrived at a commercial value of time of $44.20 per hour ($44.04 in $2010 dollars) [22].

In contrast to the study done in Austin that identified discounts on toll facilities as being an influence on commercial travel, empirical research done by Holguin-Veras et. al. [23], using focus groups in New Jersey, found that freight operators rarely base travel decisions on tolls that vary by time of day. Approximately 62% of the respondents indicated that customer demands compel travel decisions, 26% had identified congestion as being an influence, and 21% had wanted to deliver during normal business or daytime hours. Only 3.5% of the participants had mentioned that making a toll cheaper by time period as a reason to change travel behavior [23].

2.3 Measuring Reliability

Brownstone and Small [24] examined how most travel time reliability statistics were derived and listed their limitations in use for practical analysis. Most data collection efforts rely heavily upon embedded loop detectors placed within the roadway surface that measure traffic volume and density. Using the collected count information, spot speeds can be determined for a single location, but applying speeds to a corridor requires a series of assumptions that usually make final results less certain. Often, spot speed data were supplemented by recording the time it takes for a small group of vehicles to travel between two distinct points on the corridor. Electronic loops are also prone to failure with some readings being misread or missing from the final dataset [24].

Lam and Small [25] collected 533 surveys from passenger vehicle drivers and matched that information to estimated loop detector travel time statistics for both the tolled and non-tolled sections of State Route 91 in California. The authors note the common procedures to determine the reliability metric were: (1) the standard deviation of the travel time distributions and (2) the differences between percentiles within the dataset, usually the difference between the 90th percentile and the median for personal passenger vehicle trips. When looking at the log-likelihood of both methods, the differences between the median and selected percentiles (either the 80th or 90th percentile) resulted in a better-fit choice model as compared to the standard deviation or mean [25]. Bates et. al. [26] agree with this conclusion in their assessment of travel unreliability for rail trips. Lam and Small explained that a reliability ratio (the value of reliability to the value of time) on a range of 0.8 to 1.3 for personal car travel was appropriate and that public transportation modes can expect higher ratios, but not usually higher than 2.0 [26].

However, the use of revealed preference data has been highly suspect because of the difficulty in gathering sufficient information to test situations with a significant enough variation. Li et. al. [27] referenced a series of studies and found that cost, travel time, and variability tended to be highly correlated in revealed preference surveys. Observations need to be repetitive with actual, distinct, and limited choice situations to truly capture the experience with revealed preference. For instance, a choice set consisting of tolled and non-tolled lanes for a highway would be a good example.

Because of these restrictions, stated preference surveys are still believed to be the preferred source for information regarding measuring value of time among users [27].

Batley and Ibáñez [28] in 2009 considered a mean-lateness model in their analysis, where only the differences in departure and arrival times were considered as scenarios of being late. Rail travelers were asked for their preference in a survey that outlined a series of conditions in journey times, lateness, fares, and a scheduled timetable. Across 11,763 observations for 2,395 respondents, travelers valued time savings at an equivalent of $27.30 per hour and reliability at $56.40 per hour. Batley and Ibáñez also computed an additional penalty for lateness at $34.00 per hour. The reliability ratio, defined as the ratio of the standard deviation to the scheduled journey times, was as high as 2.69 for the six segments tested, and counting for lateness based on the scheduled travel time, the reliability ratio nearly doubled to 5.19.

A report prepared by Cambridge Systematics and the Texas Transportation Institute for the Federal Highway Administration identified three additional metrics for explaining travel time reliability [7]. The measures were the planning time, the planning time index, and the buffer index. These metrics can be calculated as:

$$Planning\ Time = 95th\ Percentile\ Travel\ Time$$

$$Planning\ Time\ Index = \frac{95th\ Percentile\ Travel\ Time}{Ideal\ Travel\ Time}$$

$$Buffer\ Index = \frac{(95th\ Percentile\ Travel\ Time - Average\ Travel\ Time)}{Average\ Travel\ Time}$$

The ideal travel time for the planning time index was the non-congested travel speed for a vehicle trip. The average travel time for the buffer index considers the possibility that delay was experienced on facility for most of the time. All three measures consider the logarithmic distribution of reliability but describe the impact in different approaches [7].

Van Lint et. al. [29] argued that all of the metrics used for travel time reliability were highly inconsistent. To test the hypothesis, empirical speed data was collected from a densely congested highway in the Netherlands and take into account the standard deviation of travel times, the range of percentiles, buffer indices, and a few other proposed metrics that accounted for the skew and variance in the distribution of travel times. The skew measure was essentially the ratio of the difference from the 90^{th} to the 50^{th} percentile to the difference between the 50^{th} and 10^{th} percentiles. The variance metric was the difference between the 90^{th} and 10^{th} percentiles divided by the 50^{th} percentile. Each measure was inspected by creating "reliability maps" that graphically represented time periods of unreliability by time of day and day of week. Tests of correlation between the metrics were also performed by taking the Pearson's correlation coefficients across all the variables. In theory, if all of the measures were reliable predictors of unreliability, the correlation coefficients should be very high. However, wide deviations in the coefficients were present; indicating that some travel time conditions may be explained by a few of the measures, but not by others [29].

Fowkes et. al. [30] defined three different dimensions of delay as affecting the reliability in business delivery schedules: (1) delay that occurs when departure time is pushed to a later time, (2) delay due to increased travel times from the same departure schedule, and (3) the variability in arrival rates due to changes in travel speed over the route. Freight movements were considered for just-in-time (JIT) and non-JIT operations, with the JIT movements being doubly valued as compared to non-JIT, due to the necessity for having very strict delivery schedules. Corporate entities contracting out their freight shipments were found to have a lower value of reliability, likely the result of not having any direct data on the way in which transportation costs were impacting their business. All three dimensions of delay were found to greatly impact the reliability of delivery schedules, with some components being more influential for certain fleets than others [30].

2.4 Commercial Vehicle Tour Data

One study that used semi-passive GPS technology to monitor commercial vehicle tours was done in 2006 on 30 trucks in the Melbourne, Australia region by Greaves and Figliozzi [13]. A week of data for each truck was collected to get a total of 210 vehicle-days of activity. The devices used to monitor the vehicles required no interaction from the driver, but did rely on a cigarette-lighter or another source for external power. Travel data were stored on the device until retrieved from the vehicle [13].

An algorithm was developed in the Melbourne study to differentiate between actual stops in the vehicle tour as opposed to stops linked to signals and congestion. The process identified trips ends in the movements as stops if the distance between points was less than 30 meters for all records collected in a 240 second period. Greaves and Figliozzi also noted records where the engine was shut off for short durations of 30 to 120 seconds, detecting odd points with erroneous heading values, and times where the speed recorded was zero. Any odd information was checked through a manual process. Overall, about 95% of the collected second-by-second information was defined as being good for analysis with 70 hours of records being suspect or lost. The final output from

Greaves and Figliozzi looked at summary statistics of travel distances, stops per tour, and speeds for the entire analysis dataset [13].

2.5 Summary of the Literature Review

The literature varied considerably in the estimates for commercial vehicle value of time, ranging from $245.96 per hour [18] to $44.04 per hour [22] (values in $2010 dollars). A study referenced in a later chapter used $38.45 per hour by conducting a focus group to assess the valuation of travel time for freight industry leaders in Atlanta [31]. The differences in values are affected by the wage rate variations across geospatial markets and the methodology used to derive rates of time. The literature review took information from drivers in California [18, 20], Minnesota [21], Texas [22], and nationally [19] and assessed data by fitting a choice model to stated preference responses [18, 20-22] or simply applying survey responses to an estimation procedure [19]. Each choice model took a different approach, such as considering whether a fleet was private or for-hire [20-22], the probability of being late as a variable [18], and whether travel was conducted on a certain highway in the region [22].

Measuring travel unreliability within a transportation system was also extremely varied in definition and approach. Previous research has suggested taking the difference between the 50^{th} and 90^{th} percentile travel times [25], using the 95^{th} percentile and average travel times to calculate a buffer index [7], comparing the differences in late departure and arrival times [28], and calculating the skew and variance of the distribution in travel times [29]. Part of the reason for the difference is that every user interprets expected and unexpected delay differently, with a disparity in how each reacts to late arrivals.

Other significant findings in the literature were:

- Fleets with higher portions of truck shipping tended to be more affected by congestion as opposed to non-specialized firms that cannot easily change locations by alternating to closer suppliers [14].
- Not all travel time savings are productively utilized for other purposes by fleets [15, 16].
- A simplistic assumption of applying 100% of the labor market employment cost was used in monetary valuation assessments [17].
- A very limited percentage of freight operators would change their travel behavior if the costs to use a facility varied during the day [23].
- The use of revealed preference survey instruments to assess travel time valuation was suspect [26, 27].
- Corporate entities contracting out their freight shipments were found to have a lower value of reliability, likely the result of not having any direct data on the way in which transportation costs were impacting their business [30].
- Data collection efforts done using GPS equipment needs to correctly identify where trip locations end to discount erroneous observations [13].

CHAPTER 3

METHODOLOGY

3.1 Recruitment of Participants

Recruiting participants for a commercial vehicle monitoring study is a difficult task that required a variety of techniques and multiple contacts over a period of time. Businesses had little time to volunteer in research events and were not compensated for participation in this study. From an administrative standpoint, recruiting was problematic because of the lack of understanding how each contacting agency or company was structurally organized. The likelihood of reaching any individual with the authority to permit the monitoring of fleet vehicles was slim on the first attempt. Initially, the researchers had proposed that all contact be done through the fleet manager, but it was later discovered the lead shop mechanic often filled this role. Successfully recruited companies were usually convinced to participate by a person with a more established leadership role, such as a company Vice President. Therefore, it was crucial to identify key leaders within potential candidate organizations.

The preferred source for contact information came from professional industry databases maintained by groups such as the Georgia Motor Trucking Association and the National Association of Fleet Administrators (NAFA). The NAFA database was useful because it specifically listed individual fleet supervisors. If the listing did not indicate a specific person, getting participation required calling multiple people within the company to get the proper approval to monitor the fleet.

The process for recruitment utilized phone calls, e-mail messages, and in-person contact. Recruitment by phone initiated the conversation by presenting a scripted 30-

second summary of the study and what would be expected from participants. The initial discussion was followed with asking the company representative if they would be willing to proceed and if they had any questions. A few written letters were sent to prospective fleets when they desired additional detailed information. After an interested organization indicated a willingness to be involved, an e-mail message was sent to the responsible person, detailing the extent and purpose of the survey. A positive reply in writing meant that an installation could proceed because the participant had given informed consent to the scripted research description, as required for the Institutional Review Board (IRB) for research compliance with ethical standards at Georgia Tech.

The exhaustive outreach toward 130 organizations in recruitment yielded a success rate of approximately 10%. Many of the companies contacted were not interested, with the principal reasons being concerns with the amount of time and effort involved, worries that instrumentation might hamper the functions of a driver, and anxiety that detailed trip data might be given to the public and local media outlets. Surprisingly, concerns about access to proprietary data was not a principal motivation for non-involvement, but rather, candidate fleets were deterred because participation in the study yielding no direct benefit to their business.

