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VARIABILITY OF TRAVEL TIMES ON NEW JERSEY HIGHWAYS

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Submitted by

Principal Investigator
Steven I. Chien, Ph.D., Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology

NJDOT Bureau of Research Project Manager
Robert Sasor

In Cooperation with

New Jersey
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and
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16. Abstract

This report presents the results of a link and path travel time study conducted on selected New Jersey (NJ) highways to produce estimates of the corresponding variability of travel time (VTT) by departure time of the day and days of the week. The travel time data were collected through the use of an In-vehicle navigation device equipped with a Global Positioning System (GPS)-receiver. The main outcomes of the study are: 1) The majority of the NJ routes studied follow a shifted log-normal path travel time distribution, 2) For each route the buffer index was estimated utilizing the 95th percentile travel time, which provides a comparative measure on the predictability of the corresponding arrival time to a motorist's destination, 3) The impact of incidents on path travel time could not be estimated due to rather limited data, 4) The use of GPS-based link/path travel time data collection could produce the corresponding distributions and buffer index in a systematic way thereby assisting real-time traffic operations (e.g. signal timing) traveler information (e.g. real-time route planning), and transportation short term and long term planning (e.g. infrastructure and traffic management strategies). It is recommended that the methodology developed in this study to produce link- and path-based travel time distributions and associated Buffer Indices be included in the set of performance measures to aid planners, traffic operators and engineers of the New Jersey Department of Transportation (NJDOT) in making highway improvements and implementing traffic management strategies to reduce recurring delays and improve reliability of New Jersey highways.

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EXECUTIVE SUMMARY

A study for estimating travel time variability was conducted for NJDOT on the segments of the following highways: Routes US 1, NJ 3, NJ 4, US 9, NJ 17, US 22, NJ 24, NJ 42, US 46, NJ 70, NJ 73, NJ 29, I-76, I-78, I-80, NJ 208, I-280, and I-287. The travel time data were collected from 6:15 A.M. to 8:15 A.M. on weekdays between October 8, 2007 and April 21, 2008. The travel time on each route was collected through the use of Co-Pilot™ Global Positioning System (GPS)-based in-vehicle navigation devices. The collected data were stored and formatted in a database developed and maintained by the research team with NJIT.

A computer software was programmed with MATLAB to convert the collected Co-Pilot™ GPS data into link- and path-based travel times. The node locations of the link boundaries were defined by NJDOT. The indicators of travel time reliability were then analyzed using Microsoft Excel 2003.

The Measures Of Effectiveness (MOEs) generated for this study are: 1) Link/path travel time distribution per time interval of the day, 2) Link/path speed distribution per time interval of the day; 3) the 95th link/path individual travel time percentile – based on all data per time interval of the day; 4) Buffer Index for each route per MOE 3, respectively. The results were summarized in both table and graph formats.

The lowest and highest mean speeds of 28.3 and 59.9 mph were found on the segments of NJ 208 & NJ 4 and NJ 24 & I-78, respectively. Correspondingly, the route with the lowest and highest buffer indices (e.g. the 95th percentile travel time) of 10.9

and 73.8 % were observed on the segments of US 1 (from I-295 to US 130) and US 46 & NJ 3, respectively.

During the study period only a few incidents were reported at the segments of NJ 17, NJ 208 & NJ 4, NJ 24 & I-78, US 46 & NJ 3, and US 22. However, the reported incidents did not significantly impact the corresponding path travel time of the vehicle probes for the time periods they traveled on those routes. Given the rather small incident data set per route and departure time period it was difficult to produce statistically sound estimates of the incident impact on the travelers' path travel time.

The main findings of this study are:

- The highest mean travel speed (59.9 mph) for all records in the A.M. peak was observed on the segment of NJ 24 & I-78, while the lowest speed (28.3 mph) occurred on the segment of NJ 208 & NJ 4. For the mean speed of each departure time period, the highest speed (68.4 mph) was found at 6:30 A.M. on I-287 (Segment B). The lowest speed (23.5 mph) occurred at 7:30 A.M. on the segment of NJ 70.

- The highest travel time coefficient of variation of the mean (CV=0.4) for all records in A.M. peak was found on the segment of US 46 & NJ 3, while the lowest CV (=0.09) was observed on US 1 (Segment C). For the CV of each departure time period, the highest CV (=0.49) was observed at 7:00 A.M. on the segment of US 46 & NJ 3. The lowest CV (=0.03) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The highest range of travel time (43 minutes 45 seconds) in the A.M. peak was observed on a segment of US 46 & NJ 3, while the lowest range (e.g. 7 minutes 51 seconds) occurred on US 1 (Segment C). For the departure time periods, the highest range of travel time (42 minutes 57 seconds) occurred at 7:00 A.M. on the segment of US 46 & NJ 3, and the lowest range (1 minute 41 seconds) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The greatest buffer index of the 95th percentile travel time (73.8%) for records in the A.M. peak occurred on the segment of US 46 & NJ 3, while the smallest buffer index (10.9%) was observed on US 1 (Segment C). For each departure time period, the greatest buffer index (109.1%) occurred at 7:30 A.M. on the segment of US 46 & NJ 3, and the smallest buffer index (4.3%) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The majority of the path travel time distributions were shown – using normality and log-normality tests - to follow a shifted log-normal distribution for the morning period from 6:00 to 9:00 AM. Only the distribution on the segment of NJ 208 & NJ 4 out of the eight that were tested was shown to follow a Normal distribution. For each of these distributions the associated 95% Confidence Intervals were estimated. Due to limited data for each 15-minute time interval the corresponding path travel time distributions could not be estimated.

- The majority of studied highways had a relatively high travel time coefficient of variation to the mean (CV>0.2). This is an indication that the selected highways, all of which were selected due to high amounts of congestion, exhibit high variations in travel times. This indicates that travel times on the more congested highways in the state exhibit a high amount of travel time unreliability.

Future studies should concentrate on the following areas listed below.

1. The travel time variability study could be expanded and enhanced by conducting the following studies.

    - Conduct a widespread GPS-based study through the participation of a set of large corporations and public agencies (e.g. NJDOT, Dow Jones, pharmaceutical companies, UPS, Universities, others). Use GPS-enabled devices that also have wireless communication capability and a computer server such that you can view the vehicles in real time, record their data and produce real-time estimates of link and path travel times. This will reduce or eliminate the potential errors associated with manual observations. Obtain the corresponding traffic counts and speed from automated or manual detectors during October 2007 and May 2008 for the time period between 6:15 – 8:15 A.M. Obtain geometric and traffic flow data characteristics to conduct capacity analyses using real data.

    - The establishment of such a GPS-enabled traffic monitoring system will have the following benefits:

        (a) Continuous estimation of path-based (or called OD-based) travel time for different vehicle classes (cars, buses, trucks)

(b) Consistent calibration of transportation and traffic simulators such as transportation planning models, Dynamic Traffic Assignment (DTA) and microscopic traffic analysis.

(c) Elimination of traditional traffic monitoring systems such as inductive loop detectors or other similar devices, which will result in substantial cost savings for the State. Given that such GPS system will be met with public resistance, the State should provide strong assurances that all data to be stored will be anonymous and secure.

2. Enhance the TRANSMIT system to produce path-based travel time estimates per five and 15-minute time intervals. Currently the TRANSMIT system only provides 15-minute, link-based aggregate travel time data. In addition, utilize the TRANSMIT system to develop link/path travel time estimates under recurring and non-recurring traffic flow conditions. Furthermore, the TRANSMIT route data can be used to estimate the OD demand matrix. This task can be given priority due to the fact that the TRANSMIT system is operational and TRANSCOM and its member agencies look for ways to improve their system.

3. Implement a traffic simulator and/or DTA to the underlying network and use the collected GPS data to continuously calibrate the model together with up-to-date traffic counts. A DTA continuously calibrated model with real-traffic counts, roadway occupancy, and/or travel time data will be able to capture the impact of incidents at the network, sub-network, OD pair, path, link, and vehicle class level. Comparative analysis between recurring and non-recurring traffic conditions can

then be conducted in a systematic and consistent basis through the use of such a continuously calibrated model. A prototype can be developed for demonstration purposes at a NJDOT corridor that has an adequate traffic surveillance system such as the I-80 or the I-287 (I-287 is also covered by the TRANSMIT system that produces good travel time data).

4. Integrate the continuously calibrated DTA model to the NJDOT's Congestion Management System, the transportation planning model, the traffic operations' signal optimization and traffic flow analysis models, and the PLAN4SAFETY software developed by the Rutgers Traffic Safety Resource center. The integration of a calibrated DTA model with the PLAN4SAFETY software will produce consistent crash rates for all the links of the NJDOT transportation network by producing more accurate traffic link/movement flow rate estimates and speed profiles – especially for links where no actual traffic counts exist. Thus, the mean daily non-recurring delay for a road segment can be estimated by multiplying the daily vehicle miles traveled (VMT), found from the New Jersey Congestion Management System (NJCMS), by the mean time above the threshold time for the road segment. In driver trip making decisions, the variability of travel time might have a greater effect on travel decisions than the mean travel time. Note that the threshold discussed in this study can be used to approximate recurring and non-recurring delays. For example, delay that is below the threshold is recurring delay; otherwise, it is assumed to be non-recurring delay.

5. A measure such as the buffer index of the 95th percentile travel time divided by the mean travel time could be used in the NJCMS as a measure of reliability. Given the mean travel time, the measure would give the additional percent travel time to allow for not exceeding the given threshold of travel time 95% of the time.

INTRODUCTION

The Variability of Travel Time (VTT) in transportation systems has been a focal point of many transportation agencies because it relates to the performance and the quality of service provided by the systems. The VTT is a consequence of travel behavior (departure time, route choice, and driving characteristics), the road users (passenger cars, transit vehicles, and trucks), the transportation network topology and geometry, and traffic control. This report discusses the technologies for collecting travel time data, methodologies to process and analyze the collected data, the development of VTT measures as a component of mobility performance metrics, and the corresponding estimates on fifteen New Jersey highways.

In recent years, highway congestion in New Jersey and many urban areas in the United States has grown to critical dimension. Congestion has become a major problem and has many detrimental effects including lost time, higher fuel consumption, more vehicle emissions, increased accident risk, and greater transportation costs. The concept of congestion has been embraced by the media, the public, policy makers, and transportation professionals. However, there is no consistent definition of congestion in terms of a single measure or set of measures that considers severity, duration, and spatial extent. Quantification of congestion on individual facilities or for individual trips, measurement of the rate of congestion change in an area, and comparison of congestion severity, extent, duration, and variability between areas are very challenging tasks. Accurate estimates of congestion are needed for analytical purposes, such as system evaluation and improvement prioritization, and for use by policy makers and the public.

In addition to estimate travel time from an origin to a destination, there is a significant concern from road users who make a daily commute, which is the variability of their travel times. Travel time may increase because of delays resulting from recurring (e.g. peak hours volume) and non-recurring (e.g. incidents) traffic conditions. Frequent but stochastic, irregular delays make it difficult for people to plan their journey – e.g. when to depart from home, which mode(s) and route(s) to use so that they arrive at work on time. Recognition of this problem has led to the use of VTT as a parameter to estimate traffic congestion, measure non-recurring delay, and predict travel time.

A study for estimating travel time variability was conducted for NJDOT on the segments of the following highways: Routes US 1, NJ 4, US 9, NJ 17, US 22, NJ 24, NJ 29**,** NJ 42, US 46, NJ 70, NJ 73, I-76, I-78, I-80, I-280, and I-287. The travel time data were collected from 6:15 A.M. to 8:15 A.M on weekdays between October 8, 2007 and April 21, 2008. The travel time on each route was collected through the use of Co-Pilot™ Global Positioning System (GPS)-based in-vehicle navigation devices. The collected data were stored and formatted in a database developed and maintained by the research team with NJIT.

The research benefits of this study are:

- Implementation of GPS-based devices to collect travel time data.

- Estimation of the link- and path-based VTT on segments of fifteen NJ highways per 30-minute departure time interval in the morning peak on every weekday.
- Estimation of Buffer Indices for the studied fifteen New Jersey highways using the 95th percentile of individual probe vehicle travel times.
- Development of the time-space travel time profile per vehicle and per 30-minute time interval.
- Comparative analysis using the VTT and the Buffer Indices between various links and paths.
- Development of travel time thresholds for recurring and non-recurring traffic flow conditions.
- Development of a procedure to upload the collected data from the GPS-enabled devices into MATLAB and MS Excel, and fuse and analyze the data into table and graph formats.
- Training NJDOT volunteers and university students on the use of the GPS-enabled in-vehicle navigation systems for collecting travel time data.

OBJECTIVES AND WORK SCOPE

In order to identify New Jersey highways with high variability in day-to-day travel times to work, obtaining good traffic estimates with high accuracy of recurring and non-recurring delays is critical. It is challenging to design a data collection plan, recruit qualified data collectors, and collect travel time data containing enough samples to reflect time-varying travel time information suitable for transportation modeling and planning. The objectives of this study are:

1. To collect and measure travel times for repetitive day-to-day trips in the A.M. peak period on 15 congested New Jersey highways;
2. To study the VTTs on these highways and determine good estimates of travel time reliability; and
3. To identify roadways with high variability in day-to-day travel times.

In addition to demonstrating unbiased spatial and temporal variation of travel times, the development of a sampling determination methodology for enough data collection and MS-Excel based dynamic graphic user interface (e.g., speed and travel time profiles) is extremely valuable in helping NJDOT planners, engineers, and decision makers visualize the local and regional congestion impacts.

LITERATURE REVIEW

The primary purpose of the section was to identify and review travel time data collection technologies currently used in the transportation industry and to study current methods of analyzing travel time variability. The review results of the applicability of these technologies are discussed and organized into four subsections, including Travel Time under Recurring and Non-recurring Congestion, Technologies for Collecting Travel Time Data, Methods for Estimating Travel Times, and Travel Time Variability and Reliability, and summarized in Appendix A.

RESEARCH APPROACH

As shown in Figure 1, this section discusses the research approach started from conducting comprehensive literature review, followed by developing plans for collecting data, collecting and processing data, and estimation of the VTT and reliability indices (buffer indices) for the studied fifteen New Jersey highways.

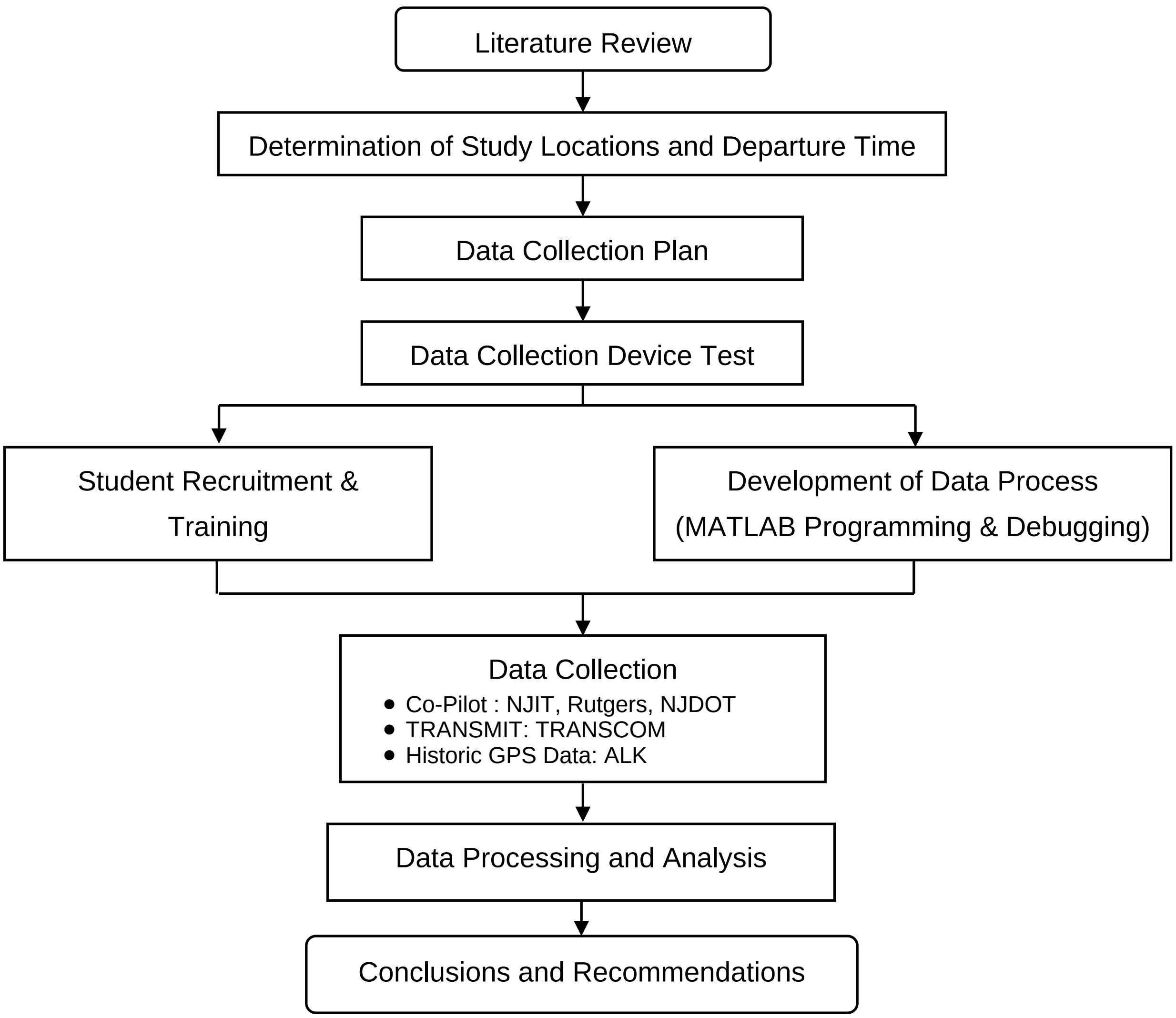


Figure 1. Configuration of Research Approach

Data Collection

The research team developed a travel time data collection plan that was reviewed and approved by NJDOT as listed below:

1. Identify the New Jersey highway segments for this study;
2. Develop a data collection plan;
3. Identify the number of drivers needed per route;
4. Recruit data collectors needed to collect sufficient data
5. Develop probe vehicle scheduling and routing plans. Purchase and test the Co-Pilot™ GPS-based data collection devices;
6. Train the recruited personnel on the use of the Co-pilot devices, and understanding the studied route and daily departure time;
7. Execute the data collection plan.

Identify the Study NJ Highway Segments

The member of NJDOT Research Panel assisted the research team to identify fifteen segments on congested NJ state highways, including the starting and ending points and the immediate nodes on each highway segment, the timing for travel time data collection (e.g., day of the week, number of weeks, and vehicle departure time, etc.). The average distance of the studied highway segments is approximately 20 miles. The scheduled vehicle departure times were 6:30, 7:00, 7:30 and 8:00 A.M. with 15-minute buffer zones before and after each designated departure time (e.g. vehicles departing between 6:45 A.M. and 7:15 A.M. were considered in the category period of 7:00 A.M).

These 15 highway segments were assigned to two universities, in which NJIT was handling 8 segments, while the Rutgers University was handling 7 segments. Notably, NJDOT volunteers were assigned to collected travel time on NJ 29. The locations of the studied highway segments are summarized in Figure 2. Additionally, ALK Technologies, Inc. provided historic travel time (also collected by Co-Pilot™) of 25 highway segments for 17 months (from February 2007 to August 2008). The historical travel time data collected by ALK Technologies, Inc. are summarized in Appendix E.

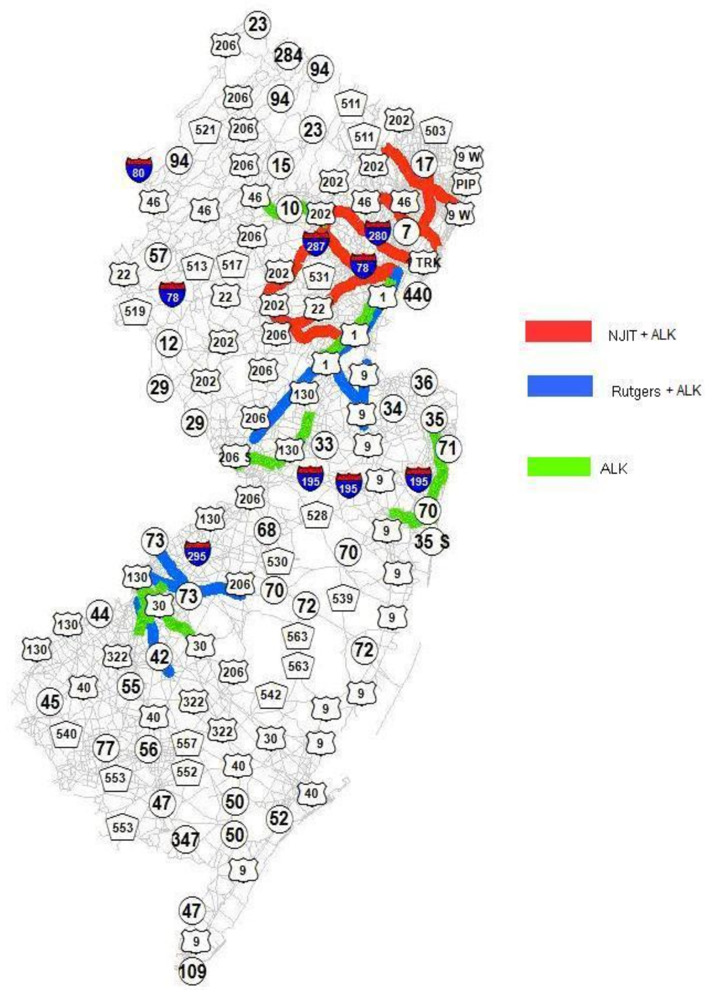


Figure 2. Studied New Jersey Highway Segments

Table 1 - Studied Highway Segments

Highway Segment	Start Point	End Point	Counties	Direction	ALK
(1) NJ 17	CR 502 (MP 18.2)	NJ 3 (MP 4.5)	Bergen County	SB	√
(2) NJ 208 NJ 4	I-287 (MP 9.3) NJ 208 (MP 2.2)	NJ 4 (MP 0.0) I-95 (MP 10.2)	Bergen County	EB	√
(3) I- 80 I-280	I-287 (MP 44.1) I-80 (MP 0.0)	I-280 (MP 46.3) CR 508 (MP 16.6)	Morris County Morris, Essex, Hudson	EB	√
(4) NJ 24 I-78	I-287 (MP 0.6) NJ 24 (MP 49.5)	I-78 (MP 10.4) NJ 21 (MP 57.0)	Morris, Essex, Union Union, Essex	EB	√
(5) US 46 NJ 3	NJ 23 (MP 56.7) US 46 (MP 0.0)	NJ 3 (MP 60.2) NJ 495 (MP 10.2)	Passaic, Bergen, Hudson County	EB	√
(6) US 22	CR 529 (MP 42.2)	US 1 (MP 60.1)	Somerset, Union, Essex	EB	√
(7) I-287 (A)	NJ Tpke (MP 0.0)	I-78 (MP 20.8)	Middlesex, Somerset,	NB	√
(8) I-287 (B)	I-78 (MP 20.8)	I-80 (MP 41.8)	Somerset, Morris	NB	√
(9) US 1 (C)	I-295 (MP 7.0)	US 130 (MP 24.4)	Mercer, Middlesex	NB	√
(10) US 1 (D)	NJ 18 (MP 27.3)	US 22 (MP 47.5)	Middlesex, Union, Essex	NB	√
(11) US 1 (E)	US 130 (MP 24.4)	I-295 (MP 7.0)	Mercer, Middlesex	SB	√
(12) US 9	GSP/ NJ 166 (MP 94.6)	Route 522 (MP 114.7)	Ocean, Monmouth	NB	√
(13) NJ 42 I-76	US 322 (MP 0.0) I-295 (MP 0.0)	I-76 MP (14.3) I-676 (MP 1.8)	Gloucester, Camden Camden	NB	√
(14) NJ 70	US 206 (MP 18.4)	NJ 38 (MP 0.0)	Camden, Burlington	WB	√
(15) NJ 73	US 70 (MP 24.3)	Vanderveer St. (MP 33.9)	Camden, Burlington	WB	√
(16) NJ 18	US 9 (MP 30.8)	NJ 27 (MP 42.1)	Middlesex	NB	√
(17) NJ 27	CR 693 (MP 15.7)	NJ 439 (MP 32.9)	Middlesex, Union	NB	√
(18) US 30	NJ 73 (MP 18.4)	I-676 (MP 0.9)	Camden	WB	√
(19) NJ 33	US 1 (MP 0.0)	US 130 (MP 7.8)	Mercer	EB	√
(20) US 130	NJ 33 (MP 62.6)	NJ 32 (MP 74.3)	Mercer, Middlesex	NB	√
(21) NJ 47	US 322 (MP 53.0)	NJ 41 (MP 68.3)	Gloucester	NB	√
(22) NJ 41	NJ 47 (MP 0.0)	NJ 70 (MP 10.8)	Gloucester, Camden	NB	√
(23) NJ 35	NJ 70 (MP 16.0)	CR 13, Red Bank (MP 34.2)	Monmouth	NB	√
(24) NJ 88	US 9 (MP 0.0)	NJ 35 (MP 10.0)	Ocean	EB	√
(25) NJ 168	NJ 42 (MP 0.0)	CR 603 (MP 10.7)	Camden	NB	√
(26) US 46[1]	Landing Rd. (MP 32.2)	NJ 10 (MP 33.3)	Morris		
(27) NJ 10[1]	US 46 (MP 0.0)	I-287 (MP 13.0)	Morris		
(28) NJ 29[2]	I-295 (MP 0.0)	US 1 (MP 3.37)	Mercer	WB	√

(A): I-95 to I-78, (B): I-78 to I-80, (C): I-195 to US 130, (D): NJ 18 to US 22, (E): US 130 to I-195

[1] No travel time data collected

[2] Travel time data collected by NJDOT

Co-Pilot™ GPS-enabled Travel Time Data Collection Devices

The ALK Technologies, Inc. developed a GPS-based in-vehicle navigation device called Co-Pilot™, which were applied to collect travel time data. The collected data were then converted into link travel times based on the corresponding NJDOT designation. Travel time data collected by Co-Pilot™ were formatted by three NMEA (National Marine Electronics Association) sentences, including GPRMC, GPGSA, and GPGSV. GPRMC consists of latitude, longitude, speed, bearing, satellite-derived time, fix status and magnetic variation, while GPGSA and GPGSV contain overall satellite reception data. As shown in Figure 3, a GPRMC sentence consists of twelve comma-delimited words that indicate time data in the coordinated universal time (UTC) format, signal reception status, longitude and latitude in the minute decimal format, speed in knot, direction, date, and checksum. The research team developed a procedure to transfer data from a Co-Pilot™ device to a personal computer.

```
$GPRMC,221030.000,A,4030.8971,N,07427.8349,W,20.07,83.87,021007,,,A*7B
$GPGSA,A,3,11,28,20,17,04,08,,,,,,,3.1,1.7,2.6*30
$GPRMC,221033.000,A,4030.8981,N,07427.8187,W,11.87,85.83,021007,,,A*7F
$GPGSA,A,3,11,28,20,17,04,08,,,,,,,3.1,1.7,2.6*30
$GPGSV,2,1,08,28,81,138,39,17,62,308,38,11,37,054,36,20,32,106,40*73
$GPRMC,221036.000,A,4030.8984,N,07427.8087,W,9.24,88.90,021007,,,A*41
$GPGSA,A,3,11,28,20,17,04,08,,,,,,,3.1,1.7,2.6*30
$GPRMC,221039.000,A,4030.8988,N,07427.7932,W,18.63,87.71,021007,,,A*79
$GPGSA,A,3,11,28,20,17,04,08,,,,,,,3.0,1.7,2.6*31
$GPRMC,221042.000,A,4030.8997,N,07427.7687,W,25.08,85.11,021007,,,A*7D
$GPGSA,A,3,11,28,20,17,04,08,,,,,,,3.0,1.7,2.6*31
```

Figure 3. Co-Pilot™ Data Format

GPS-enabled Travel Time Data Collection

The daily study period was divided into four departure time periods as follows: 6:15-6:45, 6:45-7:15, 7:15-7:45 and 7:45-8:15 A.M. Each route was traversed for the five weekdays for a total of five weeks.