3.2 Freight Data Collector

A monitoring unit was placed in each fleet vehicle for a period of two weeks, or the time it took to completely drain the portable battery. The intent of the device was to equip trucks to monitor second-by-second movements on the transportation network, to not require any interaction for the driver, and to transmit data in real-time for a two week period. As a result, the units were self-powered and autonomously processed and transmitted second-by-second data back to the central server. The assembly consisted of an internal GPS device and GSM modem to provide the vehicle tracking and communication functions, respectively [32].

Overall, the entire assembly was composed of two modules: a power cord and an antenna. The power cord physically connected the two modules and the antenna provided the means for receiving and sending data. One module housed the GPS receiver and GSM modem, and the other contained a 12-volt deep-cycle gel cell battery. Input lines for ignition and main power were protected with separate 1-amp and 3-amp fuses, respectively. Power drawn from the module depended on the amount of data transmitted, and varied from 70mA to 150mA based on a 12-volt automotive electrical system. This module had the approximate size of 3 inches wide, 6 inches long, and 1.5 inches of height [32]. A basic depiction of the assembly is shown in Figure 2.

The battery module was designed for vibrating and shifting conditions often encountered in fleet travel. The power source can last for 275 hours, or slightly less than two weeks of monitoring time, on a maximum draw of 205 mA for 33 amp-hours of battery life [32].

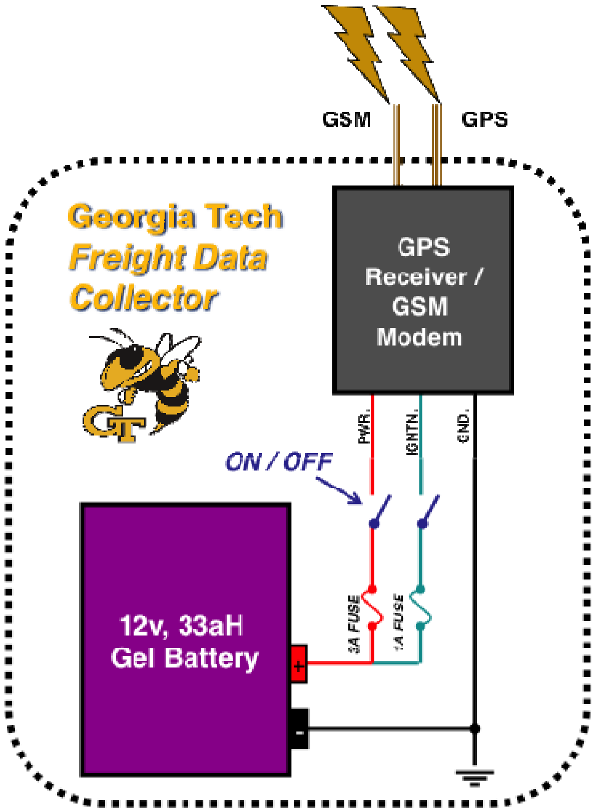

Figure 2 GT Freight Data Collector Schematic

3.3 Field Deployment

The logistics of deploying the monitoring units took a considerable amount of time outside of the actual study period for each fleet. All of the participants needed time to coordinate staff and vehicles for when the installation took place. On average, the fleets needed a week of preparation before the observation period and an additional week after, or sometimes less, to coordinate inserting and removing the assemblies. A few fleets were only available for service once or twice a week because of constant field use, placing an additional constraint on the installation. Recharging the battery after a deployment also added a few days. Between deployments, a monitoring assembly was unavailable for other use for up to four weeks per deployment vehicle during periods of fleet tracking and servicing.

A typical installation, once an appointment was scheduled and confirmed, took only 5 minutes per fleet vehicle. Both modules were placed in the cavity behind the passenger seat or the floorboard right in front of it. The antenna was fixed on the front dashboard with two-sided tape for the greatest chance of getting a good reception. Extra attention was given to placement, due to concerns of shifting during movement, which might have caused wires to strain or become disconnected. Figure 3 portrays a typical arrangement.

Figure 3 Deployed Monitoring Assembly within Vehicle Cab

Security of the monitoring units was an issue that was not originally taken into consideration. During the observation period for a municipal solid waste fleet, three of the five systems were stolen within days of the installation. A fourth unit had sustained damage when presumably a driver opened the GPS & GSM module and tried to turn off the power and ignition switches and instead snapped them off completely. Data collected from this fleet were incomplete, and were not used toward any additional analysis.

A potential solution to address security from theft and damage for potential future surveys would be to include a lock and chain for each assembly. Locks would be placed on the ends of the plastic encasings for both modules and a connecting chain would be looped around a physical constraint of the vehicle that would hold it in place. The constraint could be the bottom of the passenger-side seat or a handgrip near the door. Using this style of protection would deter theft of the major components of the assembly, but would not safeguard it from intentional damage to the power cord or the antenna.

3.4 Fleet Data Collection

Successful deployments were completed in 12 different fleets representing various commercial and government uses. The industry types monitored were: school bus transportation systems, express bus transportation systems, electric power distribution, ready-mix concrete manufacturing, local transit service, exterminating and pest control, department of transportation, supermarket and grocery store delivery, general merchandise stores, fruit and vegetable wholesalers, and motor vehicle towing. Every industry type was represented by a single fleet that was owned by one company, with the exception of express bus transit systems (separated by operator between the Georgia Regional Transportation Authority (GRTA) and Gwinnett County Transit (GCT) system). The goal was to collect approximately five vehicles per fleet, but the availability of monitoring assemblies and scheduling demands from the participants and loss of equipment in the garbage collecting fleet constrained the efforts. All of the observed data were collected between February and August 2009, except for the profiles representing the local transit system that came from prior research in 2005. Table 1 shows the industries represented by the North American Industry Classification System (NAICS), the number of vehicles observed in the dataset, and the starting and ending date for the collection period.

Table 1 Fleets Monitored by Number of Vehicles and Date

Industry Type	NAICS	Vehicles	Start Date	End Date
School Bus Transportation	485410	9	3/30/2009	4/30/2009
Express Bus Transit Systems				
- GRTA Express Transit	485113	4	4/8/2009	4/17/2009
- Gwinnett County Express Transit	485113	2	4/10/2009	4/27/2009
Electric Power Distribution	221122	6	7/1/2009	7/17/2009
Ready-Mix Concrete Manufacturing	327320	6	7/27/2009	8/15/2009
Local Transit Service Vehicles	485113	5	5/17/2005	10/23/2005
Exterminating and Pest Control	561710	5	5/11/2009	6/8/2009
Department of Transportation	926120	4	5/5/2009	5/16/2009
Supermarket and Grocery Stores	445110	3	2/13/2009	2/25/2009
Other General Merchandise Store	452990	3	3/24/2009	4/4/2009
Fruit and Vegetable Wholesalers	424480	2	2/7/2009	2/19/2009
Motor Vehicle Towing	488410	1	5/6/2009	5/16/2009

The duration of data collected per fleet, time on the expressway, time on the expressway in congestion, and percent of time spent in congestion are all shown in Table 2. Over 2,700 hours of second-by-second location and speed data were analyzed, with 240.7 hours occurring on the regional expressway system. Portions of fleet travel on the expressway varied widely by industry type from a high of about 39% of all movement to as little as 1%. The intra-regional expressway network used for analysis was defined as all of the Interstate-designated routes and Georgia State Route 400 in the counties of Fulton, Gwinnett, Cobb, Cherokee, Forsyth, Douglas, Coweta, Fayette, Clayton, Henry, Rockdale, DeKalb and Paulding. This region also represents the boundary for the 13-county non-attainment zone for the 1-hour ozone standard set by the U.S. Environmental

Protection Agency. A map depicting the counties and routes used in the analysis is seen in Figure 5.

Table 2 Duration of Collected Data and Time on Expressway by Fleet

Industry Type / Fleet	Duration of Data (hr)	Time on Expressway (hr)	Percent on Expressway (%)
School Bus Transportation	568.28	37.07	6.5
GRTA Express Transit	114.89	43.12	37.5
Gwinnett County Express Transit	65.07	25.42	39.1
Electric Power Distribution	214.04	15.98	7.5
Ready-Mix Concrete Manufacturing	156.89	18.68	11.9
Local Transit Service Vehicles	898.41	14.07	1.6
Exterminating and Pest Control	233.47	2.79	1.2
Department of Transportation	109.63	11.85	10.8
Supermarket and Grocery Stores	212.15	39.43	18.6
Other General Merchandise Store	44.33	11.57	26.1
Fruit and Vegetable Wholesalers	88.90	16.48	18.5
Motor Vehicle Towing	14.33	4.28	29.9

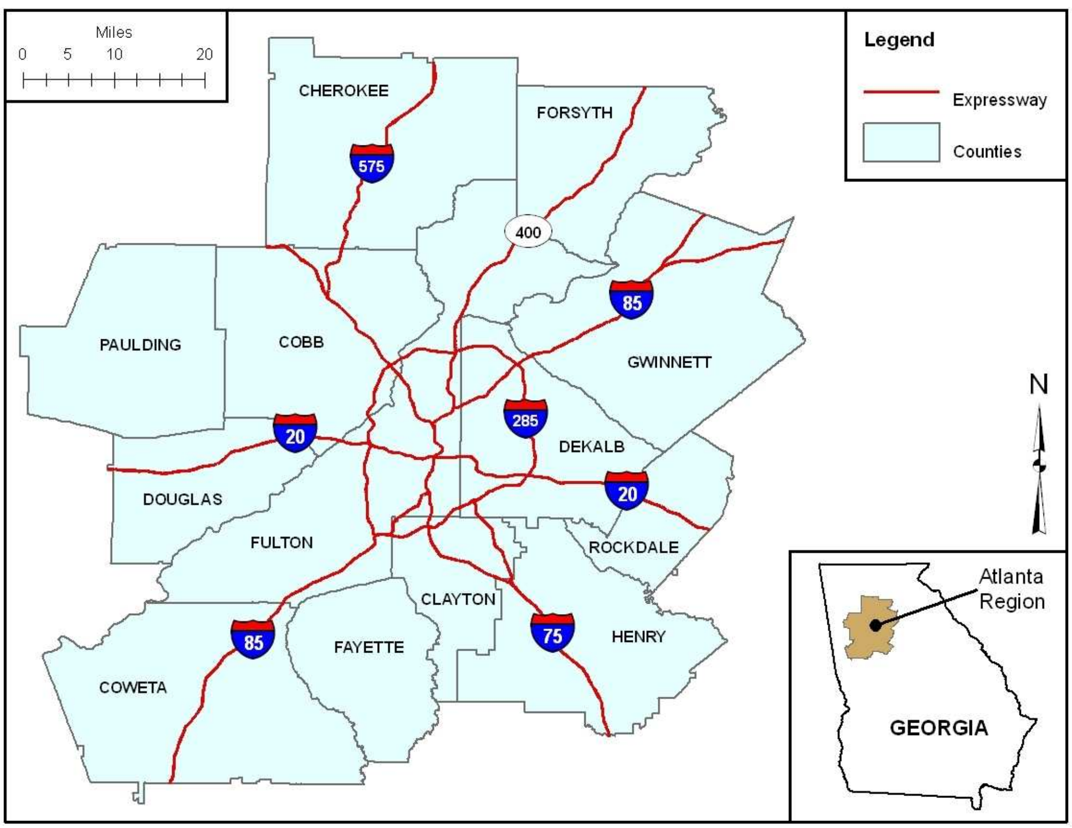

Figure 4 Intra-Region Expressway System for Analysis

Segmenting how much travel occurred on the expressway network was done through a GIS-based approach, similar to how Joonho Ko choose segments for trips on State Route 400 [33]. The GT Freight Data Collector transmitted the time, date, latitude and longitude position, and speed of the vehicle for every second of movement. One second of travel translated into one record being archived. Every record was geocoded within ArcGIS using the latitude and longitude position data, and a buffer of the regional expressway network was created to define a capture zone. Any recorded position that existed within the buffer was listed as being a part of trip conducted on an expressway. A possible disadvantage of using this approach was the tendency to overlap with other adjacent roads and overpasses. To remedy this, additional data reduction measures that excluded travel segments shorter than 60 seconds and less than one mile were incorporated into creating the final dataset for congestion assessment.