Data collectors recruitment and training were conducted to ensure the integrity of collected data. The drivers were instructed to travel using the vehicle floating driving technique and report any non-recurring events (e.g., incidents, accidents and work zone activities), weather and roadway conditions that could affect normal driving conditions. The travel time data collection schedule is summarized in Table 2.

Table 2 - Study Locations and Data Collection Timetable

Travel Segment		Time Period (dd/mm/yy-dd/mm/yy)		Research Team
(1)	NJ 17	10/08/07	11/09/07	NJIT
(2)	NJ 208 / NJ 4	10/08/07	11/09/07	NJIT
(3)	I- 80* / I-280	11/12/07	12/21/07	NJIT
(4)	NJ 24* / I-78	11/12/07	12/21/07	NJIT
(5)	US 46 / NJ 3	10/08/07	11/09/07	NJIT
(6)	US 22*	11/12/07	12/21/07	NJIT
(7)	I-287 (A)	1/28/08	2/29/08	NJIT
(8)	I-287 (B)	1/28/08	2/29/08	NJIT
(9)	US 1 (C)*	11/12/07	12/21/07	Rutgers
(10)	US 1 (D)	3/24/08	4/21/08	Rutgers
(11)	US 1 (E)*	11/12/07	12/21/07	Rutgers
(12)	US 9	1/28/08	2/29/08	Rutgers
(13)	NJ 42 / I-76	10/08/07	11/09/07	Rutgers
(14)	NJ 70	10/08/07	11/09/07	Rutgers
(15)	NJ 73	1/28/08	2/29/08	Rutgers
(16)	NJ 29	4/07/08	5/09/08	NJDOT

*: Data was not collected during Thanksgiving week (11/19/07-11/23/07)
(A): I-95 to I-78
(B): I-78 to I-80
(C): I-95M/295 to US 130
(D): NJ 18 to US 22
(E): US 130 to I-95M/295

Data Processing

The travel time data collected by Co-Pilot™ devices were in GPS data format (e.g. NMEA) in UTC (coordinated universal time). The UTC time was converted into local time (e.g., Eastern Time). Any unnecessary information was deleted (e.g., satellite reception, direction, and check sum, etc.). A computer program (see Appendix D) was then developed with MATLAB to process the data and produce the corresponding link- and path-based travel times.

The collected and processed data from highways located in New Jersey are summarized in Tables 3 and 4. For each of the 15 studied locations, 100 travel time data points were collected (e.g., 4 trips in the A.M. peak per day, 5 days a week for 5 weeks). All collected data was investigated for completeness of the route, occurrence of incidents, weather and roadway conditions.

Table 3 depicts the travel time data collected by NJIT for each study segment. The total number of travel time trips conducted is 97 - 73 records were considered complete and the remaining 24 records incomplete. The drivers reported only 2 trips that were conducted under incident conditions. In addition, the numbers of records collected under “good”, “rain”, “wet”, and “snow” are 83, 9, 5, and 0 records, respectively.

Table 3 - Data Collection Result (NJIT)

	Completed Route Trip			Incidents		Weather Conditions			
	Total	C	I	N	Y	1	2	3	4
NJ 17	97	73	24	95	2	83	9	5	0
NJ 208 & NJ-4	88	51	37	86	2	77	11	0	0
I-80 & I-280	88	67	21	88	0	72	8	4	0
NJ 24 & I-78	84	82	2	81	3	61	12	11	0
NJ 46 & NJ 3	77	74	3	76	1	74	2	1	0
US 22	88	76	12	83	5	66	7	14	1
I-287 (A)	94	94	0	94	0	69	9	10	6
I-287 (B)	94	94	0	94	0	74	6	4	10
NJ 29*	136	111	25	108	3	100	9	2	0

(A) I-95 to I-78 (B) I-78 to I-80 *: data collected by NJDOT

Processed Data: C=Complete Route, I=Incomplete Route
Incident: N=w/o incident, Y=w/ incident
Weather: 1 =good, 2 =rain, 3 =wet, 4 =snow

The data collected by the Rutgers University from 7 highway segments located in central and southern New Jersey are summarized in Table 4. As shown in Table 4, there were no incidents reported by the drivers during the period of the data collection.

Table 4 - Data Collection Result (the Rutgers University)

	Completed Route Trip			Incidents		Weather Conditions			
	Total	C	I	N	Y	1	2	3	4
US 1 (C)	79	74	5	79	0	53	26	0	0
US 1 (D)	60	8	52	60	0	60	0	0	0
US 1 (E)	84	51	33	84	0	48	29	0	0
US 9	86	79	7	86	0	74	8	0	4
NJ 42 & I-76	89	58	31	89	0	54	35	0	0
NJ 70	98	32	66	98	0	58	36	0	0
NJ 73	74	41	33	74	0	64	8	0	2

(C) US 130 to I-295 (D) NJ 18 to US22 (E) I-295 to US 130

Processed Data: C=Complete Route, I =Incomplete Route
Incident: N=w/o incident, Y=w/ incident
Weather: 1 =good, 2 =rain, 3 =wet, 4 =snow

DATA ANALYSIS

Co-Pilot™ GPS-based Travel Time Data Analysis

A statistical analysis is applied to examine the conformity of the collected travel time distribution to theoretical distributions (e.g., Normal and Log-Normal) as well as to analyze the travel time variability and reliability measures. The travel time distributions of the studied routes are estimated by statistically summing up the directly observed travel time from the four departure time intervals of the day (i.e., 6:15-6:45 A.M., 6:45-7:15 A.M., 7:15-7:45 A.M., and 7:45-8:15 A.M.).

Standard statistical measures such as mean, median and standard deviation are calculated and compared to normal distributions. Then, the travel time data is also compared against a log normal distribution to test if the data is meets the associated characteristics. Confidence intervals and buffer zones were developed to show for where the travel times fall outside only 5% of the time. The buffer zone shows how much additional time is needed beyond the mean travel time so that the upper limit of the buffer time is not exceeded 95% of the time. If there is a large difference between the mean and the 95% travel times, this indicates that the travel times lack reliability.

In order to estimate the travel time variability of the collected data from 15 New Jersey Highways, the following statistical measures were produced per link and path with 30-minute time interval using the raw GPS data.

- Sample Mean Path Travel Time ($\bar{X}$) per Departure Time Period

- Sample Log Mean Path Travel Time ($\bar{x}_{log}$) per Departure Time Period
- Variance and Corresponding Standard Deviation of Path Travel Time (σ) per Departure Time Period
- Log Variance and Corresponding Standard Deviation of Path Travel Time (σ_{log})
- Log 95% Confidence Interval ($\log \mathbf{x}_{95\%CI}$)
- Median of Path Travel Time
- Coefficient of Variation of the Mean (CV)
- the 95th Percentile Travel Time ($tp_{95\%}$)
- Range of Path Travel Time per Departure Time Period
- Percentage of Travel Time Data Less than the Mean
- Ratio of Mean to Median of Travel Time
- Buffer Index

The data collected by the GPS-enabled devices were used to produce estimates of the travel time distributions per 30-minute departure time interval of the day (i.e., 6:15-6:45 A.M., 6:45-7:15 A.M., 7:15-7:45 A.M., and 7:45-8:15 A.M.). As drivers either arrive at the departure location earlier or later, each route has different departure time period - at the link and path level. The boundaries of each link were defined by NJDOT in collaboration with the research team.

1. Sample Mean Path Travel Time ($\bar{x}$) per Departure Time Period for each route was estimated. The following equation is used to calculate mean path travel time for the analysis period

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

where x_i : travel time

N: number of travel time records

2. Sample Log Mean Path Travel Time ($\bar{x}_{log}$) per Departure Time Period for each route was also estimated to measure the mean of log value of path travel time. The following equation is used to compute log mean path travel time

$$\bar{x}_{log} = \frac{1}{N}\sum_{i=1}^{N} x_{log\ i} \tag{2}$$

3. The Median ($\hat{x}$) was used to measure of central tendency of the collected travel time distribution. Median is calculated using the following equation

$$\hat{x} = \begin{cases} x_{[(N+1)/2]} & n : \text{odd} \\ \dfrac{x_{(N/2)} + x_{[(N/2)+1]}}{2} & n : \text{even} \end{cases} \tag{3}$$

where $\hat{x}$: median of travel time

4. Variance and Corresponding Standard Deviation of Path Travel Time (σ) per departure time period was calculated to measure variability or dispersion of the collected travel time data. Standard Deviation is calculated using the following equation

$$\sigma = \sqrt{\frac{\left(\sum_{i=1}^{N} x_i - \bar{x}\right)^2}{N-1}} \tag{4}$$

where $\bar{x}$: mean travel time

5. Log Variance and Corresponding Standard Deviation of Path Travel Time (σ_{log}) per departure time period was also computed to measure log value of variability of the collected travel time using the following equation

$$\sigma_{log} = \sqrt{\frac{\left(\sum_{i=1}^{N} x_{log\,i} - \overline{x_{log}}\right)^2}{N-1}} \tag{5}$$

6. Lognormal Distribution 95% Confidence Interval ($\log \mathbf{x}_{95\%CI}$) was estimated using following equation

$$\bar{x}_{log} - z_{95\%}\sigma_{log} / \sqrt{n} \le \log x_{95\%CI} \le \bar{x}_{log} + z_{95\%}\sigma_{log} / \sqrt{n} \tag{6}$$

Where z is the standard normal distribution, n is a sample size of normal population with known variance (σ^2_{log}).

7. The variability and reliability of travel time are calculated by using the following measures:

- Coefficient of Variation of the Mean (CV): a measure of relative dispersion of a probability distribution. It is useful when comparing the variability of two or more data sets originating at 0 that differ considerably in the magnitude of the observations. It is defined as the ratio of the standard deviation σ to the mean $\bar{x}$:

$$CV = \frac{\sigma}{\bar{x}} \qquad (7)$$

- The 95th Percentile Travel Time ($tp_{95\%}$): a percentile is the value of a variable below which a certain percent of observations fall. For example, The 95th percentile travel time is the travel time below which 95% of the observed travel time may be found, which represents a threshold where the travel time does not exceed 95% of the observed travel time.

- Range of path travel time data: the range is the length of the smallest interval which contains all the data. It is calculated by subtracting the smallest travel time (t_{MIN}) from the greatest travel time (t_{MAX}) and provides an indication of statistical dispersion

$$Range = t_{MAX}-t_{MIN} \qquad (8)$$

- Percentage of the data less than mean

$$\text{Percentage}(<\text{mean}) = \frac{\text{number of data less than mean}}{\text{total number of data}} \times 100 \qquad (9)$$

- Ratio of Mean to Median of Travel Time (r)

$$r = \frac{\bar{x}}{\hat{x}} \qquad (10)$$

- Buffer Index: The buffer index is utilized by FHWA as the main measure of reliability. The buffer Index (the the 95th percentile travel time) is the distance of the 95th percentile from the mean expressed as percentage. The FHWA (2005) recommended that the 90th or 95th percentile travel time, buffer index, planning time index, and frequency should be used to quantify the *travel time reliability*. The 95th percentile travel time is the simplest measure of travel time reliability for specific travel routes or trips, which indicates how bad delay will be on the heaviest travel days. The corresponding buffer index represents the extra buffer time (or time cushion) that most travelers add to their mean travel time when planning trips to ensure on-time arrival. This extra time is added to account for any unexpected delay. The buffer index is expressed as a percentage and its value increases as reliability gets worse. For example, a buffer index of 40 percent means that, for a 20-minute mean travel time, a traveler should budget an additional 8 minutes (20 minutes × 40 percent = 8 minutes) to ensure on-time arrival most of the time. Thus, the 8 extra minutes is called the *buffer time*. The equation of the buffer index is as follow:

$$\text{Buffer Index} = \frac{tp_{95\%} - \bar{x}}{\bar{x}} \times 100\% \tag{11}$$

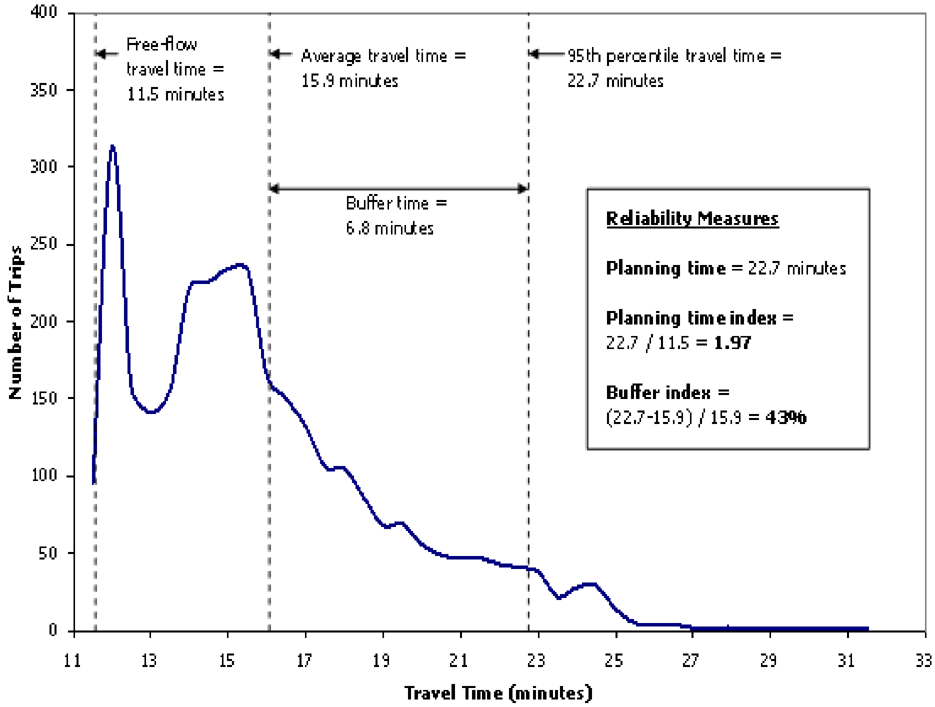
Figure 4 shows an example of calculating the mean travel time and the size of the buffer (i.e. the extra time needed by travelers to ensure a high rate of on-time arrival), which helps to illustrate a variety of reliability measures that describe reliability in slightly different ways:

- Planning travel time: The total travel time including buffer time (i.e., calculated as the 95th percentile travel time).

- Planning travel time index: The amount of the total travel time larger than the ideal or free-flow travel time (i.e., calculated as the ratio of the 95th percentile to the ideal).

- Buffer travel time: The extra time required (i.e., calculated as the difference between the 95th percentile travel time and the mean travel time).

- Buffer travel time index: The size of the buffer as a percentage of the mean (i.e., calculated as the 95th percentile minus the mean, divided by the mean).



Source: Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation (2005) available at http://ops.fhwa.dot.gov/congestion_report/.

Figure 4. Traffic Congestion and Reliability

Sample Analysis of the Path Travel Time Data of NJ 17

This section summarizes the analysis of measures produced from the travel time data collected on NJ 17 segment which begins at the interchange of NJ 17 and County Route 502 and ends at the interchange of NJ 17 and NJ 3.

- Length of Study Route Segment: 14.33 miles
- Study Dates: From October 8, 2007 to November 9, 2007
- Study Departure Time Period: 6:15 A.M. to 8:15 A.M.
- Sample Size: 73
- Sample Mean Path Travel Time ($\overline{X}$) for the entire time interval: 23 min 13 sec

- Sample Log Mean Path Travel Time ($\overline{X}_{log}$) for the entire time interval: 5.5
- Variance and Corresponding Standard Deviation of Path Travel Time (σ): 6 min 15 sec
- Log Variance and Corresponding Standard Deviation of Path Travel Time (σ_{log}):1.04
- Median of Path Travel Time: 20 min 47 sec
- Coefficient of Variation of the Mean (CV): 0.27
- The 95th Percentile Travel Time ($tp_{95\%}$): 32 min 54 sec
- Ratio of Mean to Median of Travel Time (r): 1.11
- Range of Path Travel Time per Departure Time Period: t_{max} = 47 min 29 sec, t_{min} = 16 min 46 sec
- Percentage of Path Travel Time Data Less Than the Mean: 61.6%
- Buffer Index: 32.8% - A NJ 17 traveler should budget an additional 7 minutes 36 seconds (23 minutes 13 seconds × 32.8 percent = 7 minutes 36 seconds) to ensure on-time arrival 95% of the time.

In order to identify the link- and path-based travel time distribution the following analysis was conducted:

1) The frequency of the route travel time for the entire departure time period from 6:15 to 8:15 A.M. is shown in Figure 5. The path travel time data were classified into four-minute time intervals, and the distribution is a shifted log-normal distribution. The Y- axis is intercepted at the free flow travel time then it is

followed by a bell shape and then it has a long tail of path travel time observations that reflect the delays experienced due to various traffic flow conditions such as increases in demand and incidents. In this study it was rather difficult to collect information on the occurrence of incidents other than construction that was visible to the drivers. Minor accidents that are not generally reported to the police could not be captured. Therefore any incident that was not observed by the drivers was not recorded.

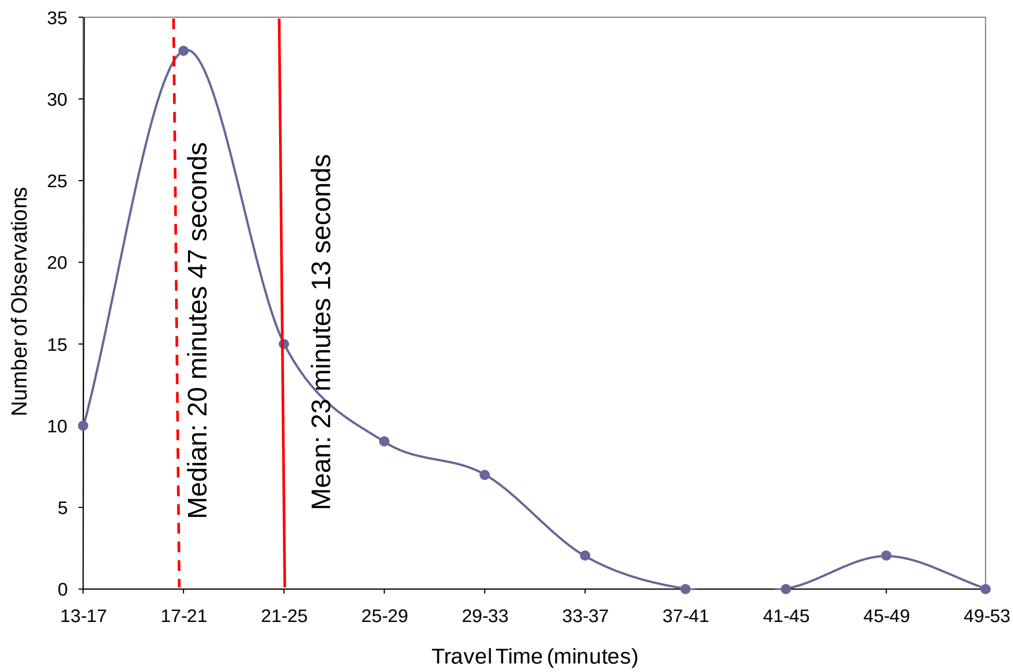


Figure 5. Path Travel Time Distribution (NJ 17)

2) A normality test was conducted for each route that had a sufficient sample size. Normality tests are for testing whether the input data is normally distributed. It is required by some statistical tests such as Student's t-test, one-way and two-way ANOVA, because they make assumptions that data comes from a normally

distributed population, and if such assumptions are not valid, the results of the tests will be unreliable. In general, the normality test can be performed by using options such as Anderson-Darling test, Shapiro-Wilk test, and Kolmogorov-Smirnov test, which can be selected based on the sample size. More detailed information about these tests are shown in Appendix C. The characteristics of each test is summarized as follow:

a. Anderson-Darling Test [see references 35,36,37,38,and 39] : This test compares the empirical cumulative distribution function of the sample data with the expected distribution. Anderson-Darling test may be used with small sample sizes (e.g. less than 25). Very large sample sizes may reject the assumption of normality with only slight imperfections, but data with sample sizes of 200 and more or less can be tested with the Anderson–Darling test. If this observed difference is sufficiently large, the test will reject the null hypothesis of population normality.

b. Shapiro-Wilk Test[29,32]: This test assesses normality by calculating the correlation between the sample data and the normal scores of the sample data. If the correlation coefficient is near 1, the population is likely to be normal. If the sample size is 2,000 or less, Shapiro-Wilk test is used.

c. Kolmogorov-Smirnov Test[9]: This test compares the empirical cumulative distribution function of the sample data with the distribution expected if the data were normal. If the p-value of Kolmogorov-Smirnov test is less than the chosen α-level, the null hypothesis of normality is rejected, and it is concluded that the population is non-normal. A large sample size (> 2,000) is preferable for the Kolmogorov-Smirnov test. Note that the p-value is a statistical measure for the probability that the results observed in a study could have occurred by chance. The smaller the p-value, the more strongly the test rejects the null hypothesis. A p-value of 0.05 or less rejects the null hypothesis.

3) A Log-Normality test for path travel time was also conducted. In order to conduct the test, the collected path travel time was converted log-value and the smallest travel time was subtracted from each observation since the travel time distribution has a shape that looks like a shifted log-normal distribution.