After all expressway travel was partitioned, segments were then labeled to demarcate consecutive records by time. This meant that records close to one another by at least 10 seconds were assumed to be of the same trip segment. Each segment in the dataset was given a specific number to note which records should be grouped together. This process created 2,176 segments and consisted of 232.8 hours of data, which was roughly 96.7% of all expressway records. The remaining 3.3% of data were excluded because using less than 60 consecutive second-by-second records within a trip segment on an expressway corridor was not truly representative of travel. An expressway trip segment where a driver would enter and exit a limited-access facility takes longer than 60 seconds.

3.5 Smoothing Speed Data with a Cubic Spline Fit

The GPS units provided speed profiles based upon the Doppler shift of GPS signals, bypassing the need to consider position data or calculate speeds based on latitude and longitude data [33]. Because this process uses satellites in geosynchronous orbit, it can be prone to deterioration of reliability due to obstructions in the natural and built environment. Overpasses, buildings, and the weather can influence calculated speed accuracy. Studies have taken the of number of satellites and the positional dilution of precision (PDOP) for every record and used it as metric toward rating data [33, 34]. However, this research did not have either statistic and had to rely on other means of correcting occasionally erroneous data points.

The instances of erroneous data usually occurred with large changes in reported speed. For instance, a point with a speed of 60 had a proceeding recorded speed of zero. It is not possible for a vehicle to decelerate from 60 to 0 mph in one second (unless it is involved in a crash), so this type of occurrence was identified as a likely data error. A process that implemented a cubic spline to smooth the speed profiles was created to bridge the gap with more realistic data.

The method of predicting corrected speeds began with correctly defining which data points were in potential error. To do this, a Perl script was created that calculated acceleration values based on the time and speed records. Acceleration was defined dividing the change in speed by the change in time between two consecutive records. If the acceleration was greater than 15 mph/sec, that record was identified as an error. Subsequent records were then checked for quality because errors typically existed in a tandem series due to signal interference over a period of time; that is a zero speed value was commonly followed by another zero value. All of the consecutive bad records in a single trip segment were labeled as an error until a speed value that was greater than 5 was found. However, if a bad portion was greater than 10 successive data points, only the series of erroneous records would be set aside from an estimated correction because it was unlikely that any process could reasonably predict the speed for a gap of 10 seconds or more. Whole trip segments with deleted gaps were still used in the analysis because an algorithm to calculate lost time only considered the summation of good records to compute time, not the difference between the first and last timestamps for a segment.

A cubic spline function was executed on gap segments shorter than or equal to 10 seconds. The script recognized the first three good data points before and after the erroneous series to predict what the corrected speed should have been. Figure 5 graphically shows an example of this process. Instances where three good speed values could not be found or when a bad series was at the start of the trip were designated as uncorrected. Applying the algorithm corrected 18.1 hours of data, or 7.8% of the data accumulated before running the cubic spline Perl script. About 3.3% of the dataset, or 7.7 hours, could not be corrected due to large data gaps. Approximately 88.9%, or 207.0 hours, contained valid data points and no spline fit was applied.

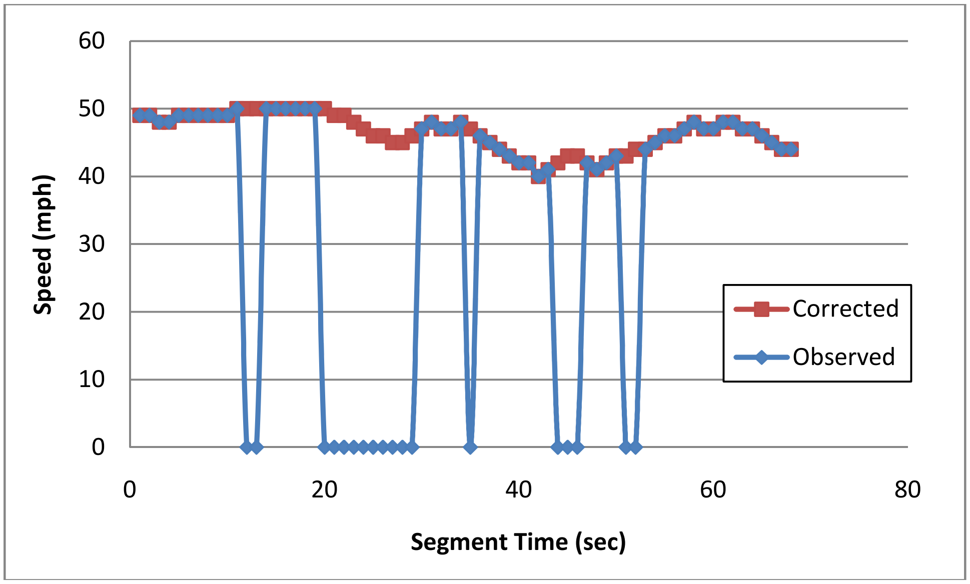

Figure 5 Example of Applying a Cubic Spline to a Speed Profile

The final data correction step was to ensure that the distance traveled per trip was appropriate for inclusion in the analysis. There were still instances, even after the 60-second trip segment screen that resulted in records being observed on overpasses instead of the actual expressways. As mentioned earlier, a minimum of a one mile freeway segment was established as the benchmark. Shorter trips were not considered because the distance between most entry and exit points in the expressway network were usually longer than one mile. The longer duration of travel observed on the overpasses was the result of delay experienced by fleet vehicles for signalized intersections on top of the freeway. The entire data reduction process to partition out segments with less than 60 seconds of good data and travel distances of less than one mile resulted in 90.4% of all expressway records being retained.

To calculate distance, the speed values were averaged over the duration of data collected per trip. The duration of time represented in the analysis, the vehicle-days observed, total trip segments observed, and the average numbers of trip segments per vehicle-day by fleet are all shown in Table 3. A total of 354 vehicle-days were observed across all fleets in the analysis. The school bus fleet compromised most of the trip segment freeway data with 507 segments observed for 102 vehicle-days. However, the supermarket fleet was observed for a longer total duration with 3 fleet vehicles at 38.67 hours of recorded data compared to the nine school buses with 32.06 hours of data. The median average freeway trip segments conducted per vehicle-day was 6 trip segments.

Table 3 Duration of Analysis Dataset and Trip Segments by Fleet

Fleet	Duration of Analysis Dataset (hr)	Vehicle-Days	Total Freeway Trip Segments	Average Segments per Vehicle-Day
School Bus Transportation	32.06	102	507	5
GRTA Express Transit	38.59	21	158	8
Gwinnett County Express Transit	24.76	11	86	8
Electric Power Distribution	14.78	33	93	3
Ready-Mix Concrete Manufacturing	15.10	37	218	6
Local Transit Service Vehicles	9.52	45	139	3
Exterminating and Pest Control	2.60	17	30	2
Department of Transportation	11.04	24	87	4
Supermarket and Grocery Stores	38.67	28	214	8
Other General Merchandise Store	11.17	15	56	4
Fruit and Vegetable Wholesalers	15.94	16	88	6
Motor Vehicle Towing	3.43	5	35	7

3.6 Summary of the Methodology

In summary, this chapter presented a methodology whereby prospective fleets were recruited, monitored on a second-by-second basis, and assessed by creating a dataset that represented trip segments on an expressway network. Recruitment of fleets was constrained by the fact that companies were not compensated for their participation and that no direct benefit for their business would result from involvement. The freight data collector made installation simple by only requiring that a vehicle be stationary for five minutes to place the monitoring assembly either in front or behind the passenger seat. A dataset of observed trip segments was derived by taking the second-by-second records and partitioning out erroneous recorded speeds and travel conducted on overpasses. This dataset was then used to calculate the delay rate per trip segment and to assess the distribution of travel time unreliability.

CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Dataset Characteristics

Roughly 80% of all travel across the 12 monitored fleets occurred during a weekday, within typical daylight hours. Table 4 shows the number of freeway trip segments collected on weekdays, by time period, for each fleet. Five fleets did not have any observed travel on the weekend. The time periods for analysis were selected to match the travel demand model for the Atlanta Regional Commission [35]; where the morning period was from 6 – 10 AM, midday period was from 10 AM – 3 PM, afternoon period was from 3 PM – 7 PM, and the night period was from 7 PM until 6 AM the next day. The travel during the entire day was dispersed throughout all four time periods, with some variation.

Table 4 Number of Segments on Weekdays by Time Period

Fleet	Weekday Segments (% of total)	Weekday Time Period (% of weekday total)			
		AM	Midday	PM	Night
School Bus Transportation	503 (99.2%)	168 (33.4%)	196 (39.0%)	129 (25.6%)	10 (2.0%)
GRTA Express Transit	158 (100%)	41 (25.9%)	3 (1.9%)	79 (50.0%)	35 (22.2%)
Gwinnett County Express Transit	86 (100%)	28 (32.6%)	12 (13.9%)	40 (46.5%)	6 (7.0%)
Electric Power Distribution	93 (100%)	41 (44.1%)	6 (6.5%)	44 (47.3%)	2 (2.1%)
Ready-Mix Concrete Manufacturing	189 (86.7%)	43 (22.8%)	70 (37.0%)	23 (12.2%)	53 (28.0%)
Local Transit Service Vehicles	124 (89.2%)	22 (17.7%)	21 (16.9%)	26 (21.0%)	55 (44.4%)
Exterminating and Pest Control	28 (93.3%)	9 (32.1%)	9 (32.1%)	8 (28.6%)	2 (7.2%)
Department of Transportation	87 (100%)	28 (32.3%)	23 (26.4%)	31 (35.6%)	5 (5.7%)
Supermarket and Grocery Stores	147 (68.7%)	30 (20.4%)	51 (34.7%)	27 (18.4%)	39 (26.5%)
Other General Merchandise Store	51 (91.1%)	4 (7.8%)	17 (33.3%)	19 (37.3%)	11 (21.6%)
Fruit and Vegetable Wholesalers	88 (100%)	43 (48.9%)	33 (37.5%)	7 (8.0%)	5 (5.7%)
Motor Vehicle Towing	29 (82.9%)	0	27 (93.1%)	2 (6.9%)	0

Within the regional expressway network, most of the travel across all the fleets converged on the I-75/I-85 Connector, adjacent to the central business district for the City of Atlanta. Figure 6 shows the distribution of the second-by-second location data. The one-mile segment with the greatest amount of data (300 minutes of observation) was the northbound section of the I-75/I-85 Connector that ends a half mile before the interchange with I-20. Other routes with significant sample size include: I-85 from the north split with I-75 to the junction with I-985; I-575 from Canton, GA to I-75; I-75 from I-575 to the northern arc of I-285; I-20 from the western interchange with I-285 to the East Lake neighborhood of Atlanta; and the northern arc of I-285 from I-20 to US Route 78. These number of segments represented approximately 65% of the analysis dataset, in number of trips, although they only accounted for roughly 30% of the observed mileage on the regional expressway network. That is, fleets tended to utilize select corridors within the network and made numerous short trips on those corridors.