In order to determine whether a travel time distribution is normal or log-normal, hypothesis test was applied. The statistical statement for the normality test is

- Null Hypothesis(H_0): The route travel time distribution for NJ 17 follows the Normal distribution
- Alternative Hypothesis (H_a): The route travel time distribution for NJ 17 has a different distribution than the Normal.

Figure 6 indicates that the null hypothesis – the route travel time distribution is normal - is rejected as quite a few observations fall away from the line. The p-value (<0.005) of less than 0.05 confirms the visual observation of the normality test.

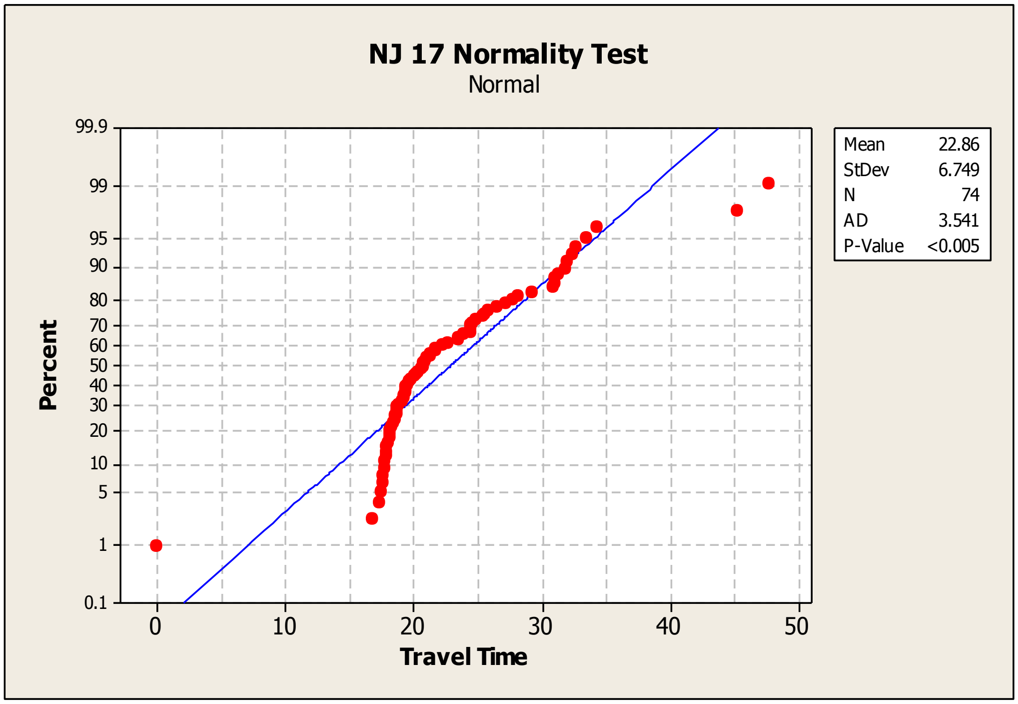


Figure 6. Path Travel Time Distribution for Normality Test (NJ 17)

The corresponding hypothesis test for the Log-Normality test is:

- Log-Normality Test Null Hypothesis (H_0): The route travel time distribution for NJ 1 7 follows a Shifted Log-Normal distribution.
- Alternative Hypothesis (H_a): The route travel time distribution on NJ 17 is different from a Shifted Log-Normal.

Figure 7 indicates that the null hypothesis – the route travel time distribution is log-normal - is not rejected as only a few observations fall away from the line. The corresponding p-value (0.36) of greater than 0.05 confirms the visual observation of the log-normality test.

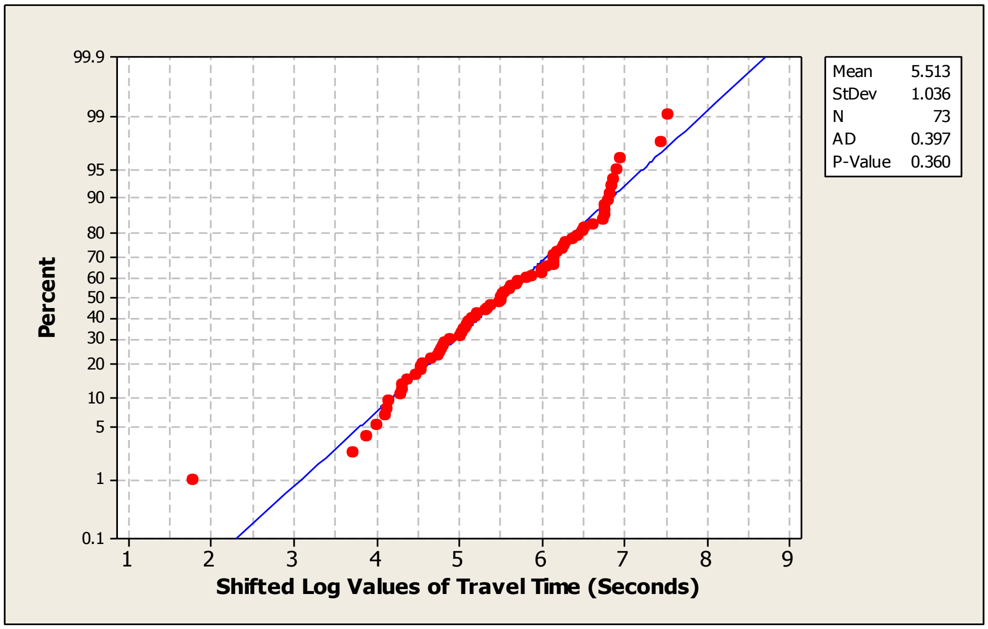


Figure 7. Path Travel Time Distribution for Log-Normality Test (NJ 17)

Normality and Log-Normality tests for travel time distribution tests aforementioned were conducted only for the routes collected by NJIT because the collected sample sizes were sufficient to conduct these tests. The results of two tests are summarized in Table 5, and the corresponding figures of travel time distribution for other routes are illustrated in Appendix D.

Table 5 – Normality and Log-Normality Test Results

Locations	Normality Test (p-value)	Log-Normality Test (p-value)	Log Mean	Log Standard Deviation	Log 95% C.I.
NJ 17	-	√ (0.36)	5.5	1.06	0.22
NJ 208 & NJ 4	√ (0.083)	-	6.9	0.94	0.26
I-80 & I-280	-	√ (0.095)	5.5	1.04	0.25
NJ 24 & I-78	-	-	2.1	0.74	0.14
US 46 & NJ 3	-	√ (0.051)	5.7	0.85	0.19
US 22	-	√ (0.058)	5.9	1.00	0.18
I-287 (A)	-	√ (0.056)	5.7	0.85	0.18
I-287 (B)	-	-	5.3	0.90	0.18

√: p-value is greater than 0.05

The majority of the path travel time distributions [NJ 17, I-80 / I-280, US 46 & NJ 3, US 22, I-287 (A), and I-287 (B)] were shown – using normality and log-normality tests - to follow a shifted log-normal distribution for the morning period from 6:00 to 9:00 AM. Specifically route NJ 208 & NJ 4 is the only one that shows some semblance of a Normal distribution. For each of these distributions the associated 95% Confidence Intervals were estimated. Due to limited data for each 15-minute time interval the corresponding path travel time distributions could not be estimated.

Link and Path Travel Time Analysis for NJ 17

The studied segment of NJ 17 begins at the interchange of NJ 17 and County Route 502 and ends at the interchange of NJ 17 and NJ 3. It is 14.33 miles long and consists of 9 nodes. The geographical information (e.g., mile post and geo-coordinate) for each node is summarized in Table 6.

Table 6 - Node Location and Coordinates on NJ 17 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 17	1	18.33	-	-74.100959	41.000399	near CR 502
	2	16.56	1.77	-74.084549	40.980345	@ CR110
	3	13.66	2.90	-74.071371	40.939776	@ INT GSP
	4	12.33	1.33	-74.072440	40.920650	@ NJ 4
	5	9.90	2.43	-74.068483	40.886541	@ I-80
	6	9.13	0.77	-74.063980	40.876260	@ I-80 (INT 64)
	7	8.44	0.69	-74.064262	40.867419	@ US 46
	8	5.76	2.68	-74.088817	40.832712	@ NJ 120
	9	4.00	1.76	-74.102751	40.814459	near NJ 3
Total	-	-	14.33	-	-	-

*: Link distance from node 1 to node 2

In order to analyze the impact of departure time on travel time, Figure 8. Travel Times for Different Departure Time Periods (NJ 17) was developed to illustrate the cumulative travel times from the first node to all downstream nodes for different departure time periods for every 15-minute interval from 6:15 A.M. to 8:15 A.M. with the moving mean method. It was found that the longest mean travel time (from node 1 to node 8) occurred when vehicles departed during the 8:00 A.M. - 8:15 A.M. interval was 31 minutes. In contrast, the departures in the 6:45 A.M. – 7:00 A.M. time interval needed only 19 minutes to complete the same highway segment due to light traffic flow conditions.

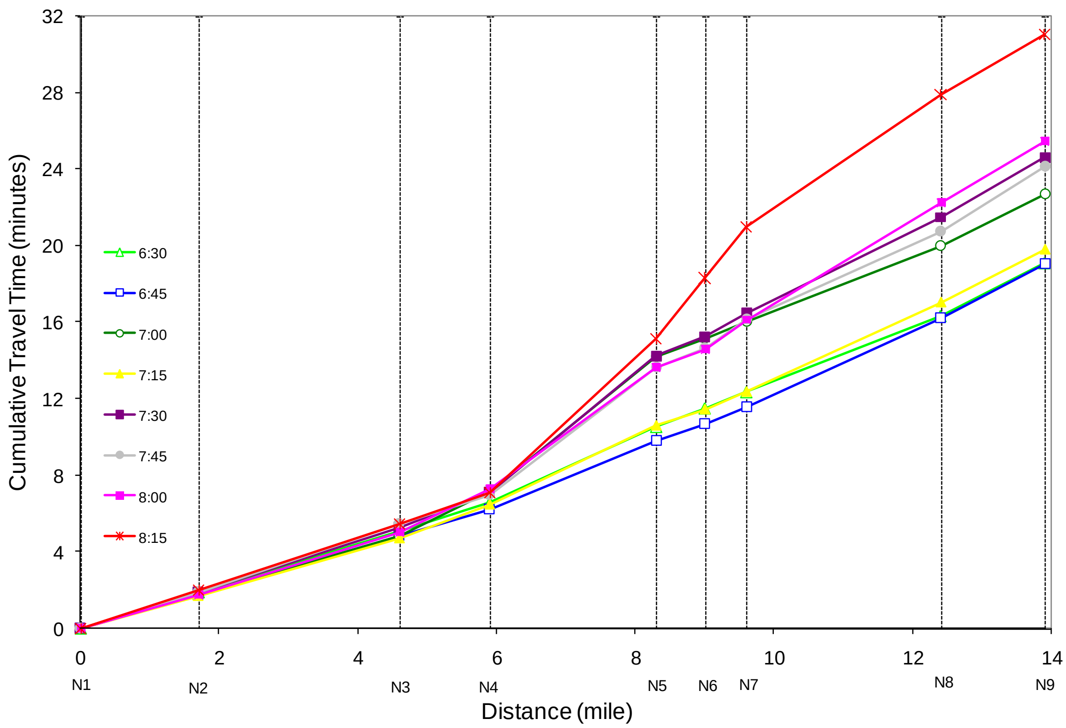


Figure 8. Travel Times for Different Departure Time Periods (NJ 17)

Figure 9 illustrates the variations between cumulative path time and the resulting one from individual link-based travel time distributions. The mean cumulative travel time plus or minus link-based standard deviation, colored in red, is greater than the corresponding cumulative mean travel time plus or minus path-based standard deviation for the entire traveled distance. It was found that as travel distance increases, the difference between the path and the cumulative link-based standard deviation also increases.

Figure 9 also shows that the path travel time variation is less than the sum of link travel time variation. This is due to the sum of link based travel time variation assumes a worst situation at which the longest travel times of all links occur simultaneously. This demonstrates that the use of consecutive link travel time estimates should be avoided as it will overestimate the actual variation of path travel time. In cases where only link travel times are available, a correction factor should be applied to account for the covariance terms that are ignored if the consecutive travel links are simply added together.

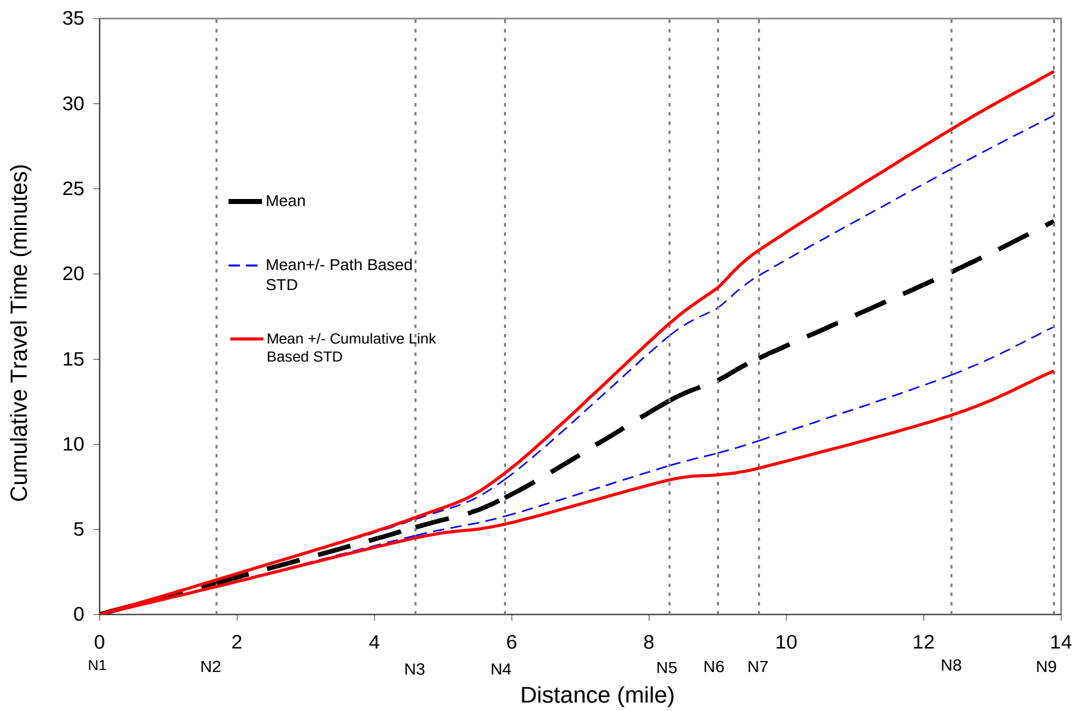


Figure 9. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 17)

Figure 10 shows the mean link travel speed, the corresponding standard deviation, and mean link speed for moving mean per departure time interval. The speed of each link is relatively proportional to the link travel times shown in Figure 8. The mean speed on link 4 is apparently lower than the other links because of an on-going construction activity while collecting the data, and the mean speeds on links 5, 6, and 7 decreased between 7:45 and 8:15 A.M. due to the effect of increased traffic volume.

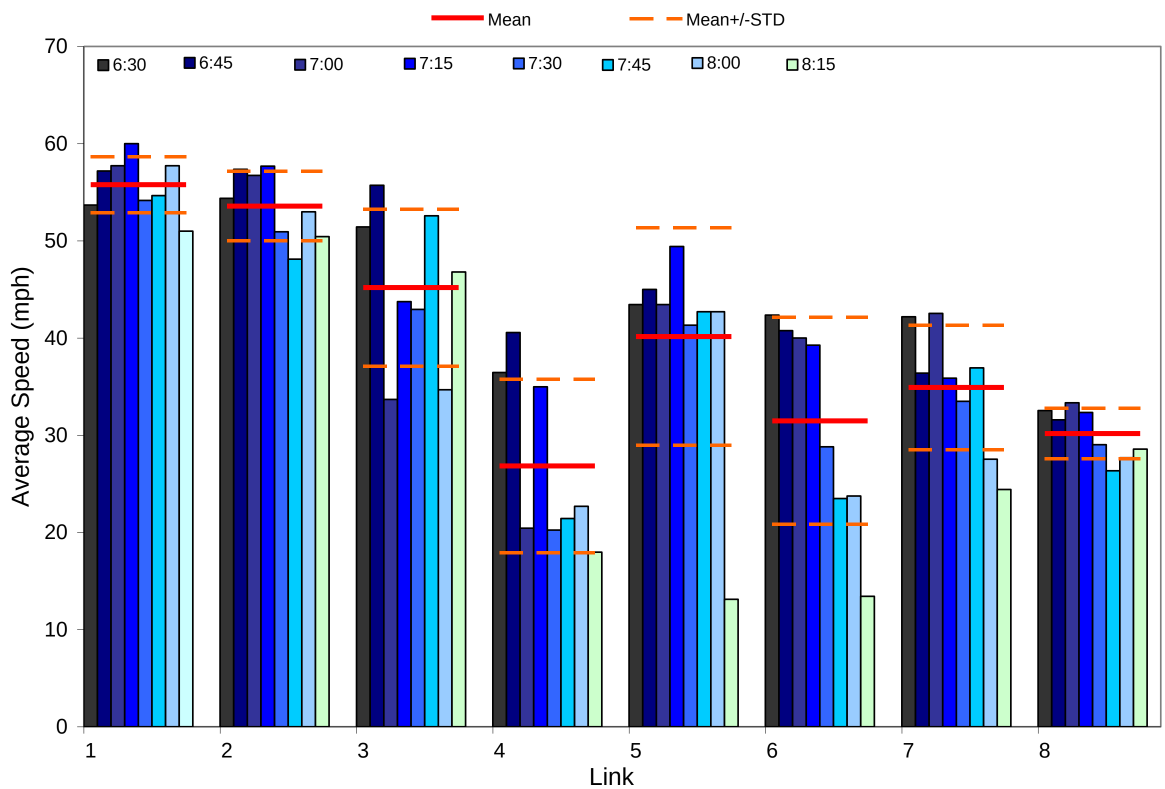


Figure 10. Speed Variation vs. Link for Different Departure Time Periods (NJ 17)

Based on the collected data, the corresponding path travel time distribution and the associated parameters –(e.g., mean, mean plus or minus standard deviation, median, and the the 95th percentile travel time, etc.) were approximated. In Figure 11, the median of travel time is about 20.8 minutes, and the mean travel time is 23.6 minutes.

The mean travel time is 46th of 73 samples, which is about 62% of the data below the mean. This indicates that the distribution has more samples on the low side of the mean and higher variation on the high side of the mean. The 95th percentile travel time was used as the threshold to approximate the recurring from the non-recurring traffic conditions. Four travel time records greater than the threshold travel time were observed due to unknown delay.

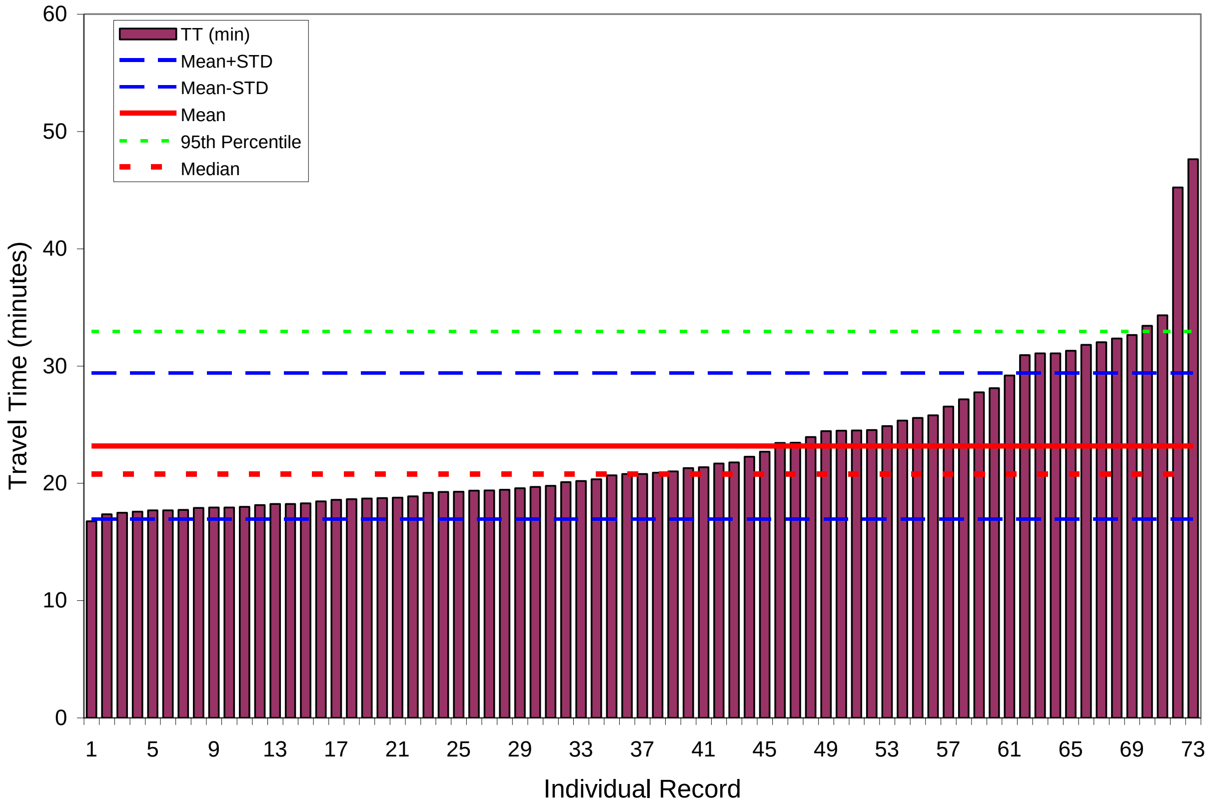


Figure 11. Path Travel Time Distribution (NJ 17)

The impact of departure time on path travel time is depicted in Figure 12. The mean path travel time with its deviation (e.g. plus and minus standard deviation) and the 95th percentile travel time were estimated for each time period. Figure 12 shows that the travel time distribution for the departure time periods of 6:45-7:15, 7:15-7:45, and 7:45 -

8:15 A.M had a significantly larger travel time variation, compared to that in the period of 6:15-6:45 A.M. The delay observed in each time period was caused by construction activity on the roadside between node 4 and node 5 and increased demand at signalized intersections between node 8 and node 9.

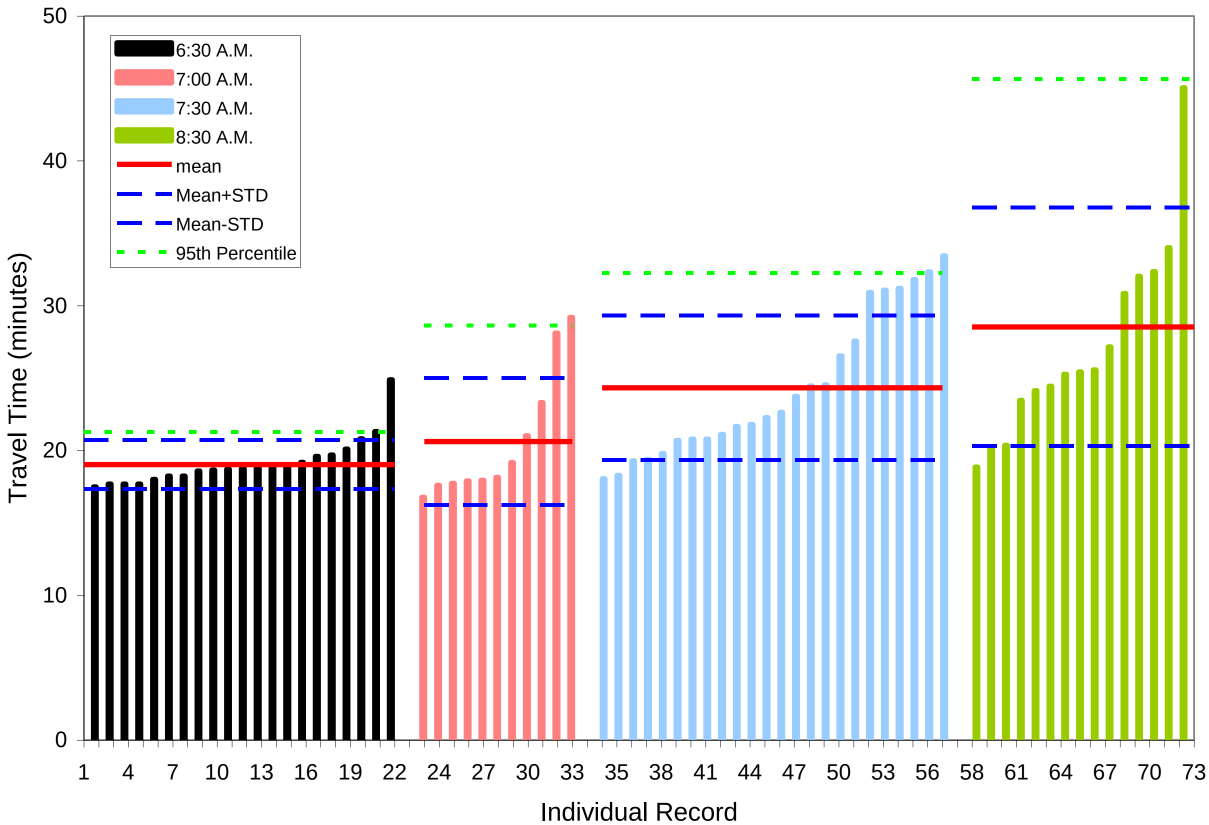


Figure 12. Path Travel Time Distribution by Departure Time Period (NJ 17)

A summary of the statistical analysis results for NJ 17 is shown in Table 7.

Table 7 - Path Travel Time Reliability Indices per Departure Time Period (NJ 17)

Departure Time (A.M.)	**Sample Size**	**AVG. TT (mm:ss)**	**STDEV (mm:ss)**	**CV**	**the 95th percentile (mm:ss)**	**Buffer Index (%)**	**Range (mm:ss)**	
						95th percentile	**t_{MIN}**	**t_{MAX}**
6:15-6:45	22	19:19	01:41	0.09	21:17	10.2	16:58	24:53
6:45-7:15	11	20:37	04:23	0.21	28:39	39.0	16:46	29:11
7:15-7:45	24	24:20	04:59	0.20	32:15	32.5	18:03	33:26
7:45-8:15	16	28:32	08:14	0.29	45:39	60.0	18:51	47:29

Travel Time Analysis for NJ 208 & NJ 4

The studied segment of NJ 208 & NJ 4 begins at the interchange of NJ 208 and I-287 and ends at the interchange of NJ 4 and I-95. It is 17.52 miles long and consists of 9 nodes. Table 8 presents the characteristics of this segment.

Table 8 - Node Location and Coordinates on NJ 208 & NJ 4 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 208	1	9.30	-	-74.216496	41.017236	near I-287
	2	7.87	1.43*	-74.192458	41.007138	@ CR 502
	3	2.88	4.99	-74.136937	40.949944	@ CR 507
	4	0.00	2.88	-74.093758	40.926497	@ NJ 4 MP 2.0
NJ 4	5	2.9	0.90	-74.079881	40.922679	@ INT GSP
	6	3.34	0.44	-74.071906	40.920632	@ NJ 17
	7	5.67	2.33	-74.033210	40.905750	@ CR 503
	8	9.04	3.37	-73.981007	40.878904	@ NJ 93
	9	10.22	1.18	-73.974483	40.864962	near I-95
Total	-	-	17.52	-	-	-

*: Link distance from node 1 to node 2

The scheduled departure interval was from 6:15 - 8:15 A.M., but three records were observed between 8:15 - 8:45 A.M. Thus, actual departure time interval for NJ 208 & NJ 4 was ranged from 6:15 - 8:45 A.M. Figure 13 presents the mean cumulative travel times for 9 departure time periods (e.g. 15-minute interval) from 6:15 A.M. to 8:45 A.M. It was found that the shortest mean travel time (31.4 minutes) was observed for departures occurring during the 8:30 - 8:40 A.M. time interval where the longest (46.1 minutes) was observed for departures occurring during the 7:45 - 8:15 A.M. time interval. As shown in Figure 13, the travel time on link 8 was greater than the other links because of downstream heavy traffic which was heading to New York City in the morning peak hours.

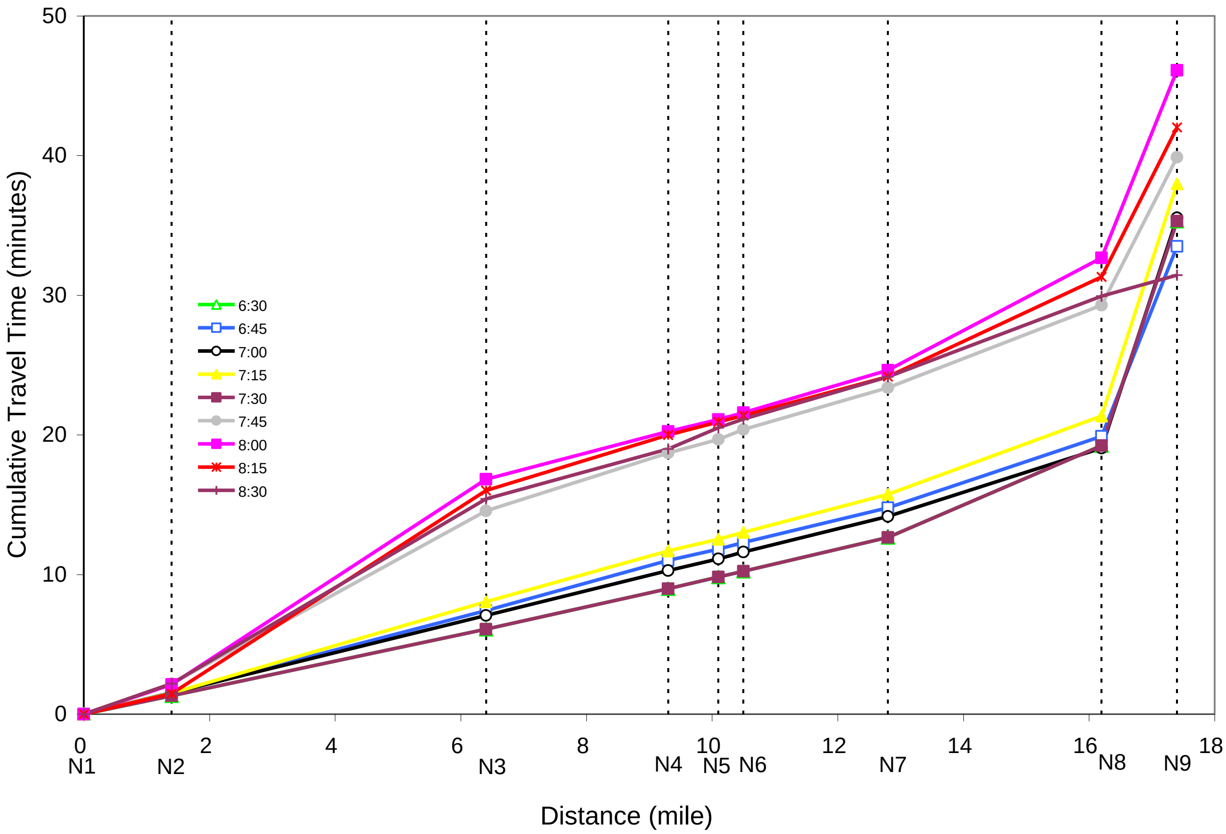


Figure 13. Travel Times for Different Departure Time Periods (NJ 208 & NJ 4)

Figure 14 shows the difference between cumulative path- and link-based standard deviation of travel time. This figure also confirms the need for estimating the path travel time distribution directly rather than through the use of consecutive link travel time distributions.

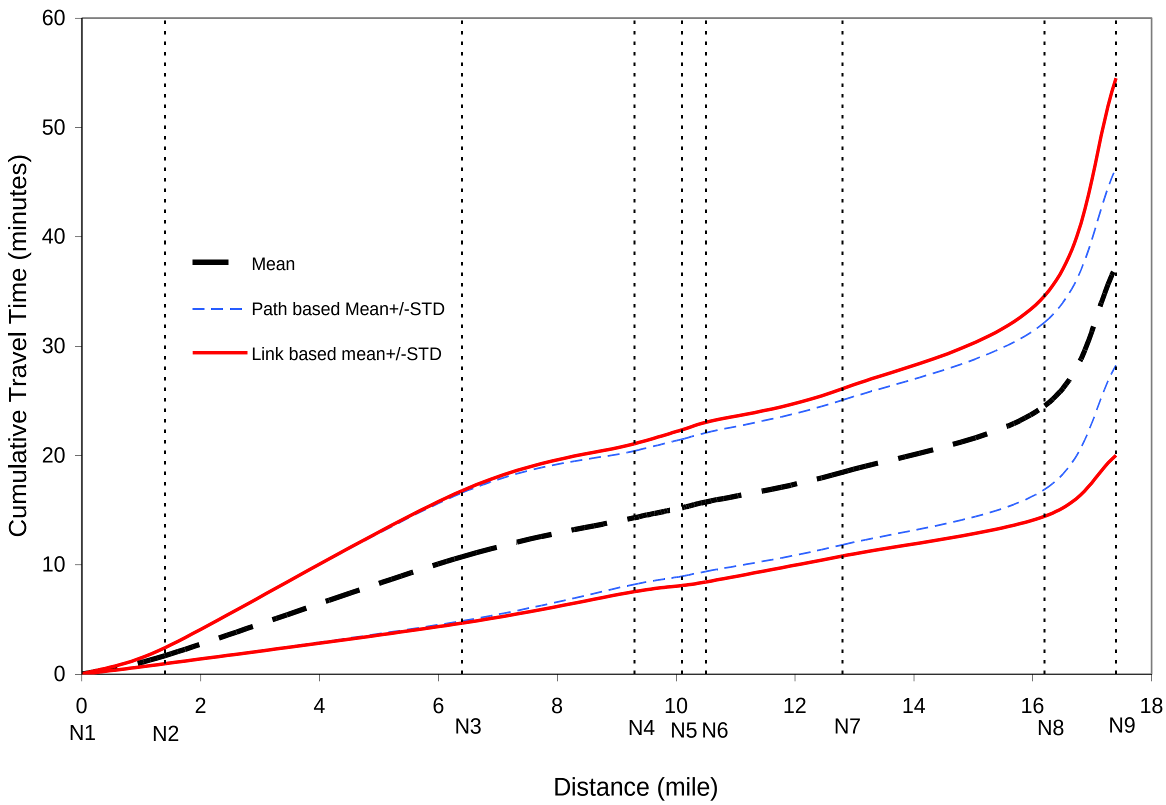


Figure 14. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 208 & NJ 4)

Figure 15 illustrates the mean speed on each link for different time periods and compares them with the mean link speed considering mean plus or minus standard deviation. The mean travel speeds for links 1 through 7 were similar for the departure times from 6:30 to 7:15 A.M. The speed on links 7 and 8 is significantly lower than the other links due to the heavy downstream congestion caused by the George Washington Bridge Toll Plaza during the A.M. peal period - the queue propagates upstream affecting links 7 and 8.

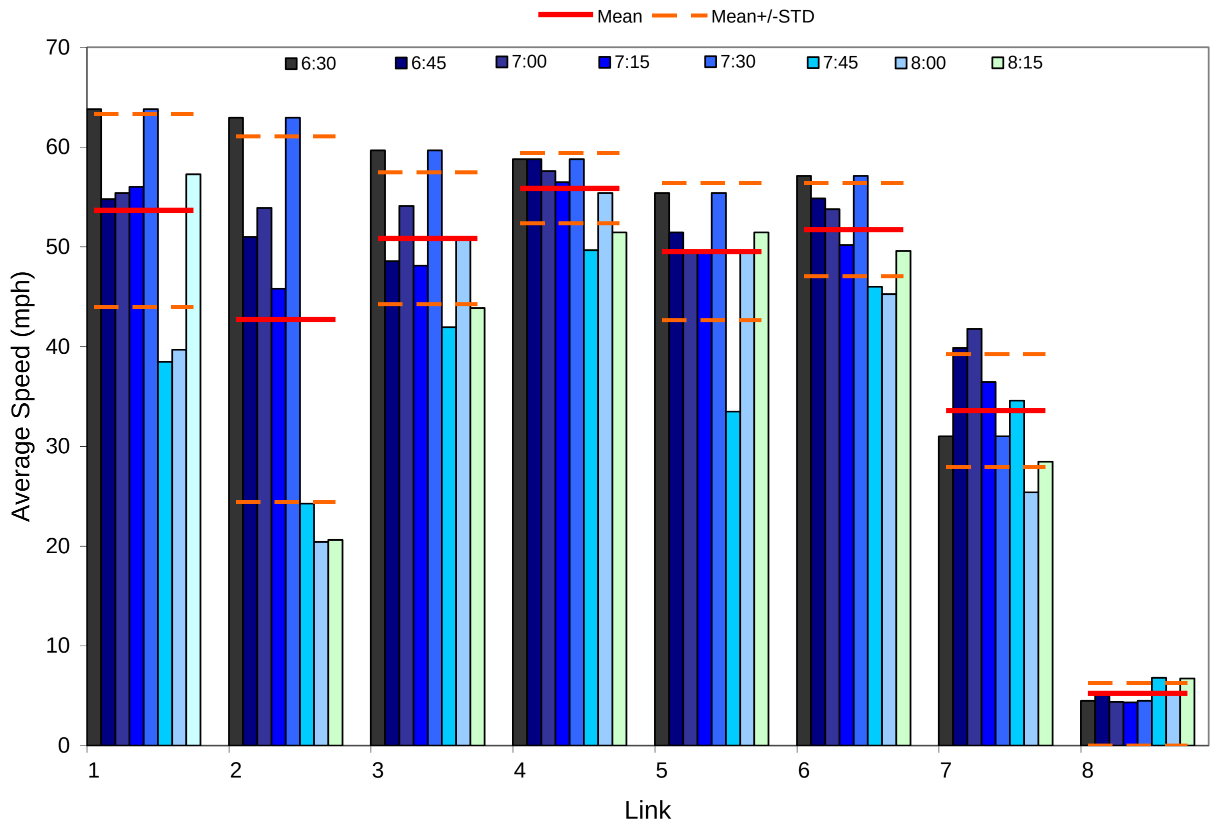


Figure 15. Speed Variation vs. Link for Different Departure Time Periods (NJ 208 & NJ 4)

The Path-based travel time distribution, mean, mean plus or minus standard deviation, and the 95th percentile travel time are displayed In Figure 16. The travel times for nine records were greater than the mean plus standard deviation, and one of them was slightly greater than the 95th percentile travel time. Given this observation we can conclude that no substantial path travel time differences were observed.

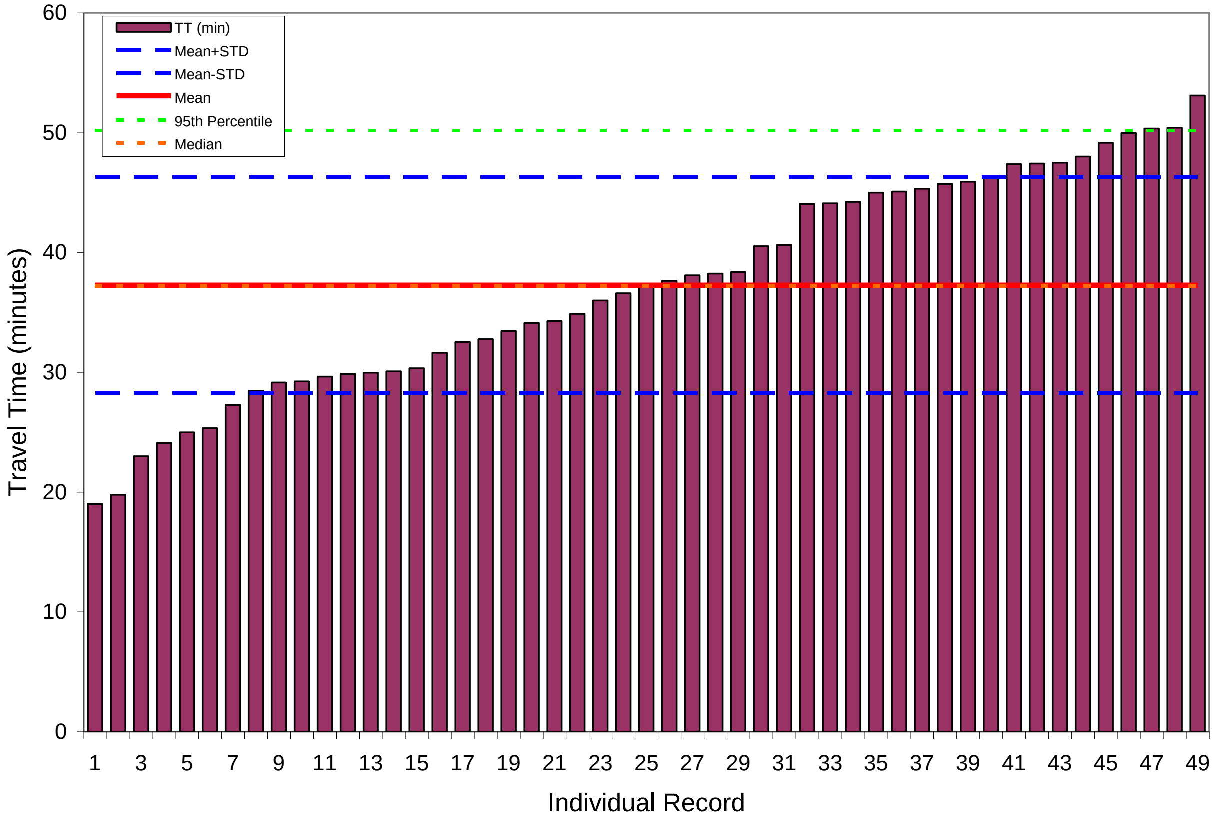


Figure 16. Path Travel Time Distribution (NJ 208 & NJ 4)

Figure 17 shows the path-based time distributions based on different departure time periods. Mean, mean plus or minus standard deviation, and 95th percentile travel time were estimated and compared for each time period. As shown in Figure 17, each 30-minute time interval has a significant path travel time variation - the range of travel time for each departure time, 6:15-6:45, 6:45-7:15, 7:15-7:45, and 7:45-8:45, A.M., is 24 minutes 12 seconds, 24 minutes 24 seconds, 31 minutes 24 seconds, and 28 minutes12 seconds, respectively. These path travel time variations are explained by the presence of the GWB toll plazas at the end of the NJ route 4 towards New York.

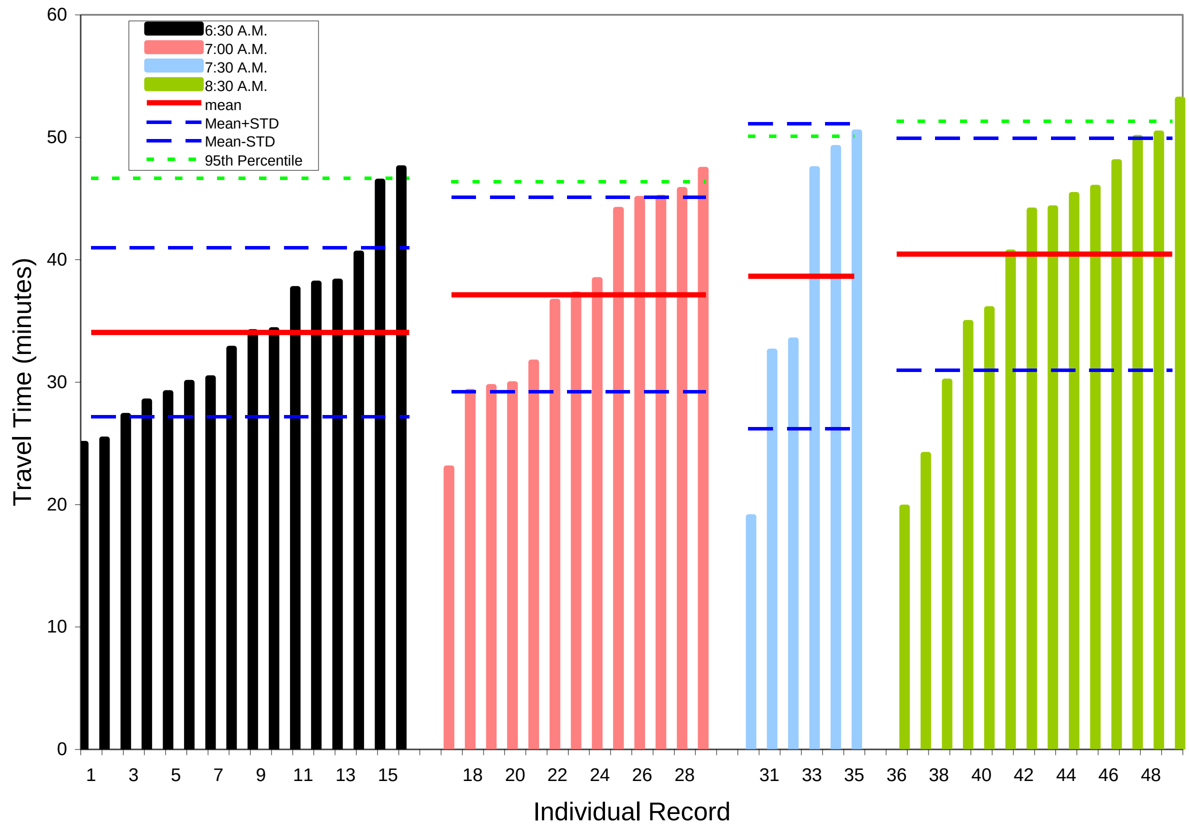


Figure 17. Path Travel Time Distribution by Departure Time Period (NJ 208 & NJ 4)

A summary of statistical analysis results for NJ 208 & NJ 4 is shown in Table 9.

Table 9 - Path Travel Time Reliability Indices per Departure Time (NJ 208 & NJ 4)

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	the 95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	16	33:24	7:12	0.21	46:06	38.0	23:18	47:30
6:45-7:15	13	37:06	7:54	0.21	46:04	24.2	23:00	47:24
7:15-7:45	6	39:12	12:54	0.33	50:40	29.3	19:00	50:24
7:45-8:45*	14	37:30	9:30	0.25	47:00	25.3	19:48	48:00

*: includes 3 data for the interval 8:15 - 8:45 A.M.

Travel Time Analysis for I-80 & I-280

The studied segment of I-80 & I-280 is 19.39 miles long starting at the interchange of I-280 and I-287 and ending at the interchange of I-280 and County Route 508. The studied segment consists of 8 nodes having the following characteristics as depicted in Table 10.

Table 10 - Node Location and Coordinates on I-80 & I-280 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
I-80	1	43.62	-	-74.410017	40.862855	near I-287
	2	46.36	2.74*	-74.369098	40.858756	@ I-280 MP 0.00
I-280	3	4.95	4.95	-74.309389	40.813142	@ CR 527
	4	8.26	3.31	-74.251397	40.797041	@ CR 577
	5	9.91	1.65	-74.241485	40.775191	@ CR 508
	6	12.12	2.21	-74.208640	40.759245	@ INT GSP
	7	14.42	2.30	-74.167612	40.747995	@ NJ 21
	8	16.65	2.23	-74.128366	40.750210	near CR 508
Total	-	-	19.39	-	-	-

*: Link distance from node 1 to node 2

Figure 18 illustrates the cumulative travel times from the first node to all downstream nodes for different departure time periods in 15-minute intervals from 6:30 A.M. to 8:45 A.M. by applying the moving mean method. The shortest mean path travel time (19.4 minutes) was observed for departures occurring between 7:15 - 7:30 A.M. and the longest (31.4 minutes) was observed for departures occurring between 8:30 - 8:45 A.M. In addition, it is observed that the mean travel time on link 6 is significantly larger from the other links - this was due to construction renovating a draw bridge over the Passaic River.

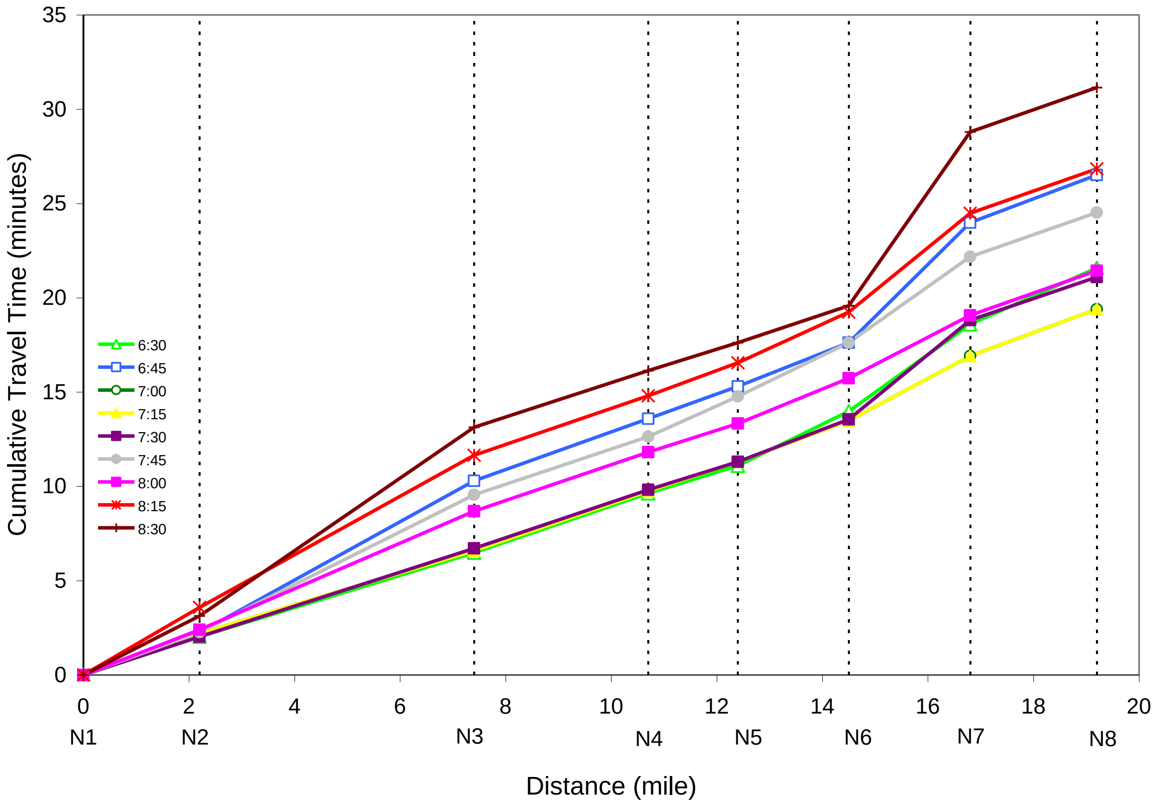


Figure 18. Travel Times for Different Departure Time Periods (I-80 & I-280)

Figure 19 illustrates the difference between cumulative path-based standard deviation and link-based standard deviation of travel time.