A quantitative method to extrapolate geography from the trip dataset was to separate the expressway network into 27 different corridors, based on facility designation and relative location to other significant highways. Expressway segment location variables were created by matching the trip segment midpoint to the intersecting highway segment. The midpoint was defined as the median in a consecutive time series for a trip segment (e.g. record #60 out of a total of 120). Although more than one segment could be traveled in a trip, the midpoint was used as a simple approximate measure of the trip geography.

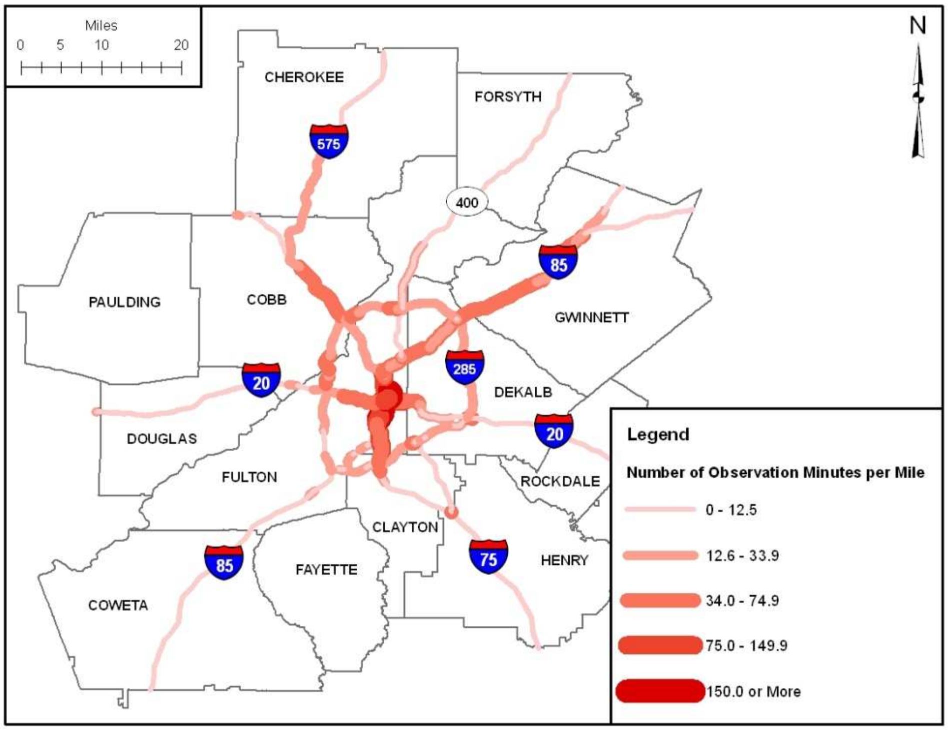

Figure 6 Duration of Data Collected by Expressway Facility

A spatial join within ArcGIS was used to create the variable as a one-to-many link between each observed record and the nearest mile-long highway segment. Table 5 describes the distribution of trip segment midpoints within the highway network. The distribution was not uniform, possibly due to the geographic locations of maintenance centers for each fleet. Those highway segments with a higher representation were apt to be influenced by having more trips originating at maintenance centers closer to those segments.

Table 5 Distribution of Trip Segment Midpoint Locations

Signed Expressway	Exit Number Range	Number of Segments	Percent of Total Segments
I-75/I-85 (Connector)	Exit 77 to 87 on I-85	489	28.6
GA 400	Exit 4 and Under	4	0.2
	Exit 4 to Exit 12	31	1.8
	Exit 12 and Above	15	0.9
I-20	Exit 51 and Under	14	0.8
	Exit 51 to 57	149	8.7
	Exit 57 to 67	204	11.9
	Exit 67 and Above	18	1.1
I-285	Exit 10 and Under	29	1.7
	Exit 10 to 20	44	2.6
	Exit 20 to 27	33	1.9
	Exit 27 to 33	23	1.3
	Exit 33 to 46	54	3.2
	Exit 46 to 58	40	2.3
	Exit 58 and Above	44	2.6
I-575	Entire Facility	44	2.6
I-675	Entire Facility	2	0.1
I-75	Exit 238 and Under	22	1.3
	Exit 238 to 242	49	2.9
	Exit 251 to 259	32	1.9
	Exit 259 and Above	77	4.5
I-85	Exit 68 and Under	36	2.1
	Exit 70 to 77	33	1.9
	Exit 87 to 94	35	2.0
	Exit 94 to 109	136	7.9
	Exit 109 and Above	38	2.2
I-985	Entire Facility	16	0.9
Total	**1711**	**100.0**	

Trip segment distance was calculated by taking the product of second-by-second speed data and the count of records, which represented time duration, within a single designated trip. The distribution of trip distances closely resembled a gamma distribution, with a median distance of 4.2 miles and a maximum freeway segment length of 52.6 miles. As noted earlier, trips representing less than 1 mile of travel on the freeway were excluded from the analysis dataset. Grouping distance by fleet per trip segment yields a maximum median value of 9.1 miles for the GRTA fleet and a minimum median value of 1.6 miles for the Gwinnett County Transit fleet. Figure 7 shows the distribution of all trip segment lengths.

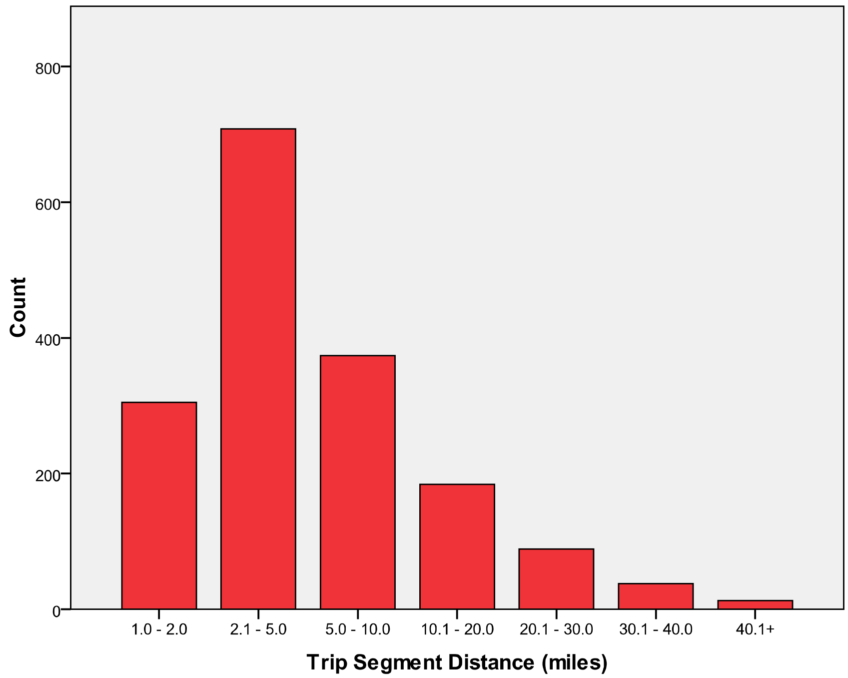

Figure 7 Distribution of Trip Segment Distance

Average travel speed for each of the trips varied considerably, with a higher probability density near the median of 57.1 mph and a long tail of lower occurrences extending toward slower speeds. Figure 8 illustrates this distribution. The maximum average segment speed is 75.5 mph and the minimum freeway average speed experienced was 5.4 mph, which was a short trip on the expressway. The median free-flow speed for uncongested travel (N= 952 trips) was 59.7 mph. Segmenting by fleet, the free-flow median speed varied from a minimum of 56.7 mph for the Concrete Truck Fleet and to a maximum of 67.1 mph for the Gwinnett County Transit Fleet.

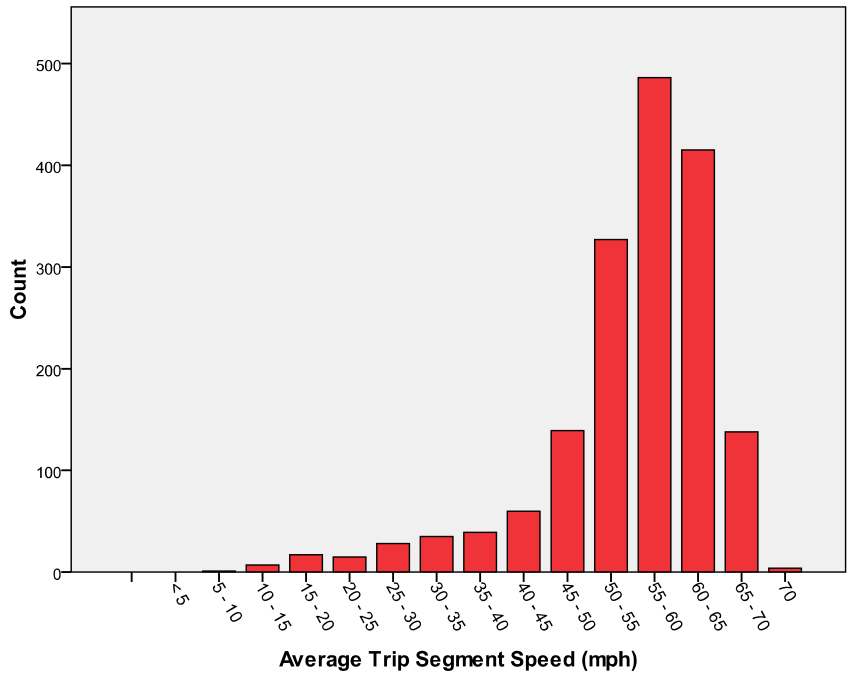

Figure 8 Distribution of Average Trip Segment Speed

The amount of time spent traveling at congested speeds varied by fleet and time period, from a range of 6.8% to 28.2% within each fleet of all time on the expressway system. A low value of 6.8% of the time spent in congestion from the motor vehicle towing fleet (but this was for a single vehicle). However, the supermarket fleet was close with 7.0% of time in congestion with three monitored vehicles. The GRTA transit fleet was shown to have a high percentage of travel time in congestion at 55.6% for midday operation, but this was influenced by the fact that express buses do not frequently operate during midday hours. All four buses were observed to be at the garage from 10 AM – 3 PM, except for three instances where travel was recorded on the expressway network just before the 3 PM threshold between the midday and PM weekday time periods (where the early onset of congestion was experienced prior to the natural peak period). Each trip segment was labeled by time period according to when the first observation of a segment occurred. In the case of the GRTA Express Bus fleet, the earliest movement for all three trip segments was recorded at 2:54 PM and the latest endpoint was at 3:27 PM. The total duration of expressway travel for the three segments was 7.9 minutes during midday hours and 34.8 minutes during the afternoon period. Under a different time period classification algorithm, one that used the midpoint instead of the record at the start, two of the three GRTA segments would have been indicated as PM trip segments instead of midday segments.