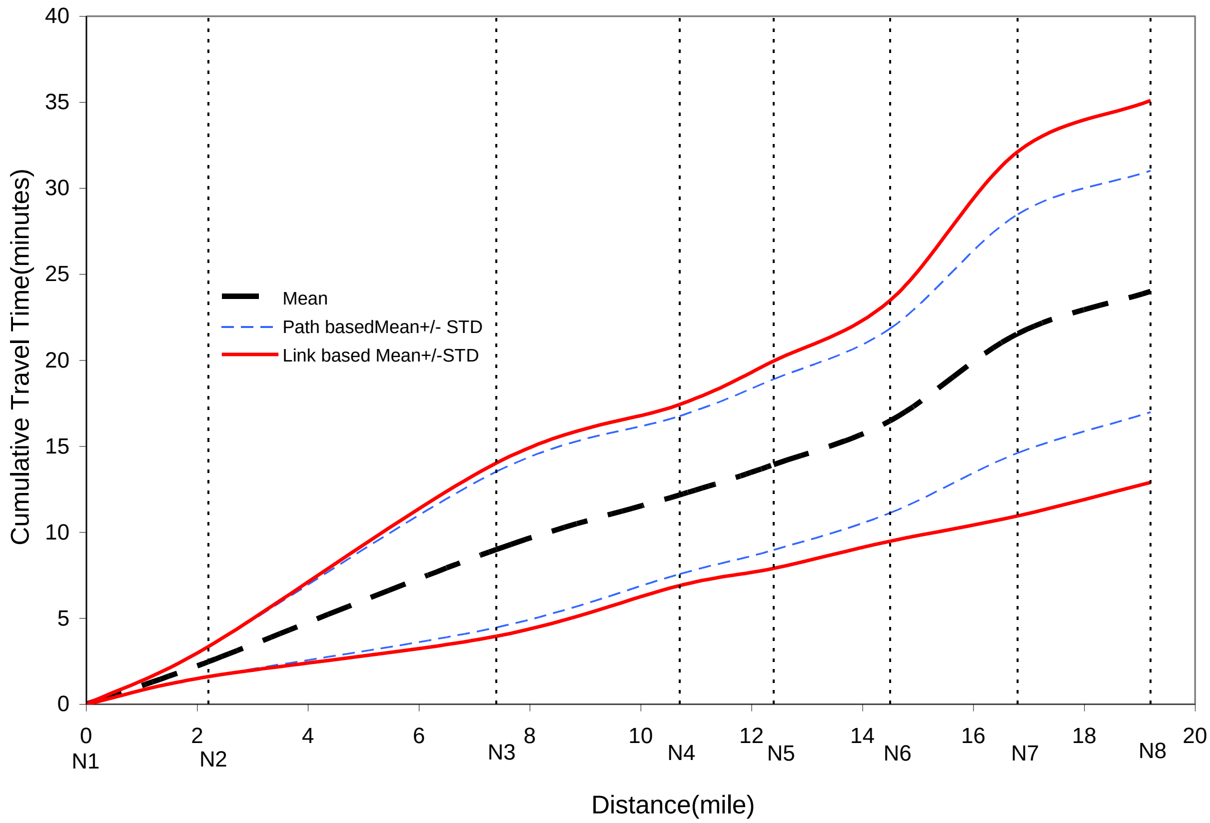


Figure 19. Travel Time Variation with Link-Based vs. Path- Based Data (I-80 & I-280)

Figure 20 shows the mean travel speed for each link with its standard deviation, and the mean link speed for each of the moving mean different departure times. The mean travel speed variation on link 3 is very small, while the mean speeds on the other links have noticeable variations.

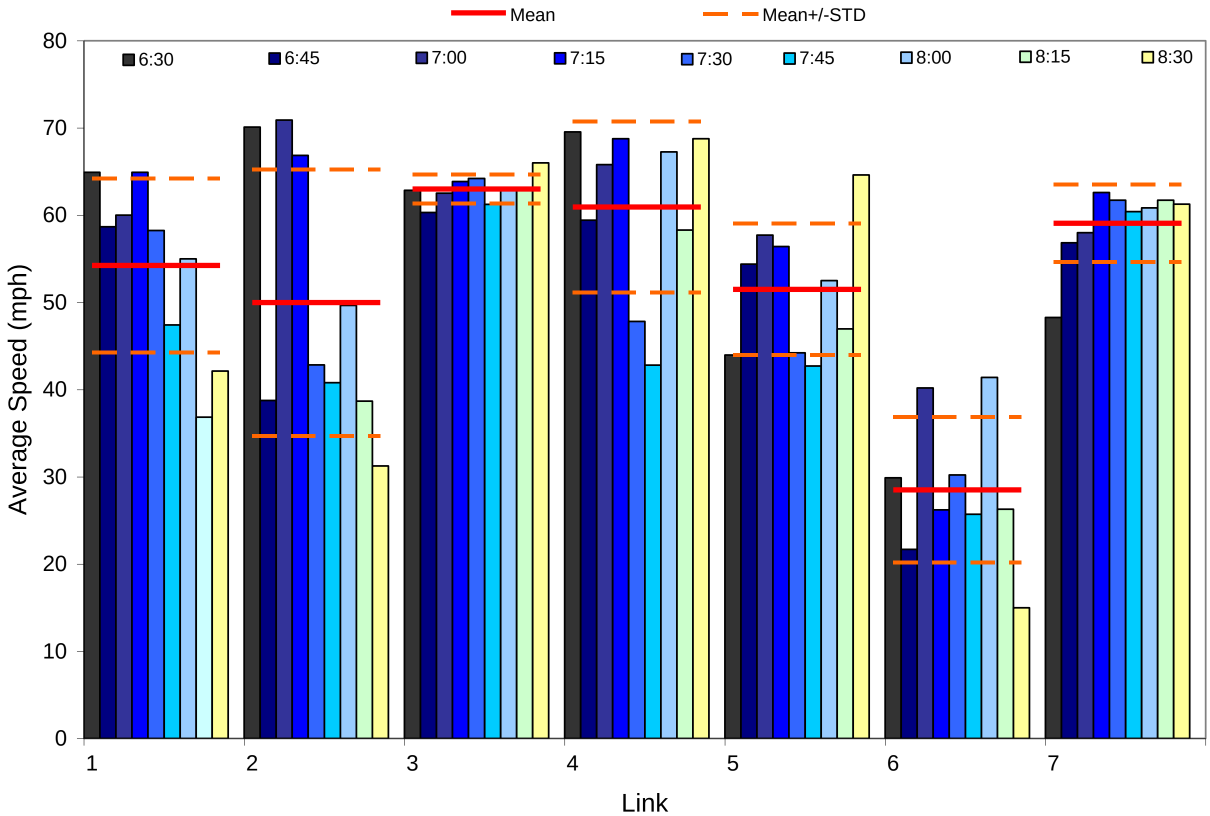


Figure 20. Speed Variation vs. Link for Different Departure Time Periods (I-80 & I-280)

Figure 21 shows the path-based travel time distribution for each driver, including mean, mean plus or minus standard deviation, and the 95th percentile travel time. The travel time of 9 collected data was greater than the mean plus standard deviation where 4 of them were also greater than the 95th percentile travel time. The travel time distribution ranged from a 19 minute low to a 53 minutes 6 seconds high. It was found that one collected data had significantly longer travel time compared to others. As illustrated in Figure B-9 in Appendix B, the data collector experienced an unknown non-recurring congestion on link 2.

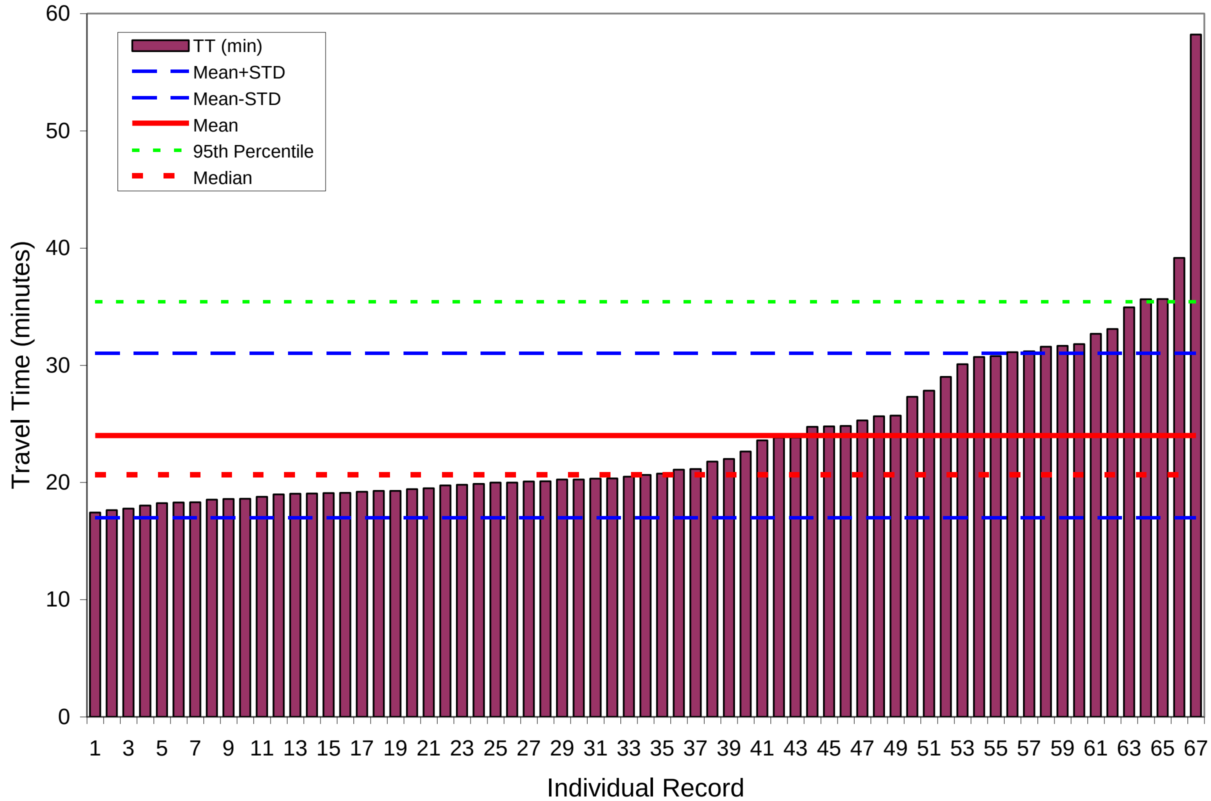


Figure 21. Path Travel Time Distribution (I-80 & I-280)

Figure 22 shows the impact of departure time on the corresponding path travel time distribution. The path-based time mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and compared for each time period. As shown in Figure 22, the largest path travel time – also depicted in Figure 20 - occurred during the 6:30 A.M time period.

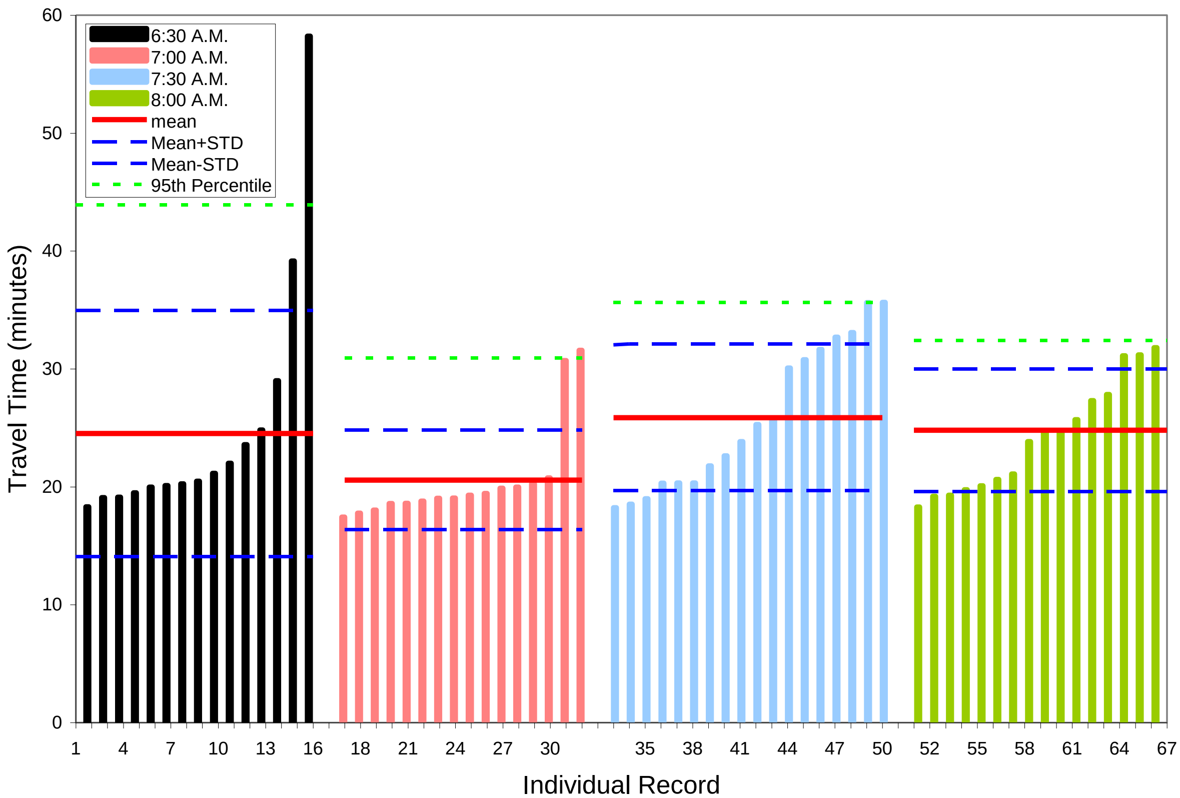


Figure 22. Path Travel Time Distribution by Departure Time Period (I-80 & I-280)

A summary of statistical analysis results for I-80 & I-280 is shown in Table 11.

Table 11 - Path Travel Time Reliability Indices per Departure Time (I-80 & I-280)

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	the 95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	16	24:30	10:24	0.43	43:54	79.0	17:36	58:12
6:45-7:15	16	20:36	4:12	0.21	30:54	50.2	17:24	31:36
7:15-7:45	18	25:54	6:12	0.24	35:36	37.5	18:12	35:42
7:45-8:15*	17	24:48	5:12	0.21	32:24	30.7	18:18	34:54

*: includes 8:15- 8:45 A.M. data

Travel Time Analysis for NJ 24 & I-78

The studied segment of NJ 24 & I-78 begins at the interchange of NJ 24 and I-287 and ends at the interchange of I-78 and NJ 21. It is 17.5 miles long and consists of 8 nodes. Table 12 presents the spatial characteristics of this segment.

Table 12 - Node Location and Coordinates on NJ 24 & I-78 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 24	1	0.60	-	-74.444417	40.804913	near I-287
	2	2.09	1.49*	-74.425178	40.790116	@ CR 510
	3	7.07	4.98	-74.367030	40.738062	@ CR 649
	4	9.45	2.38	-74.331779	40.717989	@ CR 512
	5	10.42	0.97	-74.321400	40.711779	@ I-78 MP 49.28
I-78	6	50.58	1.30	-74.297783	40.713997	@ NJ 124
	7	53.42	2.84	-74.245101	40.705230	@ INT GSP
	8	57.20	3.78	-74.184728	40.709275	near NJ 21
Total	-	-	17.74	-	-	-

*: Link distance from node 1 to node 2

Figure 23 shows the mean cumulative travel time for nine moving mean departure times. The shortest mean path travel time (16 minutes 41 seconds) was observed for departures occurring during the 6:30 A.M. time interval, while the longest mean path travel time (19 minutes 23 seconds) was observed for departures occurring during the 8:15 A.M. time interval. It was found that there was no significant travel time variation between departure times - the greatest mean travel time difference was only 2 minutes 32 seconds.

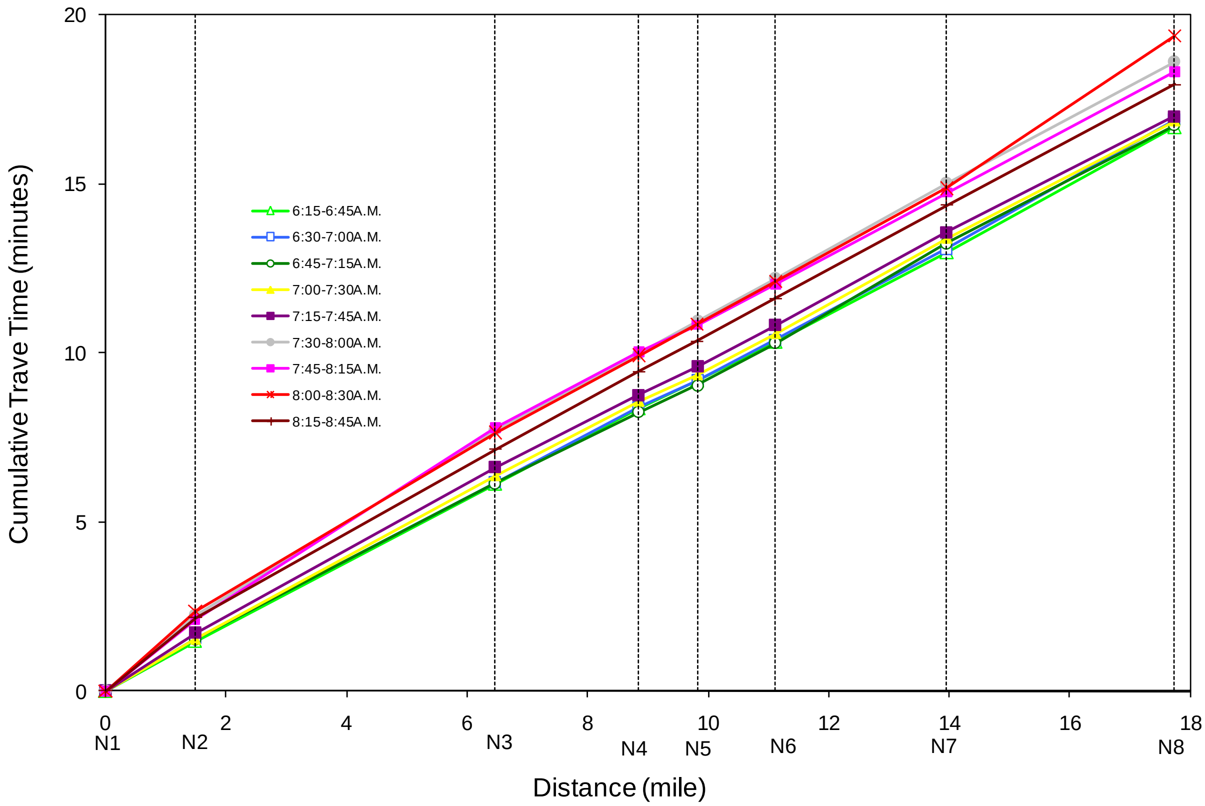


Figure 23. Travel Times for Different Departure Time Periods (NJ 24 & I-78)

Figure 24 shows the mean travel time and the difference between path-based and cumulative link-based standard deviation of travel time.

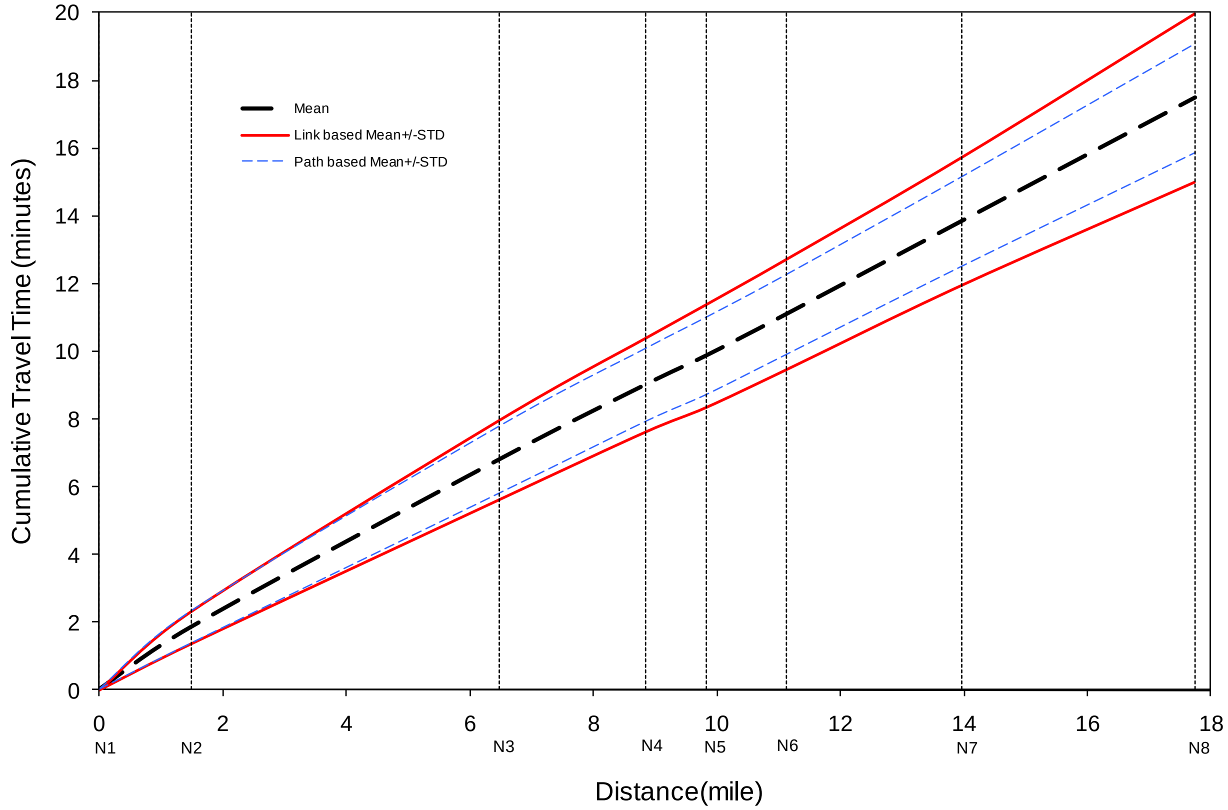


Figure 24. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 24 & I-78)

The mean speed per departure time interval for each link, the mean and mean plus or minus standard deviation are depicted in Figure 25. A significant speed variation (i.e. more than 15 mph) by departure time is observed on links 1, 2, 4, and 7, while only a slight speed variation is observed on the other links.

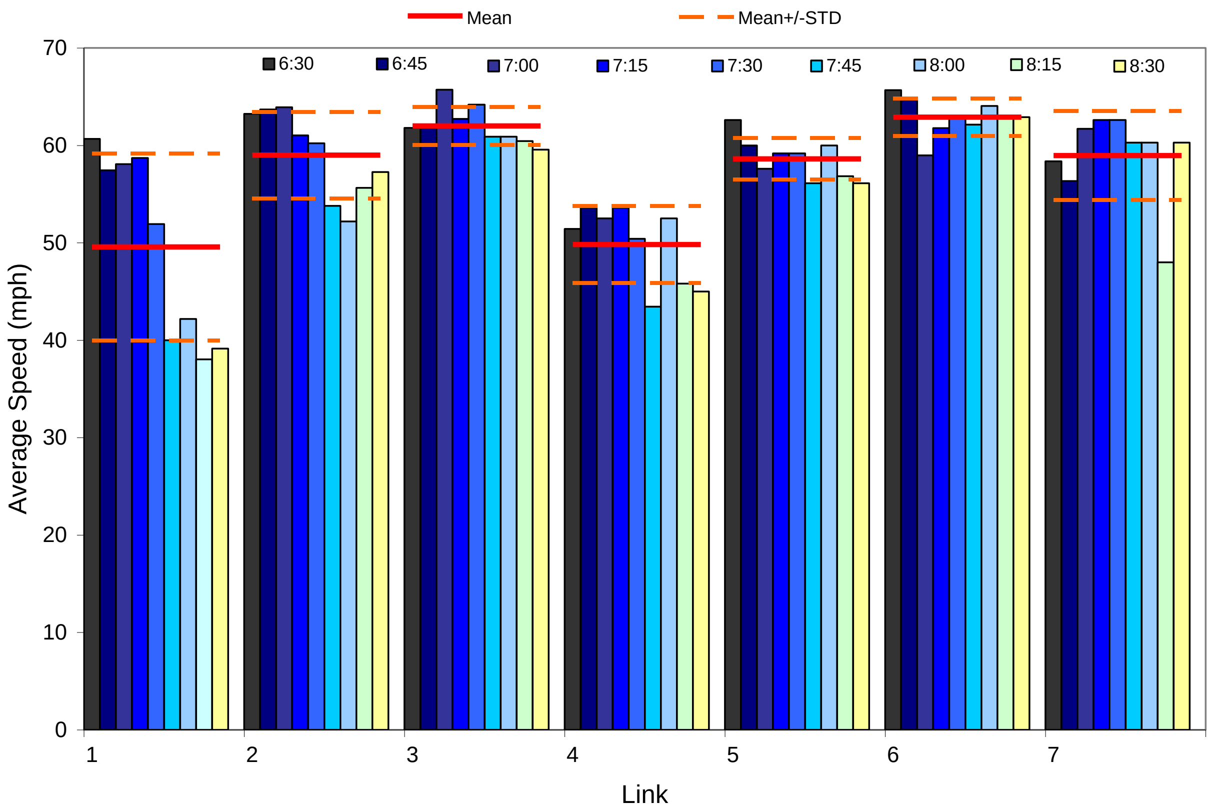


Figure 25. Speed Variation vs. Link for Different Departure Time Periods (NJ 24 & I-78)

Figure 26 presents the path-based travel time distribution for each driver, including the corresponding mean, mean plus or minus standard deviation, and the 95th percentile travel time. The range of the observed path travel times is 14 minutes 53 seconds. A total of 81 records were collected where 12 exhibited greater path travel times than the mean plus standard deviation, and further four of these 12 data records exhibited greater path travel times than the 95th percentile travel time, which were a attributed to non-recurring delay.

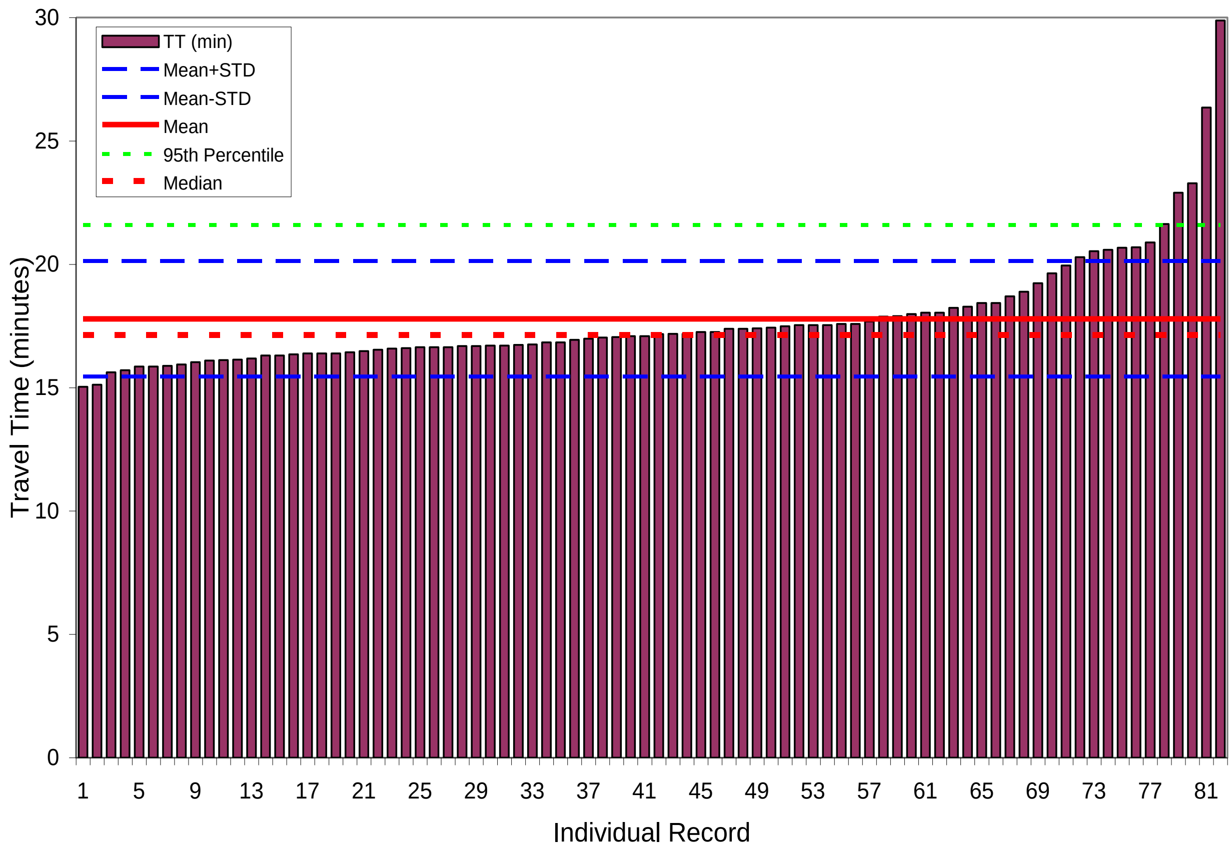


Figure 26. Path Travel Time Distribution (NJ 24 & I-78)

The impact of departure time on the corresponding path travel time distribution is illustrated in Figure 27. One driver experienced a much higher path travel time than the rest of the group for each of the departure time periods of 6:30 A.M. and 8:00 A.M., respectively. No substantial path travel time differences were observed for the departure time periods from 7:00 A.M. to 7:30 A.M.

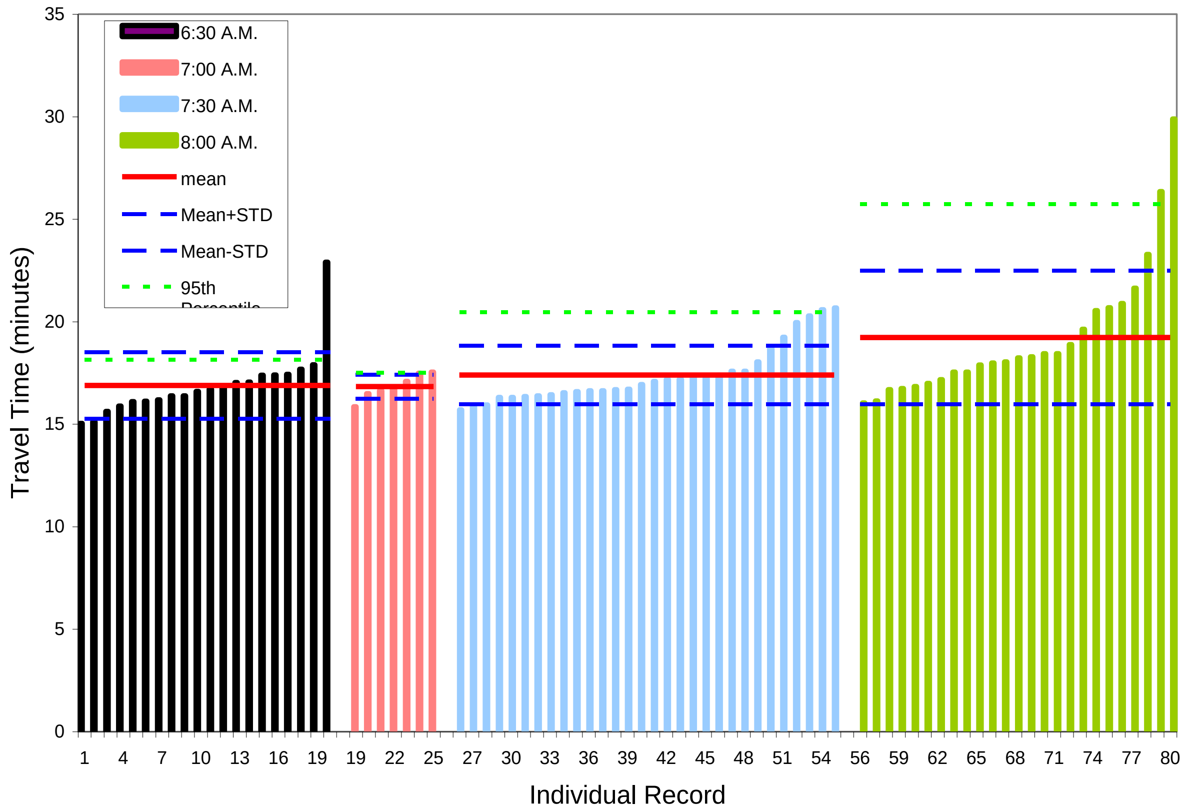


Figure 27. Path Travel Time Distribution by Departure Time Period (NJ 24 & I-78)

A summary of the statistical analysis results for NJ 24 & I-78 is shown in Table 13.

Table 13 - Path Travel Time Reliability Indices per Departure Time (NJ 24 & I-78)

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	the 95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	20	16:54	1:36	0.09	18:15	8.0	15:18	22:54
6:45-7:15	7	16:48	0:36	0.03	17:31	4.3	15:49	17:30
7:15-7:45	30	17:24	1:24	0.08	20:25	17.3	15:42	20:40
7:45-8:15	25	19:12	3:18	0.17	25:42	33.9	16:06	29:17

Travel Time Analysis for US 46 & NJ 3

The studied segment of US 46 & NJ 3 is 13.76 miles and consists of 8 nodes. It starts at the interchange of US 46 and NJ 23 and ends at the interchange of NJ 3 and NJ 495. Table 14 summarizes the corresponding spatial information.

Table 14 - Node Location and Coordinates on US 46 & NJ 3 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 46	1	56.7		-74.240614	40.894883	near NJ 23
	2	57.58	0.88*	-74.224136	40.892670	@ NJ 62
	3	60.24	2.66	-74.189700	40.871118	@ NJ 3 MP 0.0
NJ 3	4	1.53	1.53	-74.175650	40.852595	@ INT GSP
	5	4.89	3.36	-74.125150	40.823579	@ NJ 21
	6	6.39	1.50	-74.101762	40.811121	@ NJ 17
	7	8.14	1.75	-74.072627	40.802352	@ I-95W
	8	10.22	2.08	-73.974483	40.864962	near NJ-495
Total	-	-	13.76	-	-	-

*: Link distance from node 1 to node 2

Figure 28 shows the mean cumulative travel time for nine moving mean departure times. The mean path travel time was more than 28 minutes for departures at 7:00 A.M., while it was 17 minutes 40 seconds for departures at 6:45 A.M. This illustrates that the travel time for trips departing at 7:00 A.M. was significantly impacted by downstream traffic congestion between nodes 4 and 5 where downstream capacity constraints impact traffic flow.

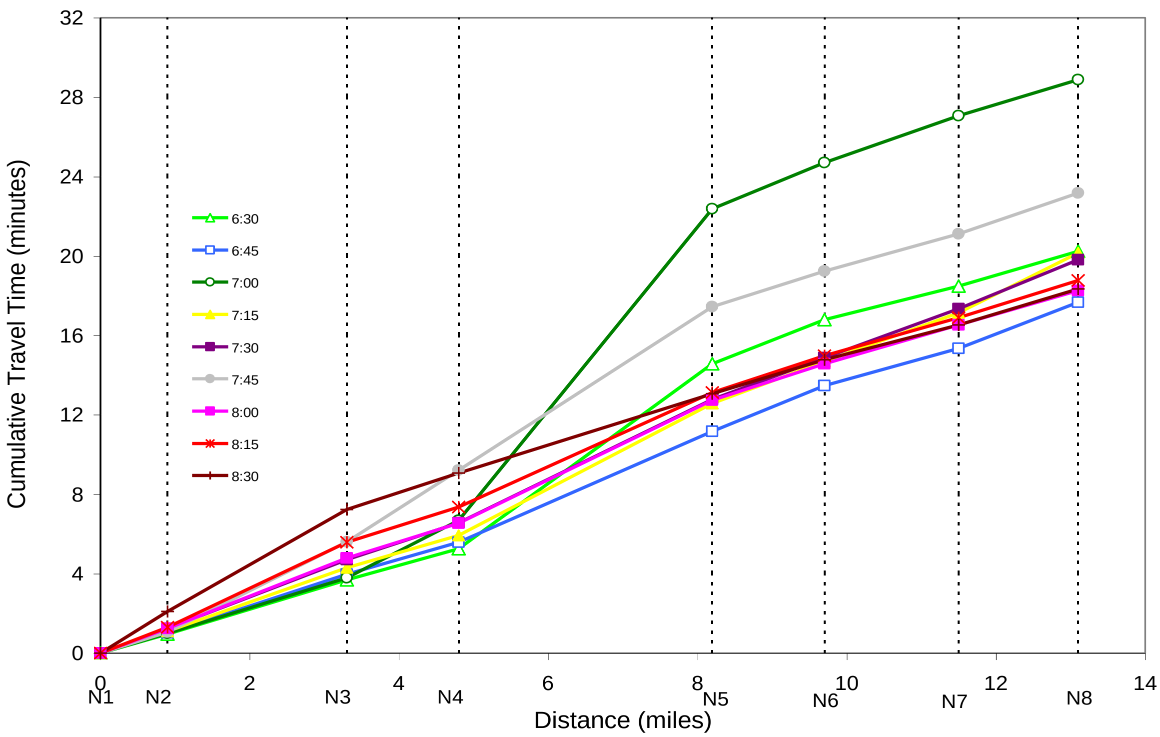


Figure 28. Travel Times for Different Departure Time Periods (US 46 & NJ 3)

Figure 29 illustrates the difference between cumulative path-based standard deviation and link-based standard deviation of travel time. As the travel distance increased, the difference between cumulative path-based standard deviation and link-based standard deviation also increased. The difference between cumulative link-based and path-based standard deviation was negligible from node 1 to 3, but the difference was approximately 3.4 minutes at node 8.

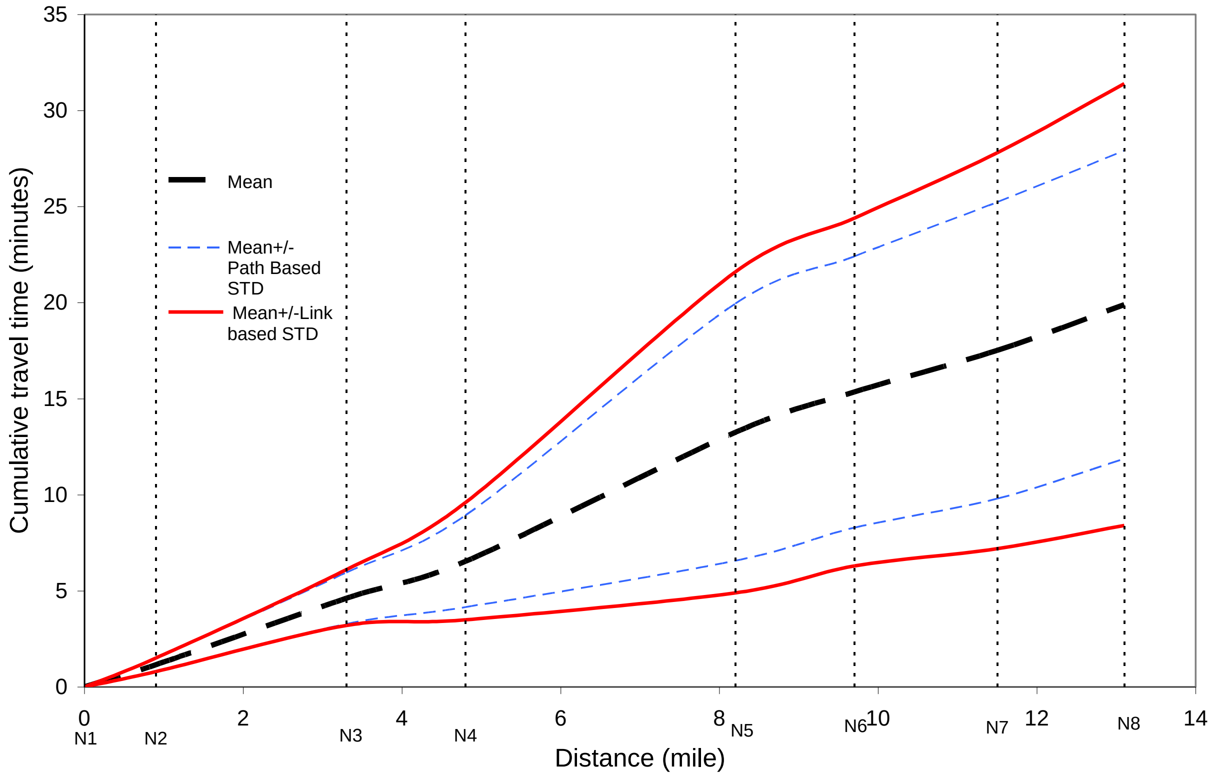


Figure 29. Travel Time Variation with Link-Based vs. Path- Based Data (US 46 & NJ 3)

Figure 30 shows the mean speed on each link based on moving mean departure time and compares the mean link speed with the standard deviation. As shown in the figure, a significant speed variation by link and departure time is observed. The speed on link 4 is comparatively lower than on the other links, and the speed per departure time on every link is varying irregularly. The mean link speed was found to be very sensitive to link and departure time on US 46 & NJ 3. Specifically, the speed variation on links 4 and 7 is comparatively larger than on the other links.

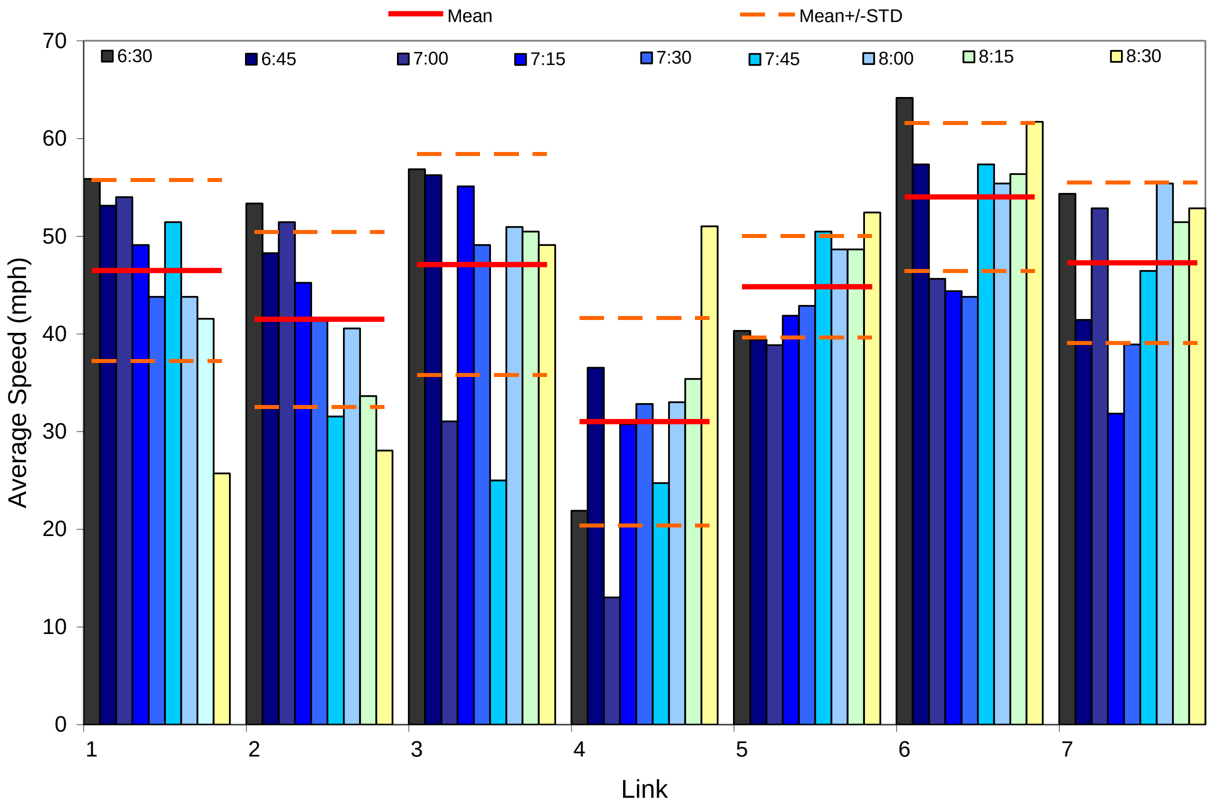


Figure 30. Speed Variation vs. Link for Different Departure Time Periods (US 46 & NJ 3)

All individual path-based travel times as well as the mean, mean plus or minus the standard deviation, and the 95th percentile travel time are displayed in Figure 31. The travel times of five records are greater than the mean plus the standard deviation, and four of them are also greater than the 95th percentile travel time. This is due to congestion observed between node 4 and 5, which is a result of a change in the roadway geometry from three to two lanes (US 46 and NJ 3 merge section).

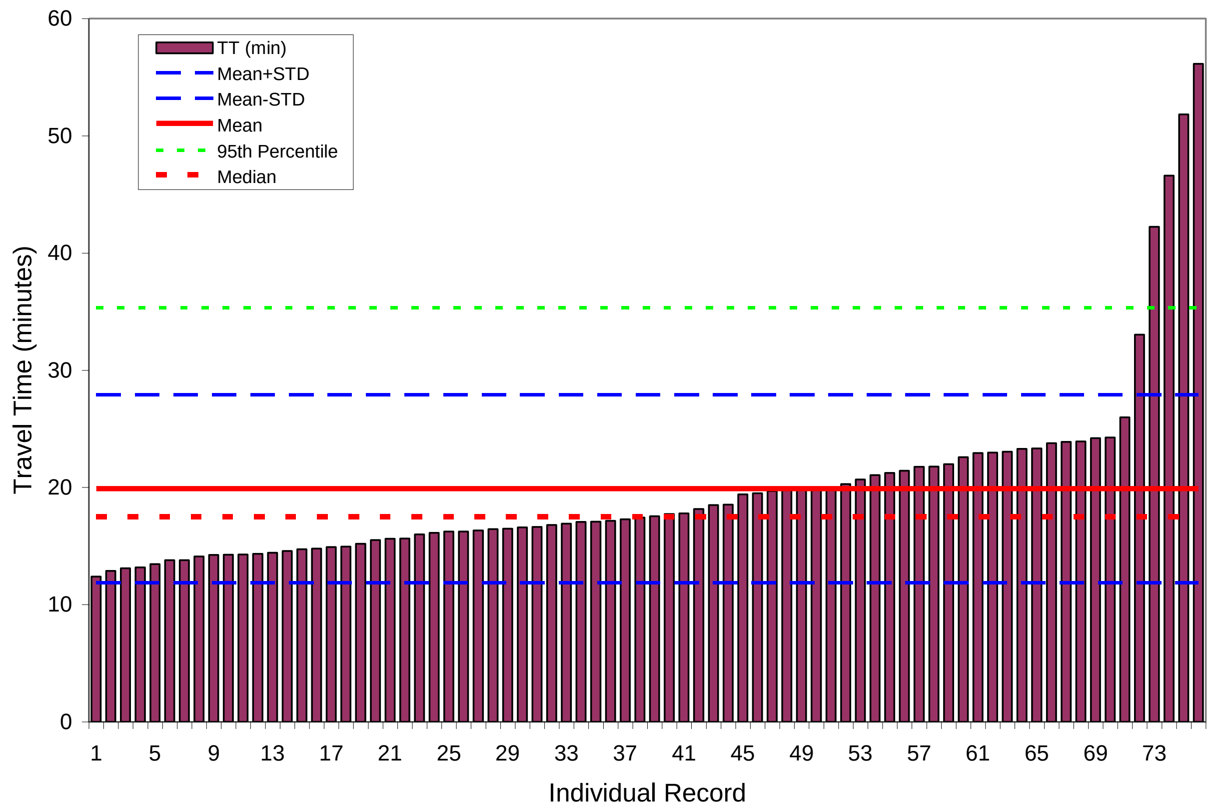


Figure 31. Path Travel Time Distribution (US 46 & NJ 3)

By rearranging the total path-based travel time data in Figure 32 to be organized by departure time, it was found that the five records with the greatest delay were observed in the departure times occurring between 7:00 A.M. and 7:30 A.M., and resulted in an increase of the standard deviation and the 95th percentile travel time of the two 15-minute departure time periods.