Separating the data by weekday time period, fleet vehicles typically spent a greater share of their time in congestion during the AM and PM time periods, and significantly less during nighttime hours. Any wide deviations in this pattern were influenced by the lack of a significant sample size for that fleet during specific weekday time periods. Table 6 shows the deviation in percentages of total time spent traveling below 45 mph by fleet and time period.

Table 6 Percentage of Cumulative Freeway Time Traveling below 45 MPH

Fleet	All Time Periods	Weekday Time Period			
		AM	Midday	PM	Night
School Bus Transportation	20.4%	16.4%	14.0%	34.0%	5.4%
GRTA Express Transit	19.1%	23.8%	55.6%	27.2%	1.3%
Gwinnett County Express Transit	7.6%	4.6%	10.9%	9.4%	3.8%
Electric Power Distribution	15.9%	3.8%	31.7%	25.1%	1.4%
Ready-Mix Concrete Manufacturing	14.8%	26.4%	18.6%	24.1%	3.7%
Local Transit Service Vehicles	9.1%	13.1%	13.3%	8.8%	7.6%
Exterminating and Pest Control	28.2%	46.8%	12.2%	24.7%	1.9%
Department of Transportation	24.2%	11.4%	6.6%	53.2%	2.4%
Supermarket and Grocery Stores	7.0%	16.5%	3.0%	23.9%	1.2%
Other General Merchandise Store	17.8%	60.5%	7.5%	24.8%	12.9%
Fruit and Vegetable Wholesalers	13.9%	15.8%	3.4%	55.2%	1.1%
Motor Vehicle Towing	6.8%	N/A	7.1%	0.0%	N/A

4.2 Calculating Delay

Delay was calculated by considering all of the speeds for a given trip segment and defining congestion as the occurrence of any travel below 45 mph. The value of 45 mph was selected because it was observed on I-85 in Atlanta to be the typical speed for which maximum throughput of vehicles can be achieved [12]. Each of the 783,592 records representing an observed speed for one second on the expressway was first analyzed to see whether it was above or below the 45 mph threshold. If the observed speed was above 45 mph, it was determined to be uncongested. However, if the GPS speed was below 45 mph, then the same speed value was recorded in a new category labeled, "congested speed." For instance, a speed of 38 mph in a record was 38 mph in the "congested speed" column, while a speed of 47 mph was 0 for the record in the same column. The congested speeds were then summed for each of the 1,711 designated trip segments and then divided by the number of records, or seconds, where a speed below 45 mph was observed. The resulting value was the average travel speed for only the duration of travel observed below 45 mph. The distance covered in one second at a speed lower than 45 mph can be traversed at less than one second at 45 mph. For each second of data, the differences in travel time for that small distance is summed to obtain congestion loss. Lost travel speeds were then converted from seconds to minutes. In summary, the equations used for the delay experienced per trip segment can be expressed as follows:

$$Sum\ of\ Congested\ Speeds = CS = \sum_{\substack{i=1 \\ v<45}}^{n} v_i$$

$$Lost\ Time\ (\text{min}) = \frac{n_{v<45}}{2700}\left[45 - \frac{CS}{n_{v<45}}\right]$$

Where:

$$v = \ Recorded\ Speed\ for\ One\ Second$$

$$n_{v<45} = \ Number\ of\ Records\ of\ Speed\ Below\ 45\ mph$$

The resulting distribution of delay for trip segments across all fleets had a high occurrence of variables with a low delay rate and a much lower frequency of instances where a high delay rate was observed. Table 7 extrapolates this distribution.

Table 7 Distribution of the Delay Rate, Lost Minutes per Mile Traveled

Delay Rate (min/mile)	Frequency	Percent	Cumulative Percent
None	398	23.3	23.3
Less than 0.05	924	54.0	77.3
0.06 to 0.10	110	6.4	83.7
0.11 to 0.20	80	4.7	88.4
0.21 to 0.50	92	5.4	93.7
0.51 to 1.00	60	3.5	97.3
1.01 to 2.00	28	1.6	98.9
2.01 to 3.00	14	0.8	99.7
More than 3.01	5	0.3	100.0

4.3 Testing Significance and Correlation Across Variables

Statistical tests were done to determine whether the delay rate was a function of the independent variables for expressway corridor traveled, time period, day of week, and fleet. Analytical results indicate that all of the variables had an influence upon the delay rate, with exceptionally strong correlations for the expressway corridor, day of week, and fleet variables. The known variables were tested for dependence using the Kendall tau rank correlation coefficients. Kendall tau was chosen as a test statistic because it relied on a non-parametric procedure that does not require any distribution for analysis. Day of week only considered weekdays from Monday through Friday since the differences between weekday and weekends were already discovered. Table 8 shows the results of this test.

Table 8 Correlation Test for Delay Rate on Weekday Trip Segments

Variable	Kendall Tau Correlation Coefficient	Two-Tailed Significance
Expressway Corridor	0.131	0.000
Time Period	0.037	0.043
Day of Week	0.068	0.000
Fleet	0.117	0.000

The strongest correlation was found between the expressway corridor and fleet variables, with a correlation coefficient of 0.229 that was likely influenced by having certain highway segments nearby the servicing stations for each fleet, typically the origin location for all trips (i.e. vehicles use the same routes per week and these routes experience recurrent congestion on most days).

The time period variable was selected as the segmenting criteria in further analyses because it was the dependent variable that allowed for a maximum sample size between the four time periods. Day of week required five values to distinguish each weekday. Fleet was selected because it denoted a specific industry type, which would allow an analysis on labor market rates, grouped by corresponding job title. Expressway corridor was not chosen for this analysis because the regional highway network was not adequately represented uniformly across the various facilities. Therefore, any further expressions of the delay rate and associated marginal cost values were not segmented by geography, but rather, fleet and time period. Future studies would focus on specific corridors with larger datasets.

4.4 Extra Time Needed per Fleet Vehicle

The reliability measure selected to capture the distribution of travel time delays expected to influence vehicle fleet decisions was based in part on the buffer index as recently described in NCHRP Report 618 [36]. The buffer index is calculated by taking the difference between the 95th percentile travel time and the average time and then dividing it by the average time, yielding an extra time buffer for which users may need to plan ahead. The intent was to gauge as a percentage how much additional time must be added per trip segment to reach a destination on-time with an expectation of greater certainty. In the analysis conducted in this section of the thesis, a similar approach was applied to assess the delay rate as time lost per mile for an entire trip segment based on an assumption that any travel speed below 45 mph was due to congestion.

The 95^{th} percentile delay rate was determined for each fleet and time period (AM, Midday, PM, and Night for weekdays and a separate category for weekends). Not all fleets and time periods had a statistically significant sample size to derive the 95^{th} percentile, so lesser values of the 90^{th} or 75^{th} percentiles were used instead. Previous research has validated the use of lower percentiles in generating unreliability statistics when confronted with limited data [24, 37]. Table 9 shows the 95^{th} percentiles by fleet and time period, and notes where the lesser percentiles were found. The exterminating and general merchandise store fleets did not have any statistically significant sample sizes to produce 95th percentile values. Generally, neither the midday, night, nor weekend time periods had enough trip segments across most fleets to derive 95th percentile values.

Table 9 95th Percentile Delay Rate by Time Period

Fleet	95th Percentile Delay Rate, min/mile (Maximum Value)				
	Weekday AM	Weekday Midday	Weekday PM	Weekday Night	Weekend
School Bus Transportation	0.54 (1.28)	0.42 (1.76)	0.86 (3.31)	*0.02 (0.04)	#0.02 (0.11)
GRTA Express Transit	1.94 (2.15)	#0.01 (2.87)	1.32 (2.99)	0.07 (0.13)	-
Gwinnett County Express Transit	0.09 (0.11)	*0.16 (0.39)	0.20 (0.21)	#0.00 (0.12)	-
Electric Power Distribution	0.04 (0.05)	#0.18 (0.20)	0.67 (1.24)	#0.01 (0.01)	-
Ready-Mix Concrete Manufacturing	0.96 (3.65)	0.35 (1.59)	1.82 (2.09)	0.54 (0.89)	0.60 (0.78)
Local Transit Service Vehicles	0.39 (0.40)	0.65 (0.67)	0.16 (0.17)	0.29 (1.15)	*0.01 (0.03)
Exterminating and Pest Control	#0.94 (1.92)	#0.02 (0.74)	#0.27 (0.31)	#0.03 (0.05)	#0.00 (0.01)
Department of Transportation	0.62 (0.65)	0.89 (1.07)	2.86 (3.14)	#0.01 (0.02)	-
Supermarket and Grocery Stores	0.61 (0.80)	0.03 (0.08)	1.57 (2.38)	0.02 (0.02)	0.03 (0.16)
Other General Merchandise Store	#0.80 (1.20)	*0.30 (0.53)	*2.99 (9.75)	*0.05 (0.34)	#0.00
Fruit and Vegetable Wholesalers	1.65 (3.06)	0.22 (0.23)	#0.26 (1.64)	#0.00 (0.05)	-
Motor Vehicle Towing	-	0.63 (1.01)	0.00	-	#0.04 (0.11)

* 90th percentile used.
# 75th percentile used.

Median delay rates by fleet and time period were determined across all fleets, with the values as shown in Table 10. The 50th percentile delay rates across all the observed fleets ranged from smaller values of less than 0.10 minutes per mile to higher rates of 0.42 minutes per mile for the department of transportation fleet during midday operation and 0.51 minutes per mile for the general merchandise fleet during morning operation. The general merchandise fleet did not have a large sample size for the time period with the high delay rate, where the department of transportation fleet did. A high common occurrence of delay for the department of transportation fleet for midday travel was influenced by taking numerous trip segments on a single corridor where the location commonly experienced congestion during the midday hours.

Table 10 50th Percentile Delay Rate by Time Period

Fleet	50th Percentile Delay Rate (min/mile)				
	Weekday AM	Weekday Midday	Weekday PM	Weekday Night	Weekend
School Bus Transportation	0.01	0.02	0.03	0.01	0.02
GRTA Express Transit	0.02	0.01	0.02	0.00	-
Gwinnett County Express Transit	0.00	0.00	0.00	0.00	-
Electric Power Distribution	0.00	0.07	0.02	0.01	-
Ready-Mix Concrete Manufacturing	0.05	0.02	0.00	0.00	0.01
Local Transit Service Vehicles	0.01	0.01	0.01	0.00	0.00
Exterminating and Pest Control	0.09	0.00	0.09	0.03	0.00
Department of Transportation	0.00	0.00	0.42	0.00	-
Supermarket and Grocery Stores	0.01	0.00	0.00	0.00	0.00
Other General Merchandise Store	0.51	0.00	0.01	0.00	0.00
Fruit and Vegetable Wholesalers	0.00	0.00	0.00	0.00	-
Motor Vehicle Towing	-	0.00	0.00	-	0.00

Expecting normal delay is not a condition of unreliability. If a driver characterizes travel delay by what is commonly experienced during the day, the 50th percentile is a reasonable expectation, but the median does not take into consideration the occurrences of high delay that would alter a schedule based upon on-time arrival certainty, such as 95% of the time. To assess unreliability, the difference between the common expectation and the unexpected experience were measured – which was the 50th and 95th percentiles, respectively (except in cases where the 95th percentile could not be calculated and either the 90th or 75th percentiles were used). Table 11 shows the differences between the 50th and 95th percentile delay rates.