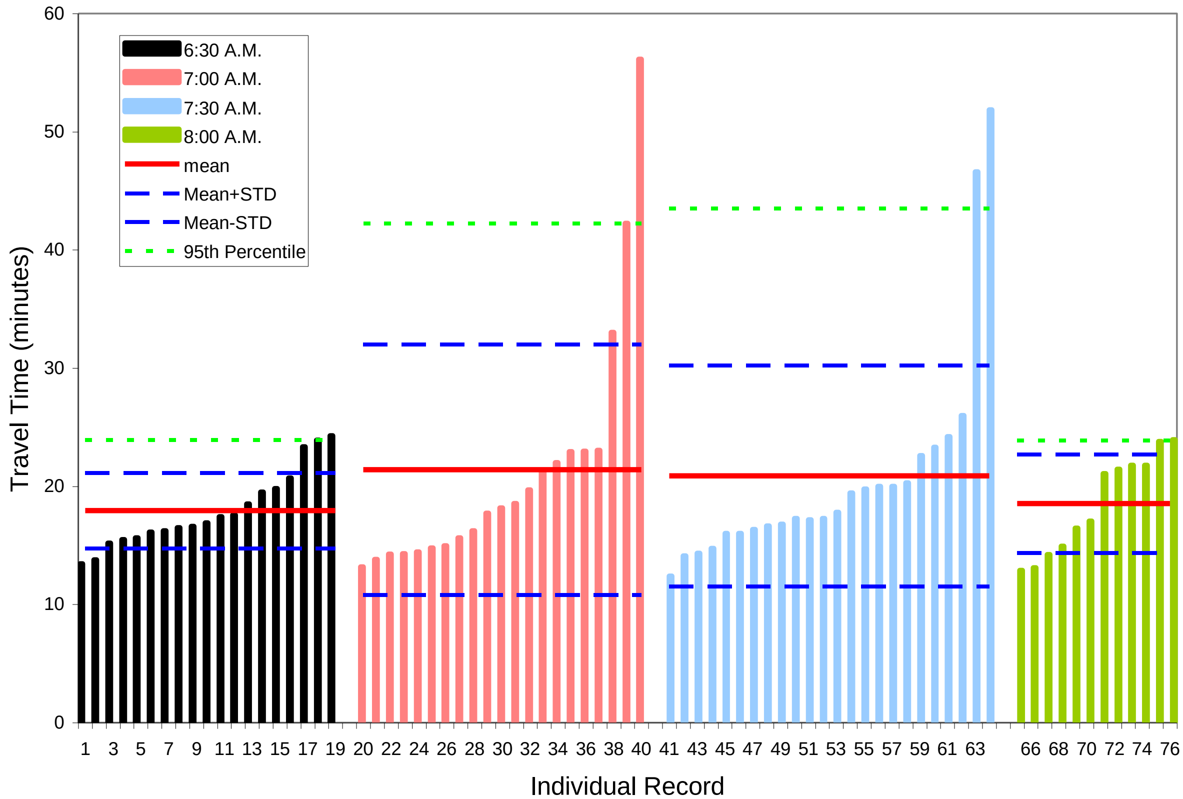


Figure 32. Path Travel Time Distribution by Departure Time Period (US 46 & NJ 3)

A summary of statistical analysis results for US 46 & NJ 3 is shown in Table 15.

Table 15 - Path Travel Time Reliability Indices per Departure Time (US 46 & NJ 3)

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	the 95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	19	17:56	03:13	0.18	23:55	33.4	13:27	24:16
6:45-7:15	21	21:24	10:35	0.49	42:14	97.4	13:11	56:08
7:15-7:45	24	20:48	09:25	0.45	43:30	109.1	12:23	51:50
7:45-8:15*	12	18:34	04:20	0.23	23:21	25.8	12:53	23:56

*: includes 8:15- 8:45 A.M. data

Travel Time Analysis for US 22

The studied segment of US 22 is 23.4 miles long and consists of 8 nodes. It starts at the interchange of US 22 and I-287 and ends at the interchange of US 22 and US 1&9. Table 16 summarizes the spatial characteristics of the segment.

Table 16 - Node Location and Coordinates on US 22 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 22	1	36.82	-	-74.563264	40.575047	near I-287
	2	39.01	2.19*	-74.526003	40.579142	@ CR 527
	3	42.16	3.15	-74.475739	40.603525	@ CR 529
	4	44.87	2.71	-74.438100	40.626730	@ CR 531
	5	47.41	2.54	-74.402768	40.654455	@ CR 655
	6	52.04	4.63	-74.328161	40.684941	@ CR 509A
	7	55.26	3.22	-74.267916	40.691901	@ INT-GSP
	8	60.22	4.96	-74.187325	40.708054	near US 1&9
Total	-	-	23.40	-	-	-

*: Link distance from node 1 to node 2

The mean path-based cumulative travel time for moving mean departure times is shown in Figure 33. The longest mean travel time (40 minutes 48 seconds) was observed during the departure time interval of 7:45 A.M., while the shortest travel time (28 minutes 48 seconds) was observed during the departure time interval of 6:30 A.M.

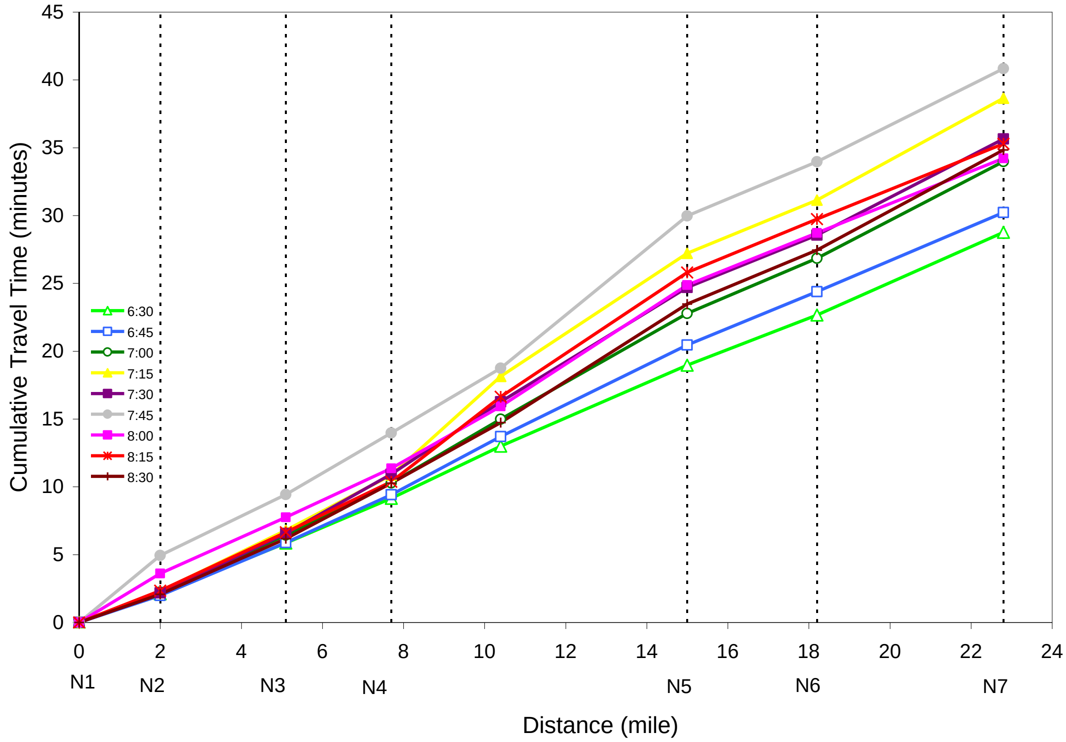


Figure 33. Travel Times for Different Departure Time Periods (US 22)

From Figure 34 one can observe that the difference between cumulative path-based standard deviation and link-based standard deviation severely increased from node 3 to 8. The difference between cumulative link-based and path-based standard deviation was negligible from node 1 to 3, but the overall difference was approximately 5 minutes at node 8.

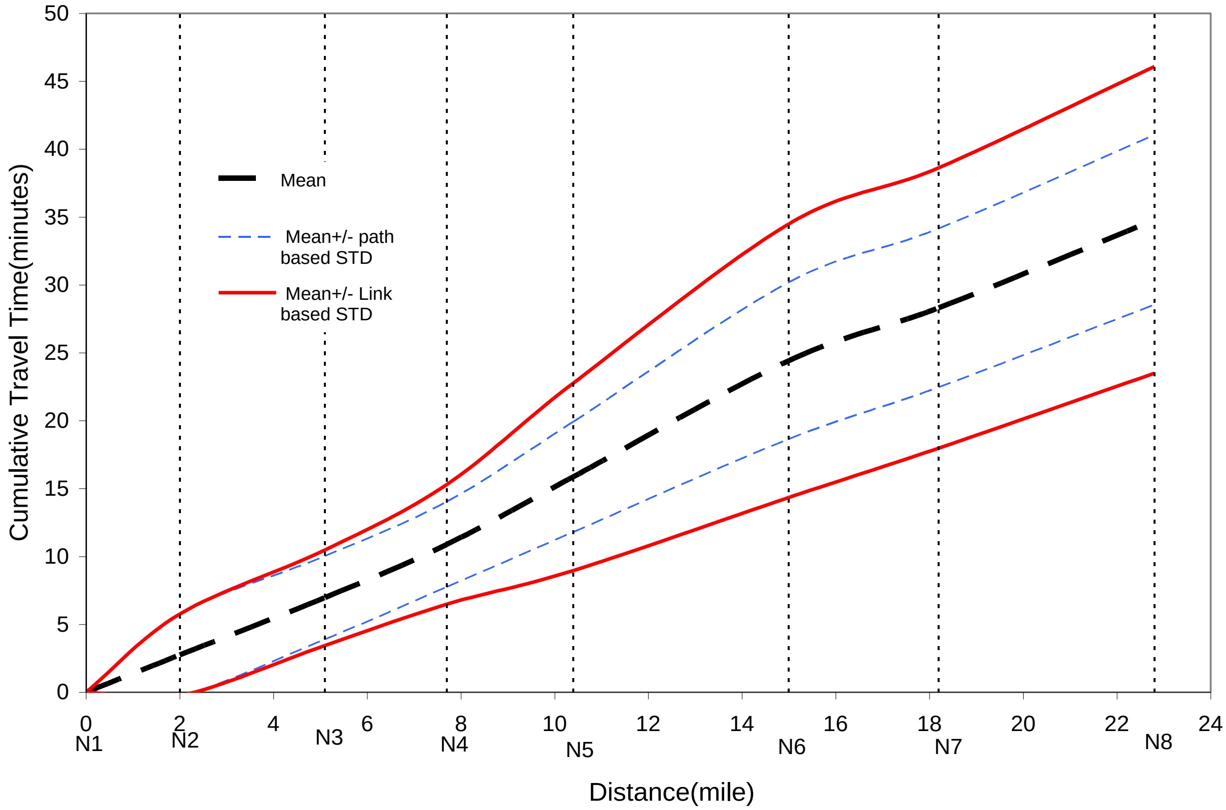


Figure 34. Travel Time Variation with Link-Based vs. Path- Based Data (US 22)

Figure 35 shows a significant speed variation by link and departure time. The speed on links 1, 2, 3, 4, 5 and 7 vary substantially by departure time, while the speed on link 6 is almost constant.

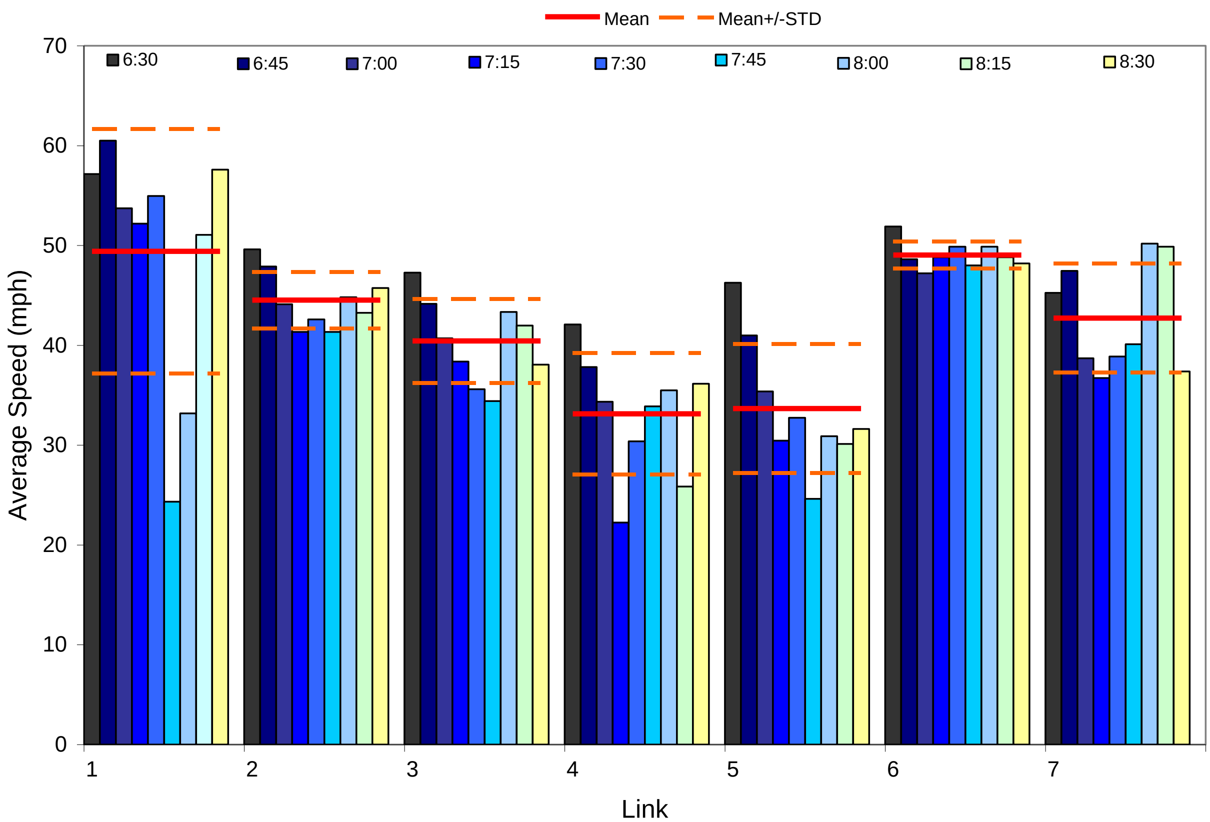


Figure 35. Speed Variation vs. Link for Different Departure Time Periods (US 22)

In Figure 36, the vehicle individual path-based travel time distribution and the associated parameters of the mean, mean plus or minus standard deviation, the 95th percentile travel time are illustrated. As shown in Figure 36, 11 records are greater than the mean plus standard deviation where four of them are greater than the 95th percentile of individual path travel time.

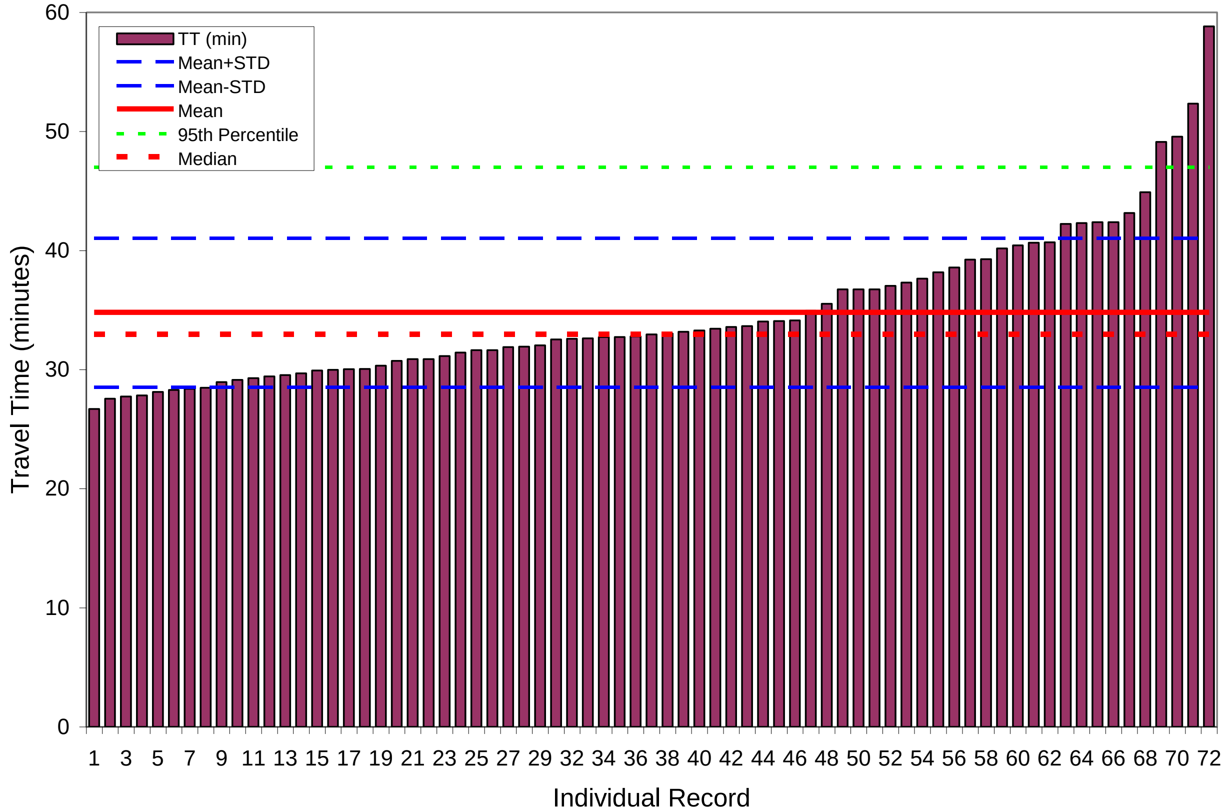


Figure 36. Path Travel Time Distribution (US 22)

Figure 37 shows the path-based travel time distributions for the different departure time periods. As shown in Figure 37, the time periods of 7:00, 7:30 and 8:00 A.M. had remarkable travel time variation due to outliers while the time period of 6:30 A.M. had the smallest travel time variation.

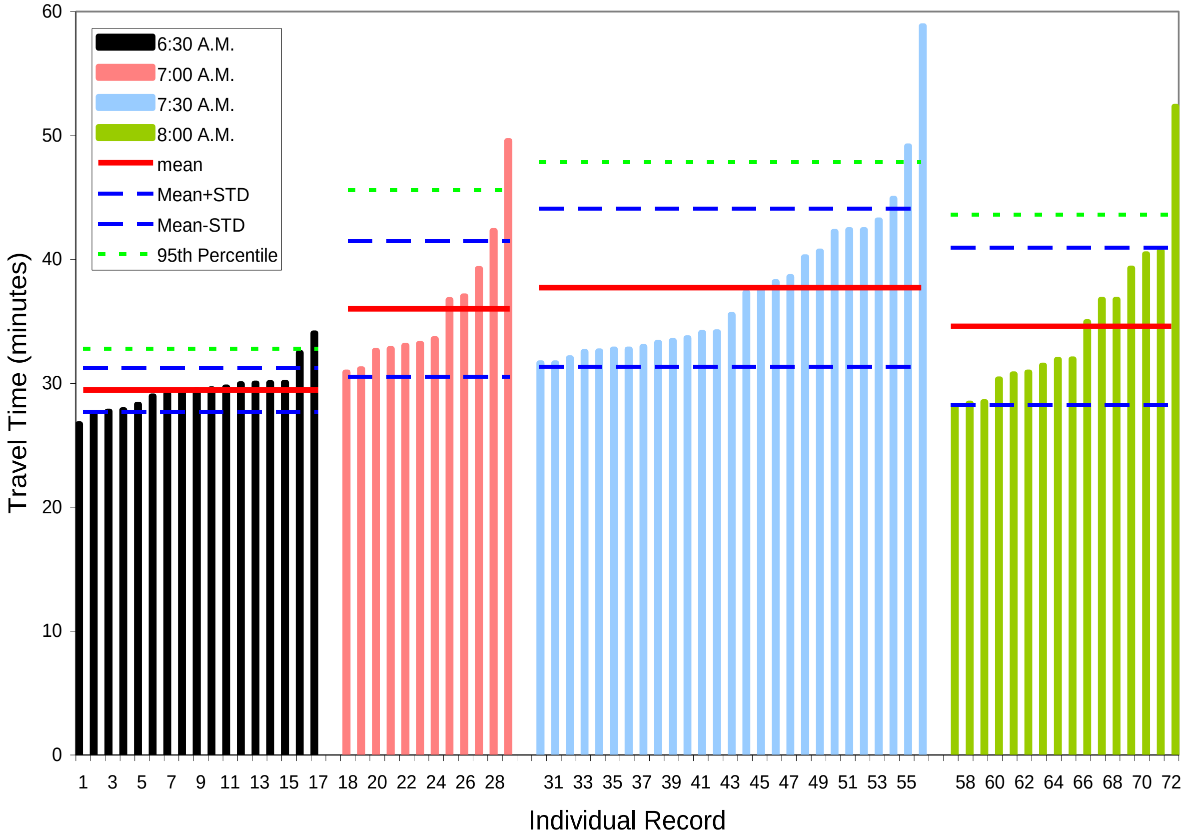


Figure 37. Path Travel Time Distribution by Departure Time Period (US 22)

A summary of statistical analysis results for US 22 is shown in Table 17.

Table 17 - Path Travel Time Reliability Indices per Departure Time (US 22)

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	17	29:24	1:48	0.06	32:47	11.3	26:43	34:00
6:45-7:15	12	36:18	5:36	0.16	45:41	26.5	30:54	49:12
7:15-7:45	27	37:36	6:18	0.17	47:52	26.9	31:36	58:49
7:45-8:15	16	34:48	6:36	0.19	43:36	26.1	28:24	52:18

Travel Time Analysis for I-287 (A)

The segment of I-287 (A) is 21.17 miles long and begins at the interchange of I-95 and I-287 and ends at the interchange of I-78 and I-287. The segment consists of 6 nodes. Detailed geographical node information such as mile posts, geo-coordinates, and interchanges, is summarized in Table 18.

Table 18 - Node Location and Coordinates on I-287 (A) Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
I-287(A) (I-95 to I-78)	1	0.00	-	-74.337098	40.528682	near I-95
	2	0.93	0.93*	-74.354263	40.528320	@ US 1
	3	10.48	9.55	-74.516936	40.539186	@ CR 527
	4	14.24	3.76	-74.567593	40.574790	@ US 22
	5	17.66	3.42	-74.623300	40.595095	@ US 202&206
	6	21.17	3.51	-74.645679	40.642668	near I-78
Total	-	-	21.17	-	-	-

*: Link distance from node 1 to node 2

Figure 38 shows the mean cumulative travel time for moving mean departure times. The longest mean travel time was 30 minutes 36 seconds attained through an 8:15 A.M. departure time, while the shortest travel time was 19 minutes 2 seconds attained through a 7:00 A.M. departure time.