Table 11 Difference Between 95th and 50th Percentile Delay Rates

Fleet	Difference Between 95th and 50th Percentile Delay Rates (min/mile)				
	Weekday AM	Weekday Midday	Weekday PM	Weekday Night	Weekend
School Bus Transportation	0.53	0.40	0.83	0.01	0.00
GRTA Express Transit	1.92	0.00	1.30	0.07	-
Gwinnett County Express Transit	0.09	0.16	0.20	0.00	-
Electric Power Distribution	0.04	0.11	0.65	0.00	-
Ready-Mix Concrete Manufacturing	0.91	0.33	1.82	0.54	0.59
Local Transit Service Vehicles	0.38	0.64	0.15	0.29	0.01
Exterminating and Pest Control	0.85	0.02	0.18	0.00	0.00
Department of Transportation	0.62	0.89	2.44	0.01	-
Supermarket and Grocery Stores	0.60	0.03	1.57	0.02	0.03
Other General Merchandise Store	0.29	0.30	2.98	0.05	0.00
Fruit and Vegetable Wholesalers	1.65	0.22	0.26	0.00	-
Motor Vehicle Towing	-	0.63	0.00	-	0.04

Relating delay rate percentile differences to a more applied measure of vehicle-minutes lost per day per fleet vehicle by time period required knowing both the distance traveled across all trip segments observed within the time periods (sum of distances) and the number of days where any expressway travel activity was observed during the same periods (time periods represented). To arrive at an average value of vehicle-minutes lost per day per fleet vehicle in operation, the difference between the 95th and 50th percentiles were weighted by the sum of all of the distances during only days and time periods with observed traveled. The averages within time periods are shown in Table 12. The value of delay is essentially the amount of extra time needed per fleet vehicle within a daily time period to maintain a schedule with on-time reliability at a 95% confidence level. For instance, the fruit and vegetable wholesaler, based on what was observed, needed to pad almost 50 minutes of extra time on average per fleet vehicle within the delivery schedule during weekdays from the hours of 7 to 10 AM to ensure on-time reliability in the delivery of goods. At 95% of the time, the median values of daily vehicle-minutes of delay per fleet vehicle observed across all 12 fleets were 6.5 minutes of extra time needed for AM weekday operation, 3.1 minutes for midday weekday operation, 9.4 minutes for weekday PM operation, and 0.1 minutes for nighttime weekday and weekend operation. The highest amount of additional time needed for the general merchandise store fleet and the GRTA Express Transit fleet during afternoon operations at about 97 and 61 minutes of extra time, respectively. However, a high value for the general merchandise fleet may have been influenced by a small sample.

Table 12 Average Daily Vehicle-Minutes of Extra Time Needed per Fleet Vehicle in Observed Operation

Fleet	Average Daily Vehicle-Minutes of Delay per Fleet Vehicle				
	Weekday AM	Weekday Midday	Weekday PM	Weekday Night	Weekend
School Bus Transportation	3.40	2.74	4.19	0.04	0.00
GRTA Express Transit	54.55	0.00	60.96	2.88	-
Gwinnett County Express Transit	6.45	2.41	16.21	0.00	-
Electric Power Distribution	0.65	0.77	10.27	0.00	-
Ready-Mix Concrete Manufacturing	6.86	3.51	8.58	13.37	6.96
Local Transit Service Vehicles	3.96	4.82	1.07	2.21	0.08
Exterminating and Pest Control	4.11	0.10	0.92	0.05	0.00
Department of Transportation	9.92	10.20	23.57	0.07	-
Supermarket and Grocery Stores	21.59	1.27	42.33	0.57	0.89
Other General Merchandise Store	5.30	5.81	97.06	1.40	0.00
Fruit and Vegetable Wholesalers	49.56	8.29	3.84	0.00	-
Motor Vehicle Towing	-	36.24	0.00	-	1.21

Periods of non-activity for fleet vehicles should be considered when assessing longer periods of analysis (e.g. weekly, monthly, annually) that estimate longitudinally how much additional time must be present to account for unexpected delay. Not all fleet vehicles traveled every day or during all observation periods, so utilization factors were considered that reduced the average daily vehicle-minutes of extra time needed per fleet vehicle (as determined in Table 12) in a conversion to weekly vehicle-minutes of delay per fleet vehicle that accounted for periods of non-activity. The periods of non-activity may have included instances where the fleet vehicle was scheduled for servicing or occasions where drivers did not use the local expressway system. Non-activity was measured by counting the number of days and time periods with recorded expressway activity per vehicle and dividing that by the total number of days and time periods between the first and last timestamps seen in the dataset for all vehicles in a fleet. A fleet vehicle that was only noticed to have used the expressway system from Monday through Thursday and had no recordings for Friday, but had observed travel the next week would have a utilization factor of 0.80 for weekdays during the first week. The utilization factors were calculated by dividing the periods of expressway activity by all periods in the observation timeframe for the AM, midday, PM, and nighttime weekday periods, and across an entire weekday and a day on the weekend. Table 13 shows the average utilization factor per fleet vehicle by time period for each individual fleet.

Table 13 Average Freeway Utilization Factor per Fleet Vehicle, by Time Period

Fleet	Probability of Travel					
	Weekday AM	Weekday Midday	Weekday PM	Weekday Night	Weekday Util.	Weekend Util.
School Bus Transportation	0.84	0.90	0.82	0.07	1.00	0.04
GRTA Express Transit	0.71	0.14	0.95	0.86	1.00	0.00
Gwinnett County Express Transit	0.73	0.73	0.91	0.55	1.00	0.00
Electric Power Distribution	0.76	0.18	0.76	0.03	1.00	0.00
Ready-Mix Concrete Manufacturing	0.59	0.66	0.38	0.28	0.71	0.47
Local Transit Service Vehicles	0.24	0.26	0.29	0.79	0.82	0.31
Exterminating and Pest Control	0.50	0.38	0.50	0.13	0.68	0.13
Department of Transportation	0.63	0.50	0.58	0.21	0.86	0.00
Supermarket and Grocery Stores	0.44	0.72	0.56	0.89	0.85	1.00
Other General Merchandise Store	0.13	0.73	0.55	0.36	0.74	0.89
Fruit and Vegetable Wholesalers	0.75	0.63	0.25	0.25	1.00	0.00
Motor Vehicle Towing	0.00	0.75	0.50	0.00	0.67	0.50

Estimates of extra time needed per vehicle to maintain a schedule of on-time reliability in the delivery of goods and services were derived by taking the daily vehicle-minutes of extra time needed by time period (from Table 12), multiplying that by the corresponding freeway utilization factor (from Table 13), and summing the results to represent a typical day and week. After each daily vehicle-minute of extra time was factored, the results from each weekday time period (AM, midday, PM, and night) were added together and the sum was then multiplied by the weekday utilization factor to arrive at a representative vehicle-minute extra time value for a single weekday. A representative delay rate of a single day of the weekend was calculated by multiplying the daily vehicle-minutes of extra time needed within the weekend category by the corresponding weekend freeway utilization factor. The typical buffers for all vehicles in a fleet (whether operating or not) are shown by weekday and day of the weekend in Table 14.

Table 14 Average Weekly Time Needed per Weekday and Weekend Day

Fleet	Extra Time Needed per Weekday (min)	Extra Time Needed per Weekend Day (min)
School Bus Transportation	8.8	0.0
GRTA Express Transit	99.5	0.0
Gwinnett County Express Transit	21.2	0.0
Electric Power Distribution	8.4	0.0
Ready-Mix Concrete Manufacturing	9.5	6.5
Local Transit Service Vehicles	3.5	0.1
Exterminating and Pest Control	1.5	0.0
Department of Transportation	21.5	0.0
Supermarket and Grocery Stores	29.4	1.8
Other General Merchandise Store	43.3	0.0
Fruit and Vegetable Wholesalers	43.3	0.0
Motor Vehicle Towing	18.1	1.2

The weekly estimates were determined by factoring the representative value for weekday time needed by 5 (one for Monday through Friday), factoring the representative day of the weekend by 2 (one each for Saturday and Sunday), and summing both values together. Table 15 shows the extra time needed per fleet vehicle to maintain on-time reliability for each fleet. The average weekly time needed per fleet vehicle varied considerably by fleet, with the highest value being 8.29 hours of added time each week per vehicle for the GRTA Express Transit fleet and the lowest being 0.12 hours of added time each week per vehicle for the exterminator. The buffer estimates seem sensible as extra buses operate primarily in congested peak conditions and exterminators use the major arterial network and avoid freeway travel. The extra time needed assumes that most fleet operations have built-in time buffers into their schedules to account for unreliable behavior. Expressway travel conditions do not affect the normal operations schedule for the exterminator, with the duration of expressway travel only consisting of

1.2% of the duration for all movement within the transportation system. The median buffer across all fleets was 1.65 hours of added time per fleet vehicle per week.

Table 15 Average Weekly Time Needed per Fleet Vehicle

Fleet	Extra Time Needed per Week (hr)
School Bus Transportation	0.73
GRTA Express Transit	8.29
Gwinnett County Express Transit	1.77
Electric Power Distribution	0.70
Ready-Mix Concrete Manufacturing	0.90
Local Transit Service Vehicles	0.29
Exterminating and Pest Control	0.12
Department of Transportation	1.79
Supermarket and Grocery Stores	2.48
Other General Merchandise Store	3.61
Fruit and Vegetable Wholesalers	3.61
Motor Vehicle Towing	1.53

4.5 Percent of Fleet Activity Time Lost

Using the information on the extra time needed per fleet vehicle, assumptions can be made regarding the percent of fleet activity lost due to unreliability to satisfy on-time performance. The percent of fleet activity lost was determined by dividing the extra time needed per fleet vehicle by the average weekly operation time per vehicle observed moving anywhere in the transportation system (including local, arterial, and expressway roads). Table 17 shows the percent of fleet activity lost due to travel time unreliability by each fleet.

Table 16 Operational Statistics and Percent of Fleet Activity Lost to Unreliability per Fleet Vehicle

Fleet	Extra Time Needed per Week (hr)	Avg. Weekly Operation Time on All Roads (hr)	Percent of Fleet Activity Time Lost to Unreliability
School Bus Transportation	0.73	18.8	3.9%
GRTA Express Transit	8.29	20.4	40.6%
Gwinnett County Express Transit	1.77	29.3	6.0%
Electric Power Distribution	0.70	25.6	2.7%
Ready-Mix Concrete Manufacturing	0.90	14.2	6.3%
Local Transit Service Vehicles	0.29	57.5	0.5%
Exterminating and Pest Control	0.12	23.3	0.5%
Department of Transportation	1.79	18.1	9.9%
Supermarket and Grocery Stores	2.48	49.7	5.0%
Other General Merchandise Store	3.61	13.8	26.2%
Fruit and Vegetable Wholesalers	3.61	29.8	12.1%
Motor Vehicle Towing	1.53	8.8	17.4%

The percent of activity lost varies considerably by fleet, with the highest percentage lost to unreliability being the GRTA Express Transit fleet with 40.6% of all travel time lost due to the scheduling of additional time caused by unreliable travel schedules on the expressway network. The exterminator and local transit service vehicles had significantly lower percentages lost because the proportion of overall trip segments on freeways was significantly less in comparison to all travel conducted. A median percent of 6.2% for all travel activity caused by unreliability in the system was found across all 12 fleets.

4.6 Considering Labor Costs

Taking the assumption that the value of time for commercial operations is at 100% of the employment cost, the associated labor wage rates were considered in calculating the marginal cost of congestion due to delay and unreliability. Each fleet was matched with a comparable profession as listed in the Georgia Department of Labor database and linked with the median hourly wage rate for 2009 in the Atlanta Metropolitan Statistical Area (MSA) [38]. The values of time are shown in Table 17. To consider the full employment costs of contributing to benefits such as paid leave, retirement, insurance, and workers' compensation factors from the U.S. Department of Labor were added to the median wage rates. The direct wages and salaries composed 72.3% of the total employment cost for private firm employees in the Southeastern U.S. Region [39] and 65.6% for public employees nationwide [40]. The only fleet observed that consisted of employees in the public sector (not including public transit) was from the Department of Transportation fleet. Factors accounting for worker benefits were added to create the hourly full employment cost, as shown in Table 18. All of these fleets were observed to have only one employee operating the vehicle.

Table 17 Comparable Professions and Median Wage Rates for Fleet Vehicle Drivers

Fleet	Comparable Profession	2009 Median Hourly Wage
Electric Power Distribution	Electricians	$19.75
Ready-Mix Concrete Manufacturing	Truck Driver, Heavy	$19.46
Exterminating and Pest Control	Pest Control Worker	$16.20
Department of Transportation	Civil Engineer	$33.60
Supermarket and Grocery Stores	Truck Driver, Heavy	$19.46
Other General Merchandise Store	Truck Driver, Light or Delivery Service	$14.50
Fruit and Vegetable Wholesalers	Truck Driver, Light or Delivery Service	$14.50
Motor Vehicle Towing	Truck Driver, Light or Delivery Service	$14.50

Table 18 Hourly Employment Cost for Non-Transit Fleets

Fleet	Percentage of Wages within the Full Employment Cost	Hourly Employment Cost
Electric Power Distribution	72.3%	$27.32
Ready-Mix Concrete Manufacturing	72.3%	$26.92
Exterminating and Pest Control	72.3%	$22.41
Department of Transportation	65.6%	$51.22
Supermarket and Grocery Stores	72.3%	$26.92
Other General Merchandise Store	72.3%	$20.06
Fruit and Vegetable Wholesalers	72.3%	$20.06
Motor Vehicle Towing	72.3%	$20.06

The value of time for public transit fleets was derived from information contained in the National Transit Database as maintained by the Federal Transit Administration [41]. The latest figures for the operating expense per vehicle revenue hour statistic were taken from the 2008 annual reports for the local transit service, GRTA Express Bus, and Gwinnett County Transit fleets. The operating expense per vehicle revenue hour value includes not only driver wages, but also considers other operating expenses needed to conduct the service. The hourly operating expense for the school bus fleet was given in the range of $80-$90 per hour, with $85 selected as the median for the analysis [42]. Hourly expense values for the public transportation fleets can be seen in Table 19.

Table 19 Hourly Operation Costs for Transit-Based Fleets

Fleet	Hourly Operating Expense
School Bus Transportation	$85.00
GRTA Express Transit	$138.38
Gwinnett County Express Transit	$94.25
Local Transit Service Vehicles	$88.50

A 95^{th} percentile delay rate was used to represent the marginal burden experienced by individual fleet vehicles as compared to a free-flowing condition where all trips made within a system is completed on-time. The difference between the 95^{th}

percentile burden and a continuously non-congested freeway is the marginal burden imposed on each driver, which can also be expressed as a marginal cost of congestion. Using the value of time, the marginal travel cost per fleet vehicle was estimated by setting corresponding toll values equal to those costs. The equivalent toll estimates were calculated by taking the 95th percentile delay rate and factoring it by the hourly employment cost or hourly operating expense, depending upon whether it was a transit or non-transit fleet. Specifically, the values contained in Table 9 were multiplied by Table 18 or Table 19. The equivalent toll rates are shown in Tables 20, 21, and 22 next to the average daily distances traveled per fleet vehicle by time period. Average daily distances were derived by taking the sum of all distances traveled by all vehicles within a fleet and time period and dividing it by the number of time periods with observed freeway activity for each fleet vehicle activity period.

Table 20 Average Operating Weekday Mileage and Equivalent Toll Rates by Time Period, AM and PM Time Periods

Fleet	AM Weekday		PM Weekday	
	Avg. Daily Distance (mi)	Equivalent Toll ($/mi)	Avg. Daily Distance (mi)	Equivalent Toll ($/mi)
School Bus Transportation	6.4	$0.77	5.0	$1.22
GRTA Express Transit	28.4	$4.47	46.9	$3.04
Gwinnett County Express Transit	71.7	$0.14	81.1	$0.31
Electric Power Distribution	16.1	$0.02	15.8	$0.31
Ready-Mix Concrete Manufacturing	7.5	$0.43	4.7	$0.82
Local Transit Service Vehicles	10.4	$0.58	7.2	$0.24
Exterminating and Pest Control	4.8	$0.43	5.1	$0.12
Department of Transportation	16.0	$0.53	9.7	$2.44
Supermarket and Grocery Stores	36.0	$0.27	27.0	$0.70
Other General Merchandise Store	18.3	$0.27	32.6	$1.00
Fruit and Vegetable Wholesalers	30.0	$0.55	14.8	$0.09
Motor Vehicle Towing	-	-	2.0	$0.00

Table 21 Average Operating Weekday Mileage and Equivalent Toll Rates by Time Period, Midday and Night Time Periods

Fleet	Midday Weekday		Night Weekday	
	Avg. Daily Distance (mi)	Equivalent Toll ($/mi)	Avg. Daily Distance (mi)	Equivalent Toll ($/mi)
School Bus Transportation	6.8	$0.60	3.5	$0.03
GRTA Express Transit	7.8	$0.02	41.2	$0.16
Gwinnett County Express Transit	15.0	$0.25	9.1	$0.00
Electric Power Distribution	7.0	$0.08	5.1	$0.00
Ready-Mix Concrete Manufacturing	10.6	$0.16	24.8	$0.24
Local Transit Service Vehicles	7.5	$0.96	7.6	$0.43
Exterminating and Pest Control	5.0	$0.01	5.1	$0.01
Department of Transportation	11.5	$0.76	6.7	$0.01
Supermarket and Grocery Stores	42.4	$0.01	28.6	$0.01
Other General Merchandise Store	19.4	$0.10	28.0	$0.02
Fruit and Vegetable Wholesalers	37.7	$0.07	23.9	$0.00
Motor Vehicle Towing	57.5	$0.21	-	-

Table 22 Average Daily Operating Weekend Mileage and Equivalent Toll Rates by Time Period

Fleet	Daily Weekend	
	Avg. Daily Distance (mi)	Equivalent Toll ($/mi)
School Bus Transportation	7.9	$0.03
GRTA Express Transit	-	-
Gwinnett County Express Transit	-	-
Electric Power Distribution	-	-
Ready-Mix Concrete Manufacturing	11.8	$0.27
Local Transit Service Vehicles	8.3	$0.01
Exterminating and Pest Control	3.3	$0.00
Department of Transportation	-	-
Supermarket and Grocery Stores	29.6	$0.01
Other General Merchandise Store	25.3	$0.00
Fruit and Vegetable Wholesalers	-	-
Motor Vehicle Towing	30.2	$0.01

The median equivalent toll rates across all fleets was $0.43 per mile for weekday mornings, $0.13 for midday weekdays, $0.53 per mile for afternoon weekdays and $0.01 per mile for weekday nights and weekends. Similar values were found when applying a value of time of $27 per hour (the median hourly cost for the 12 fleets) to an FHWA in Northern Virginia. The observed delay on I-495 was used to assess toll rates in the range of $0.78 to $0.21 per mile traveled during peak morning and afternoon times [43]. All fleets varied considerably in equivalent toll rates due to differences in employment and operating expense costs and variances in delay rates. The variances are also subject to fleets utilizing different corridors within the system during the time periods.

A weekly summary of the marginal cost of congestion was given in Table 23 by factoring the extra time needed per week to account for travel time unreliability by the hourly value of time. The cost due to unreliability was essentially the cost of having to schedule additional time for each fleet vehicle to ensure on-time delivery of goods and services.

Table 23 Weekly Costs due to Unreliability per Fleet Vehicle

Fleet	Extra Time Needed per Week (hr)	Hourly Cost ($)	Weekly Cost due to Unreliability
School Bus Transportation	0.73	$85.00	$62.05
GRTA Express Transit	8.29	$138.38	$1,147.17
Gwinnett County Express Transit	1.77	$94.25	$166.82
Electric Power Distribution	0.70	$27.32	$19.12
Ready-Mix Concrete Manufacturing	0.90	$26.92	$24.23
Local Transit Service Vehicles	0.29	$88.50	$25.67
Exterminating and Pest Control	0.12	$27.32	$3.28
Department of Transportation	1.79	$51.22	$91.68
Supermarket and Grocery Stores	2.48	$26.92	$66.76
Other General Merchandise Store	3.61	$20.06	$72.42
Fruit and Vegetable Wholesalers	3.61	$20.06	$72.42
Motor Vehicle Towing	1.53	$20.06	$30.69

The fleet with the highest weekly cost due to unreliability was the GRTA Express Transit fleet with a cost of $1,147.17 per week and the lowest was for the exterminator at a cost of $3.28 per week. The Gwinnett County Express Transit fleet had the second highest cost per vehicle at $166.82 per week, yet had a lower equivalent toll rate for morning travel at $0.14 per mile traveled in Table 20. The reason for the apparent disparity in cost values can be explained by looking at the corresponding average daily distances in Table 20. An average of daily distance of 71.1 miles for morning travel was observed to be comparatively ahead of the fleet with the next highest average daily distance for the same time period, the supermarket fleet at a value of 36.0 miles per weekday morning time period. The weekly cost due to unreliable travel times was calculated using the values of extra time needed per week, which was influenced by taking the differences between expected and unexpected delay rates across longer travel distances. Distance was correlated with the duration of time spent on the freeway system, and any increase in duration causes the summed cost of travel to also increase.

4.7 Summary of Data Analysis and Results

The section on data analysis and results took the trip segments created in the previous chapter and analyzed specific delay rate values toward assessing the marginal cost of congestion. A basic profile of how many trip segments were recorded by fleet, where the freeway trips were conducted, and the proportion of time spent in congestion characterized the dataset. A rate of delay, expressed as a unit of lost minutes per mile traveled, was derived by taking the difference in speeds observed during congestion from an optimal free-flowing speed of 45 mph and dividing that by the distance traveled per segment.

The variation between expected and unexpected delay was used as the measure for travel unreliability by selecting the difference between the 50^{th} and 95^{th} percentile delay rates within all segments observed for each time period by fleet. Daily average values of extra time needed per fleet vehicle to ensure on-time arrivals were calculated by weighting the unreliable travel buffer rates (differences between the percentiles) by distances traveled. To account for days and periods not traveled by fleet vehicles, freeway utilization factors were used to consider periods of non-activity for a longitudinal estimate of average weekly time needed per vehicle to maintain a reliable travel schedule. The GRTA Express Bus fleet had the highest weekly buffer at 8.29 hours per vehicle, which was expected due to buses operating during peak conditions on long portions of the expressway. A weekly extra time value of 0.12 hours per vehicle was found for the exterminator, who tended to avoid the expressway and primarily traveled on arterials. The median buffer across all fleets was 1.65 hours of added time per vehicle.

The percent of fleet activity lost was derived by dividing the average duration of time witnessed moving anywhere in the transportation network (expressways, arterials, and local roads included) by the amount of extra time needed per fleet vehicle to account for unreliability. Weekly marginal costs per fleet vehicle were estimated by factoring in the corresponding fleet driver wages or hourly operation costs (for transit fleets). Using the same hourly cost assumptions, equivalent toll rates were calculated by multiplying the 95^{th} percentile delay rate by the hourly costs. The optimum toll per mile traveled was representative of an equal relationship between the marginal costs of congestion experienced and a hypothetical state of free-flow travel. The median optimum toll rates across all fleets was $0.43 per mile for weekday mornings, $0.13 for midday weekdays, $0.53 per mile for afternoon weekdays and $0.01 per mile for weekday nights and weekends. An interpretation of an FHWA study in Northern Virginia assessed that with a value of time of $27 per hour, observed freeway delay can be equivalent from $0.21 to $0.78 per mile traveled during morning and afternoon peak times [43].

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Implications for Tolled Lane Concepts

The HOT Lane concept, as proposed for the I-85 corridor in Atlanta, Georgia, would permit passenger vehicles and buses to drive in the lanes, with vehicles carrying two or less persons paying a toll. However, commercial goods movement and other heavy-duty vehicles would not be allowed to use these lanes. Theoretically, the toll would change in periods of higher volume as a disincentive in having a lower share of travelers choose the HOT Lane. The operating goal is to maintain a minimum travel speed for the facility by seeking to limit users below a certain threshold. However, recent observations for the Miami Express Lanes have shown that drivers are not as sensitive to price changes during the day as previously thought and some actually view the charges as a metric for congestion, with choice behavior being influenced toward the toll lanes when the price was high [44]. This suggests that demand modeling for managed lane facilities involves complex human decision making in an environment of uncertainty.

In a scenario where a HOT Lane Network would be implemented on most of the expressway system in metropolitan Atlanta, only 8 of the 12 fleets examined in this thesis would be permitted to use the lanes due to restrictions in vehicle class. Another managed lane concept, the Truck-Only-Toll (TOT) Lane, would restrict facility usage to only those vehicles of higher classes (such as heavy trucks) and not permit passenger cars in the lanes. Implementing a TOT Lane network was indicated to be conceptually feasible and preferable for moving heavy-class vehicles around the Atlanta region [45]. Yet, a study commissioned by GDOT recommended against constructing TOT Lanes, concluding that only users of the TOT Lanes would directly benefit – despite the fact that benefits derived from its construction may outweigh the costs. GDOT also estimated that speeds for all other travelers in the general purpose lanes would only increase by 10 mph during peak congested periods [46]. However, it was found that travel speeds increased by 16 mph on I-95 in Miami [47], 3 mph on I-394 in Minnesota [48], and 9 mph on SR 167 in Seattle [49] for peak times within the general purpose lanes during the transition of HOV-to-HOT lanes. Both the HOT and TOT concepts provide relative benefits in speed for non-tolled users, given the currently known information from studies in existence. When faced with a decision to choose between either the HOT or TOT scenario for implementing a managed lane network, GDOT ultimately chose HOT lanes because of the staggering capital costs associated with constructing facilities for trucks [10].

A total of 8 fleets within the 12 observed on a second-by-second basis consisted of passenger vehicles and buses that are permitted to use the HOT Lane. The others were composed of heavy-class vehicles and trucks that cannot use HOT Lanes, but are permitted to use managed lanes under a TOT concept. Table 24 displays the fleets that can use either the HOT or TOT Lanes. It can be assumed that under a region-wide HOT Network, the fleets that can utilize the toll could directly benefit and that heavier-class fleets might have smaller improvements in travel times due to incremental increases in general purpose lane speed. All the vehicles, except for the transit fleets, would pay a toll if choosing to use the facility under both concepts since it was observed that only one driver was operating a vehicle within each fleet.

Table 24 Fleets Permitted to Use Either HOT or TOT Lanes

Fleet	Permitted to Use HOT Lane	Permitted to Use TOT Lane
School Bus Transportation	X	
GRTA Express Transit	X	
Gwinnett County Express Transit	X	
Electric Power Distribution	X	
Ready-Mix Concrete Manufacturing		X
Local Transit Service Vehicles	X	
Exterminating and Pest Control	X	
Department of Transportation	X	
Supermarket and Grocery Stores		X
Other General Merchandise Store		X
Fruit and Vegetable Wholesalers		X
Motor Vehicle Towing	X	

Transit fleets have been shown to benefit under an HOV-to-HOT Lane conversion, at least in travel times. A case for the I-95 Express Lane Project in Miami showed that travel times decreased in the corridor from 25 to 8 minutes, resulting in a 30% increase in ridership for the 95 Express Bus service. The Miami-Dade Transit agency was able to reduce the scheduled northbound travel times from 32 to 22 minutes and keep the same on-time reliability at about 76%, with roughly 13% arriving at least 5 minutes early when pricing was introduced and congestion on the lane declined. However, overall ridership across all transit routes decreased by 3.8% during the conversion to an average of 16,126 riders per weekday compared to the 2,353 average weekday users of the express service. A study concluded the ridership changes between the express service and the other routes were not likely to be related and attributed fare increases and general economic conditions as the reason behind the downward trend [50].

5.2 Study Limitations

The limitations of this research approach and methodology used in developing the data and analyses for this thesis included:

- Due to budget limitations, commercial fleets were not inclined to participate in the study due to concerns about having to allocate part of the workday to non-business purposes.
- The sample size was relatively small for analysis. Second-by-second speed data were only collected for a two-week period on a limited number of vehicles per fleet.
- Preferably, it would be best to collect data during a longer observation period to truly capture longitudinal differences in delay and unreliability between select weekdays and months. Hence, equivalent tolls on a facility can differ significantly. However, there could have been repercussions by losing potential fleets due to requiring more involvement.
- The analysis considered travel speeds on a system-wide basis. However, delay does not occur uniformly across the entire expressway network, but rather affects specific corridors and changes by time of day, day of week, season, fleet, and individual driver preferences. A larger analysis sample could have segmented the dataset by geography and considered statistics within each group.
- Delay rate characteristics were determined by using the average statistics of speed across trip segments of varying lengths. The 1,711 trip records were gamma

distributed with a median distance of about 4 miles, a minimum of 1 mile, and a long tail that reached to a maximum of 52 miles.

- The value of time estimates derived from the employment cost statistics do not explain the full cost of congestion on fleets. If a business needs to have additional vehicles to maintain services under increasing travel delays, then managers might have to include extra procurement and servicing expenses to their budgets. Penalties may also be assessed for late arrivals. For instance, a concrete mixing truck may have its shipment cancelled by a construction inspector because the time between leaving the batch plant and arriving at the field site was too great. The owner of the mixing truck fleet would bear the supplemental costs of losing the concrete materials, in addition to labor and fuel beyond loss incurred by delay. Comparatively, an Atlanta-based TOT Lane Network feasibility study steering committee in 2005 suggested $35 per hour ($38.45 in $2010 dollars) as the value of time for heavy truck drivers [31], as opposed to approximately $27 per hour for the same driver type used in this thesis. Additional costs, like the vehicle procurement and penalty expenditures are much harder to measure and quantify, but could be included in future analyses.

5.3 Conclusion

This thesis constituted an initial effort to measure the costs of congestion by analyzing commercial, public service, and transit vehicle fleets on a second-by-second basis throughout the expressway network in Atlanta, Georgia. The methodology utilized a passive GPS monitoring assembly that archived speed, position (x and y coordinates), time, and date characteristics. Algorithms processed and cleaned the dataset for quality by excluding records shorter than 1 mile, with less than 1 minute of information, or contained large numbers of erroneous speed values (e.g. instances where speed went from 60 to 0 mph in one second for two consecutive records and could not be corrected by fitting a cubic spline across good data points). This process retained roughly 90% of all the records contained within the expressway buffer. Trip segments were labeled by identifying gaps in recorded time as trip ends and linking consecutive records together. There were 1,711 trip segments across the 12 fleets observed.

Delay statistics were created for each trip segment by taking the amount of time lost by traveling at speeds less than 45 mph – the proposed optimum speed for the new HOT Lane on I-85 in Northeast Atlanta. Values of delay differed by fleet vehicle, time of day, day of week, and expressway corridor. To maximize the potential for higher samples, the trip segments were segmented by fleet and time period (AM, Midday, PM, Night). The difference between the 95th and the 50th percentile delay rates was defined as the time buffer necessary per mile traveled on the expressway to make on-time arrivals. The highest buffer rates were 2.98 minutes per mile traveled for the general merchandise store fleet and 2.44 minutes per mile for a department of transportation fleet. Both of the high buffer rates occurred during the weekday afternoon peak period. Considering instances of non-activity during the observational period, average weekly reliability buffer were estimated across all 12 fleets, with the highest being 8.29 hours per week of added time per bus for the GRTA fleet. The buffers were determined under the assumption that fleets currently in operation already take delay and unreliability into account for scheduling purposes.

An additional measure was contemplated by simply taking the hourly employment cost (or hourly operation cost for transit-based fleets) of comparable professions and factoring the weekly reliability buffers to arrive at average weekly per vehicle costs. The highest non-transit weekly cost due to unreliability was approximately $92 per vehicle in the department of transportation fleet. Equivalent toll rates were calculated by expressing the 95th percentile delay rate across all distances traveled on the expressway network. The median toll rates for the 12 fleets was $0.43 per mile for weekday mornings, $0.13 for midday weekdays, $0.53 per mile for afternoon weekdays and $0.01 per mile for weekday nights and weekends.

Conceptualizing the true costs of congestion on commercial, public service, and transit fleets is a difficult exercise that necessitates an understanding of logistics, spatial economics, and labor markets. This thesis provided a first attempt at quantifying expenses due to travel time delay and unreliability by utilizing passive GPS technology to monitor vehicle fleets on a second-by-second basis while traveling on the expressway network. Much additional work is required in this field in order to truly understand the problems affecting the transportation system and how to move forward with programs that mitigate these issues in the future.

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