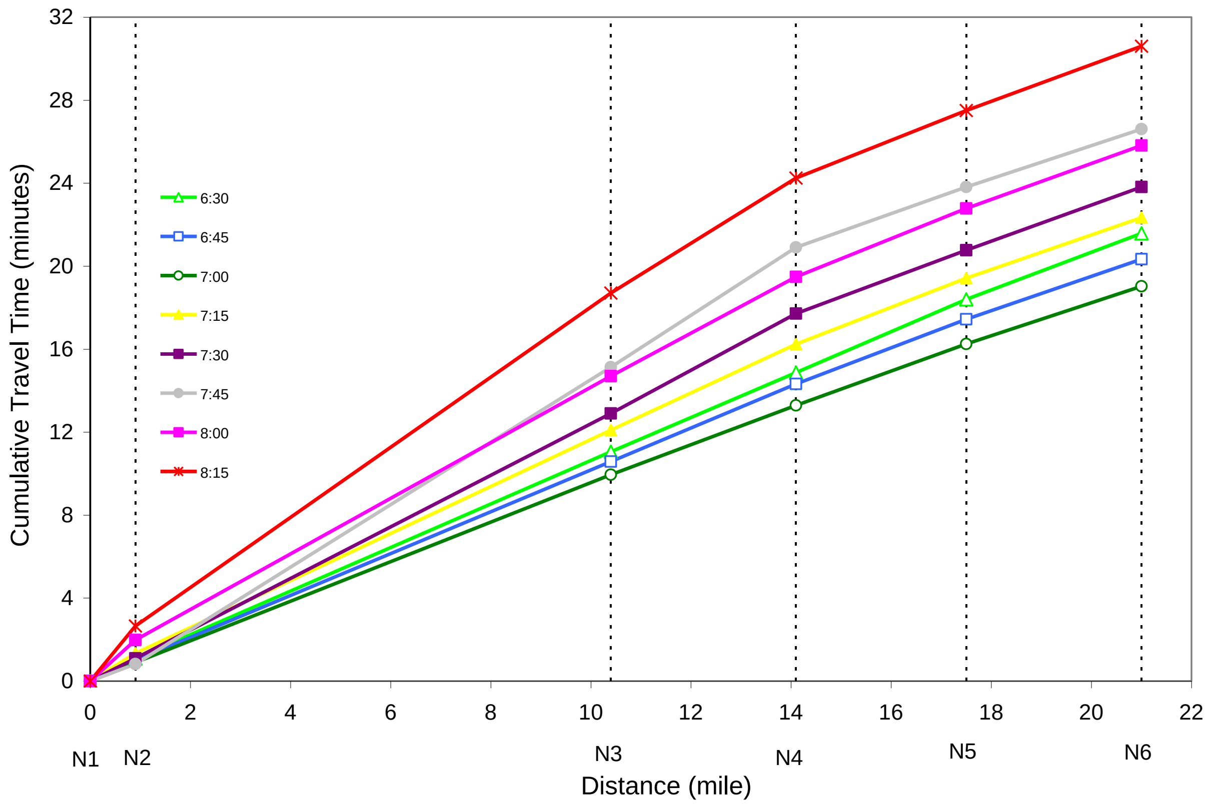


Figure 38. Travel Times for Different Departure Time Periods [I-287(A)]

Figure 39 illustrates the difference between the cumulative path-based standard deviation of travel time and the link-based standard deviation. As travel distance increases, the difference between cumulative path-based standard deviation and link-based standard deviation gradually increases. The cumulative link-based standard deviation is clearly larger than the path-based standard deviation.

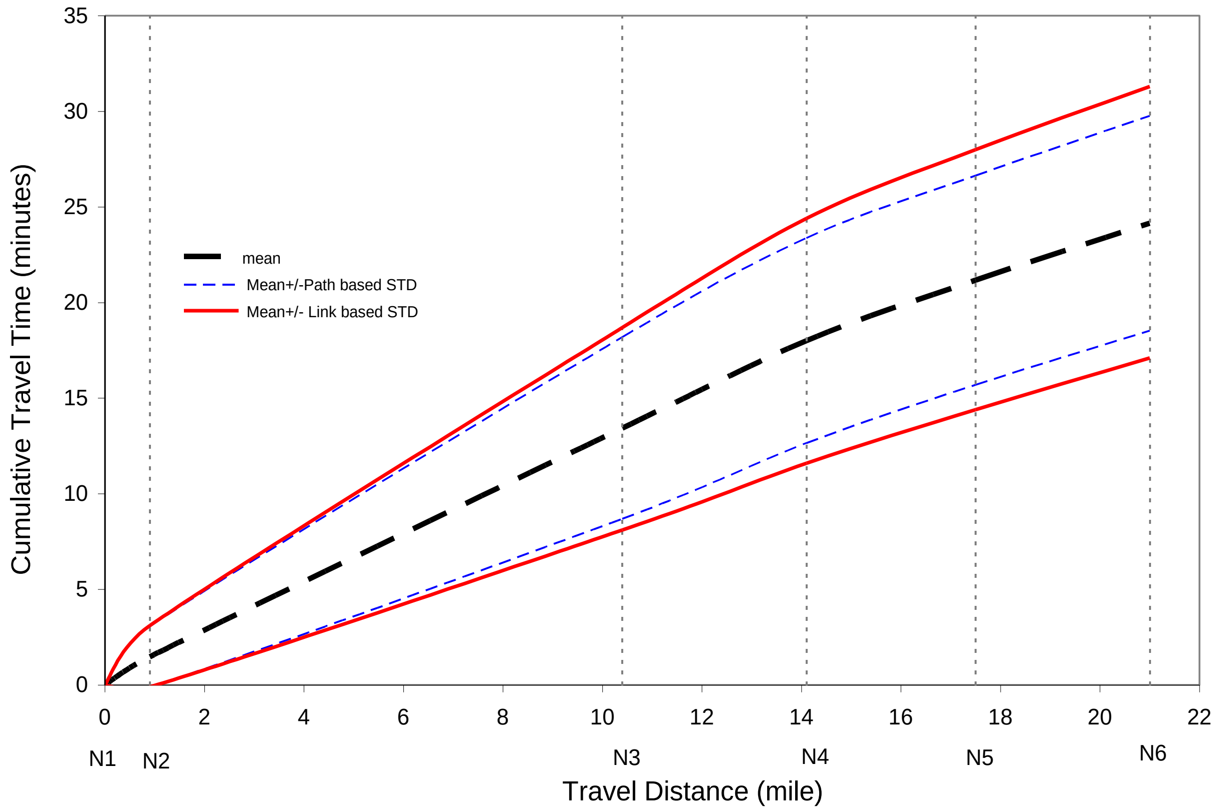


Figure 39.Travel Time Variation with Link-Based vs. Path- Based Data [I-287(A)]

The mean link speed for moving mean departure times are shown in Figure 40. A considerable speed variation by departure time is observed on links 1, 2, and 3. In particular, the speed difference between 8:00 and 8:30 A.M. departure times on link 1 is more than 44 mph. The speed variations on link 1 and 2 were larger than on the other links, and link 5 has the highest link speed.

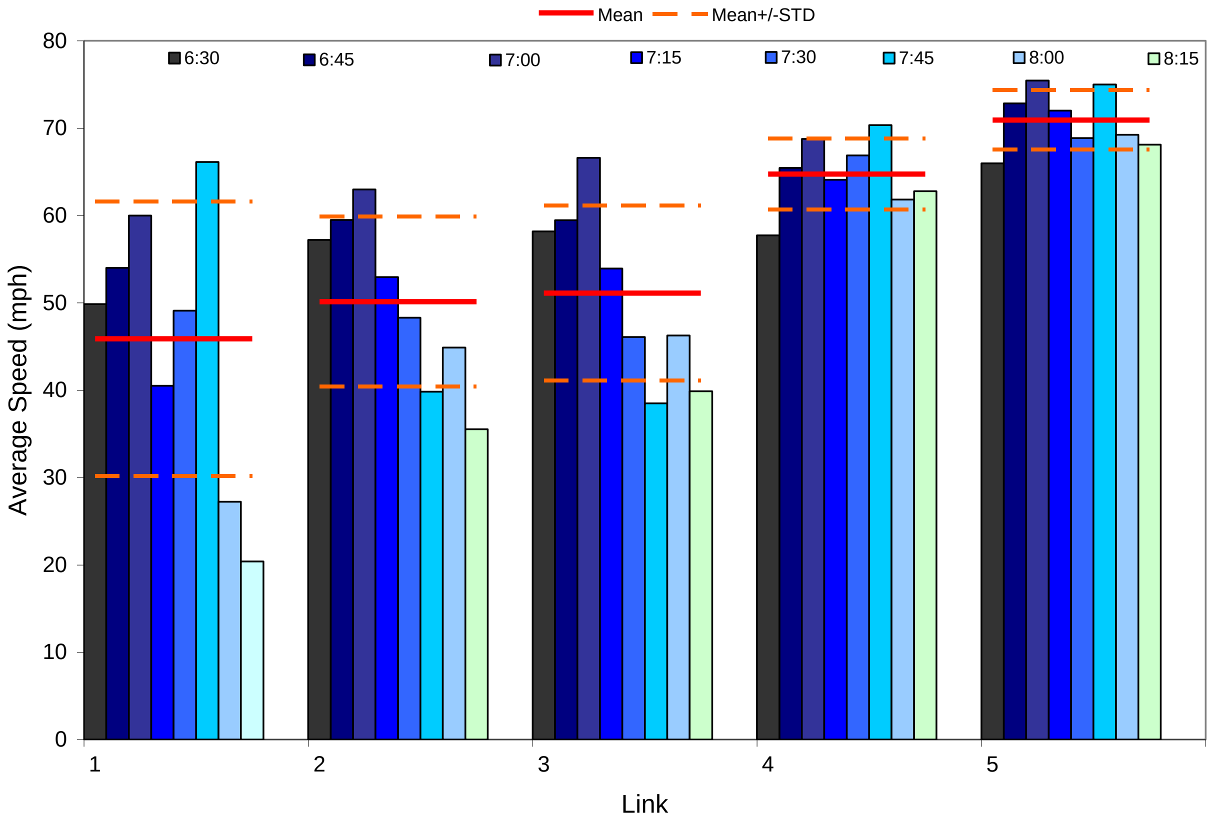


Figure 40. Speed Variation vs. Link for Different Departure Time Periods [I-287 (A)]

Path-based travel time distribution was calculated and is shown in Figure 41. All individual travel times as well as the mean, mean plus or minus standard deviation, and the 95th percentile travel time are displayed. In considering that the 95th percentile travel time is the threshold travel time, the travel time of 16 collected data was found to be greater than the mean plus the standard deviation and 5 of records were also greater than the 95th percentile travel time. Since no incident data was reported during the data collection period, the 16 records of travel time delay were probably a result of the merging traffic volume and the geographical condition between nodes 1 and 2 as well as congestion on links 1 through 4.

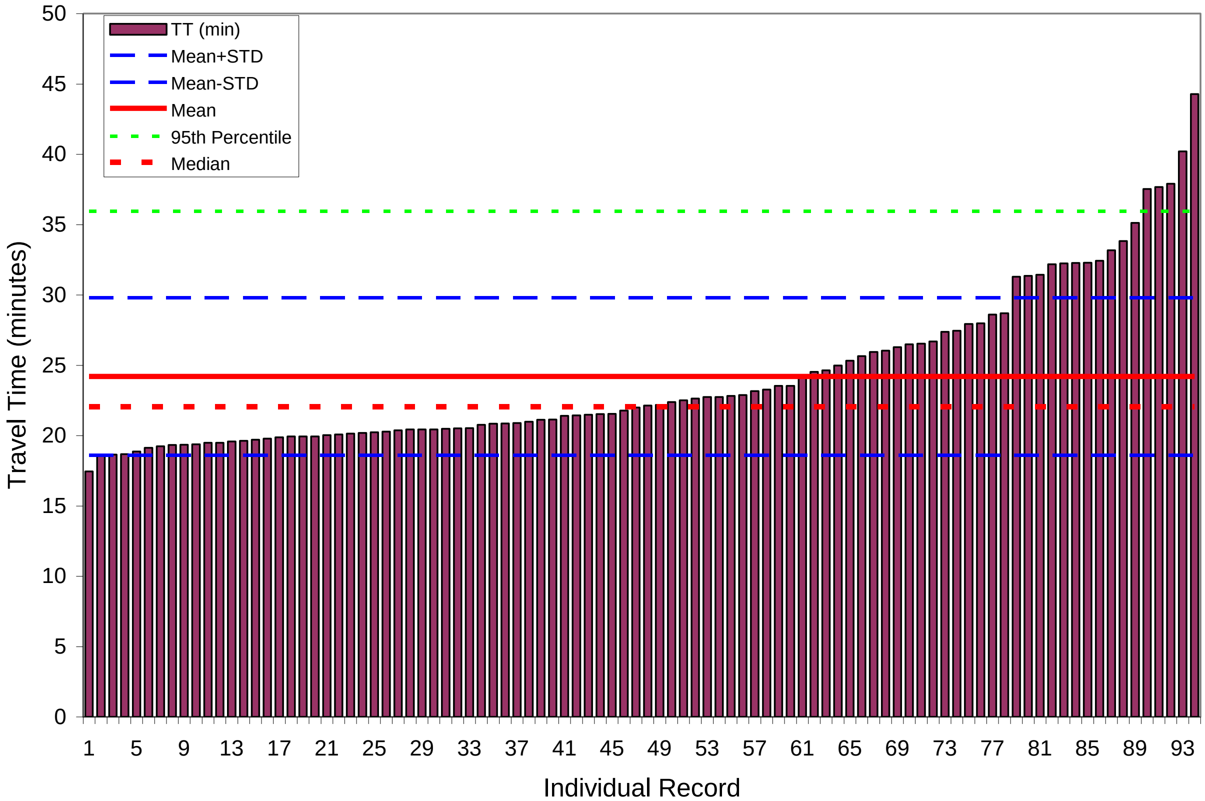


Figure 41. Path Travel Time Distribution [I-287 (A)]

The path-travel time distribution records in Figure 40 were reorganized by departure time period and presented in Figure 42. From Figure 42, one can see that the delay records observed in Figure 41 were from departure times of 7:00, 7:30, and 8:00 A.M. Thus, there is a significant travel time variation for these departure time periods. In particular, two travel time data for 7:00 A.M. and one travel time data for 8:00 A.M. seriously impacted the statistical analysis.

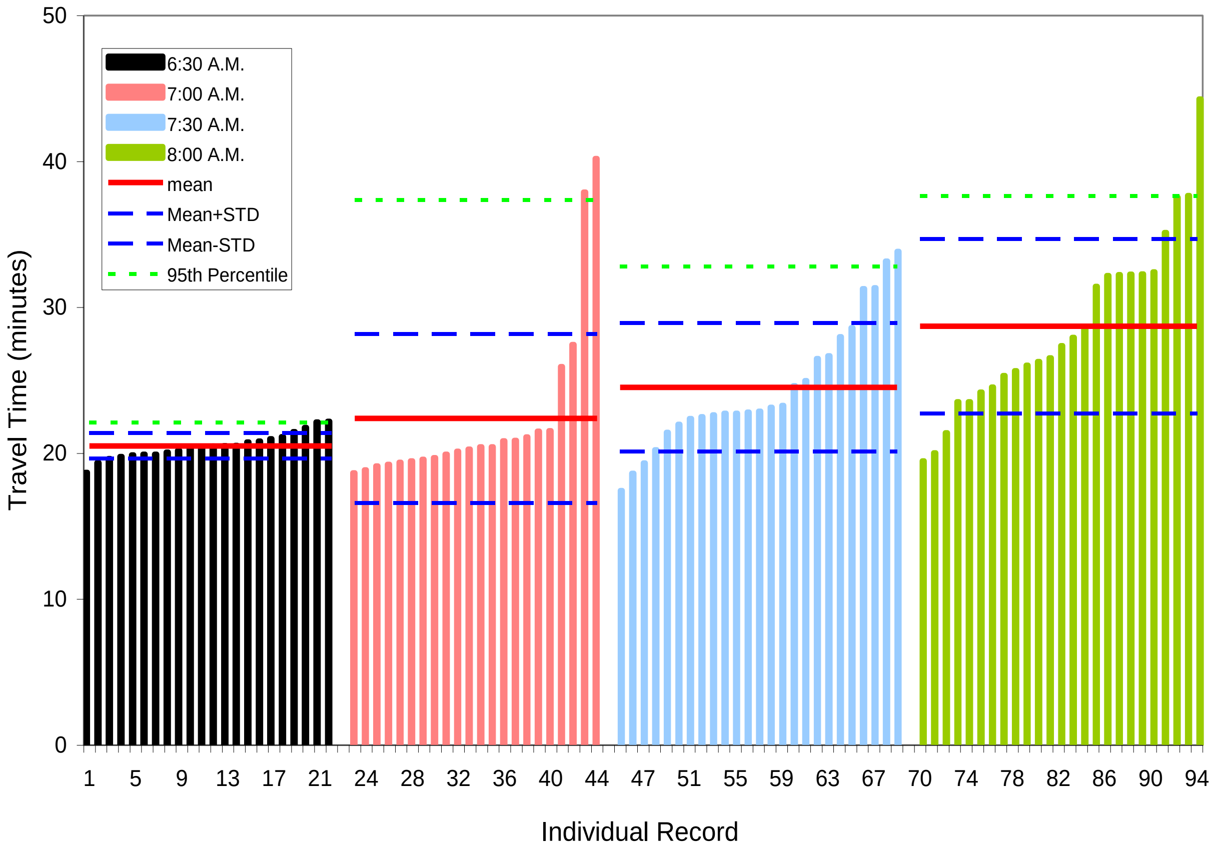


Figure 42. Path Travel Time Distribution by Departure Time Period [I-287 (A)]

A summary of statistical analysis results for I-287 (A) is shown in Table 19.

Table 19 - Path Travel Time Reliability Indices per Departure Time [I-287 (A)]

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	22	20:27	0:52	0.04	22:06	7.9	18:41	22:11
6:45-7:15	22	22:11	5:44	0.26	36:51	66.9	18:39	40:09
7:15-7:45	25	24:21	4:20	0.18	32:38	33.7	17:27	33:50
7:45-8:15	25	28:34	5:52	0.21	37:38	31.1	19:29	44:17

Travel Time Analysis for I-287 (B)

The segment of I-287 (B) is 20.85 miles and consists of 6 nodes. It begins at the interchange of I-78 and I-287 and ends at the interchange of I-80 and I-287. Table 20 presents the characteristics of this segment.

Table 20 - Node Location and Coordinates on I-287 (B) Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
I-287(B) (I-78 to I-80)	1	21.17	-	-74.645679	40.642668	@ I-78
	2	26.48	5.31*	-74.577602	40.688970	@ CR 525
	3	35.89	9.41	-74.469169	40.788571	@ NJ 124
	4	38.00	2.11	-74.468390	40.795550	@ NJ 24
	5	39.55	1.55	-74.438251	40.832549	@ NJ 10
	6	42.02	2.47	-74.418390	40.860957	near I-80
Total	-	-	20.85	-	-	-

*: Link distance from node 1 to node 2

Figure 43 shows the mean cumulative travel time for moving mean departure times. The longest mean travel time was 28 minutes attained during a 7:45 A.M. departure time, while the shortest travel time was 16 minutes 48 seconds attained during a 6:30 A.M. departure time. Additionally, the mean travel time on link 4 is greater than that of other links due to increased traffic from NJ 24.

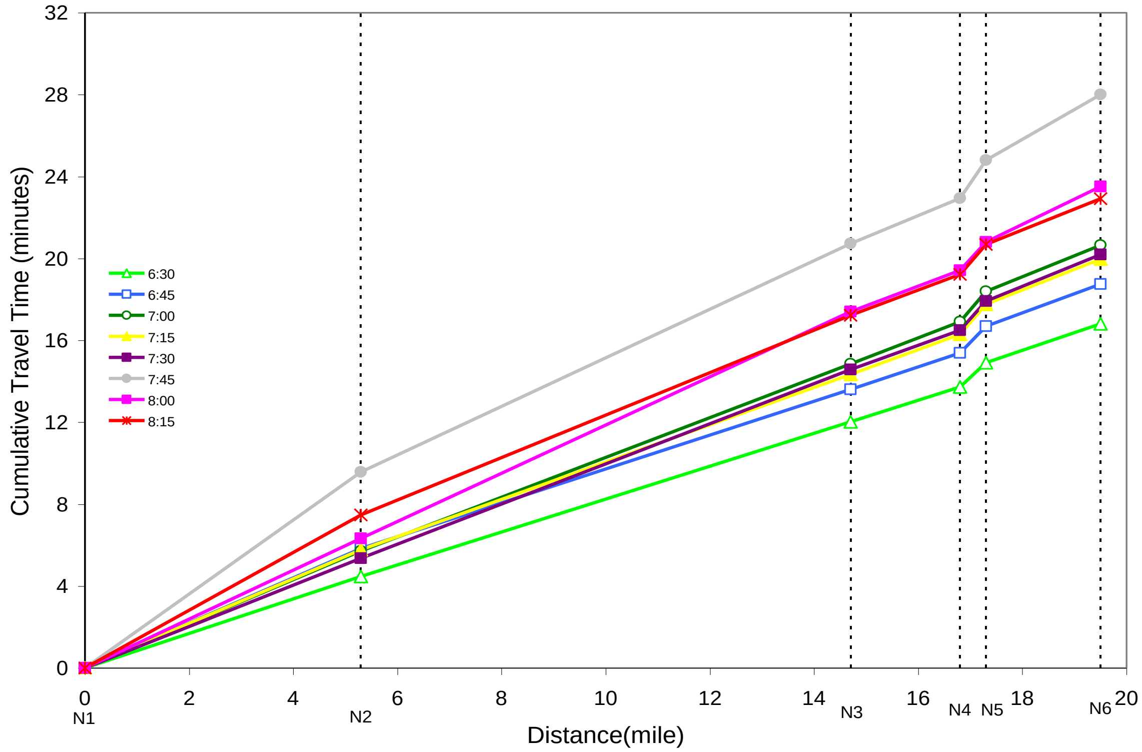


Figure 43. Travel Times for Different Departure Time Periods [I-287(B)]

In Figure 44 the difference between the cumulative path-based standard deviation of travel time and the link-based standard deviation is illustrated. As travel distance increases, the difference between cumulative path-based standard deviation and link-based standard deviation gradually increases, but the difference of two standard deviations is less than those observed in the other study locations.

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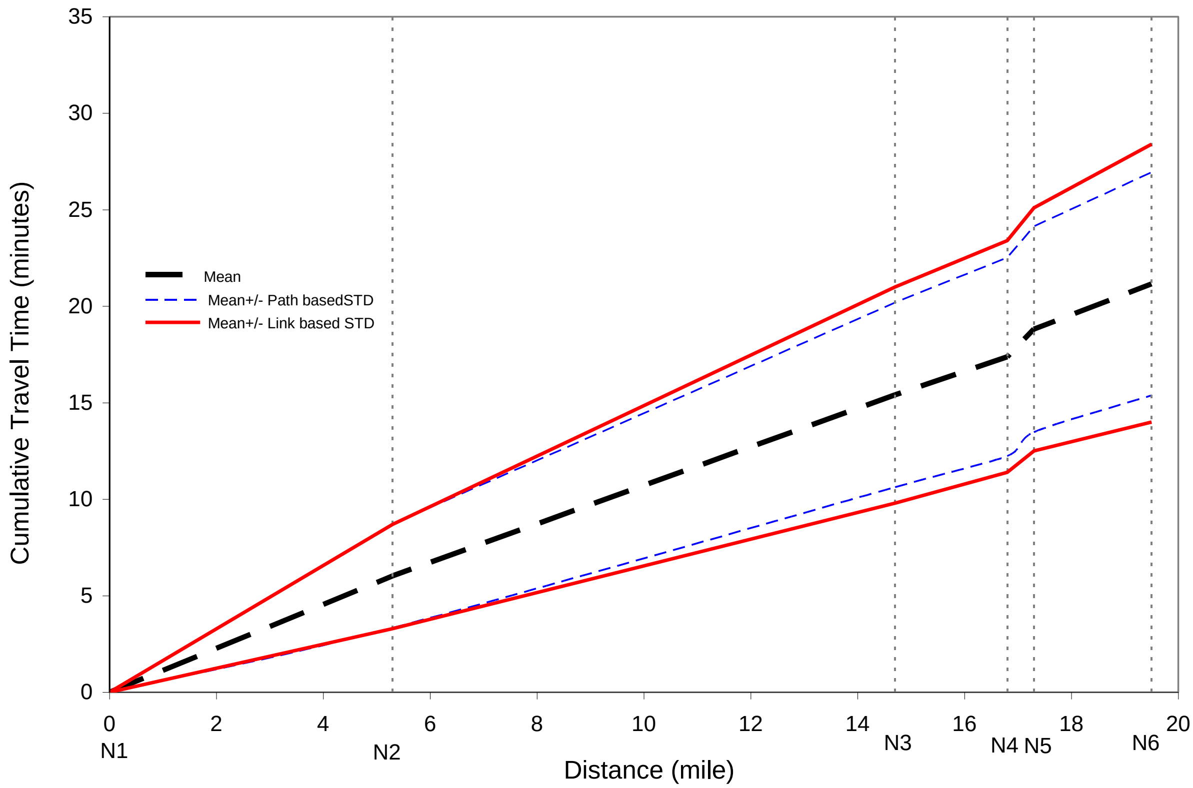


Figure 44.Travel Time Variation with Link-Based vs. Path- Based Data [I-287(B)]

The mean link speed for moving mean departure time is shown in Figure 45. The mean speed on link 4 is considerably lower than the other links due to increased traffic volume from NJ 24. A considerable speed variation by departure time is observed on links 1, 2, 3, and 5. In particular, the speed difference between 6:30 and 7:45 A.M. departure times on link 1 and that between 6:30 and 7:45 A.M. on link 5 were more than 43 mph, respectively.

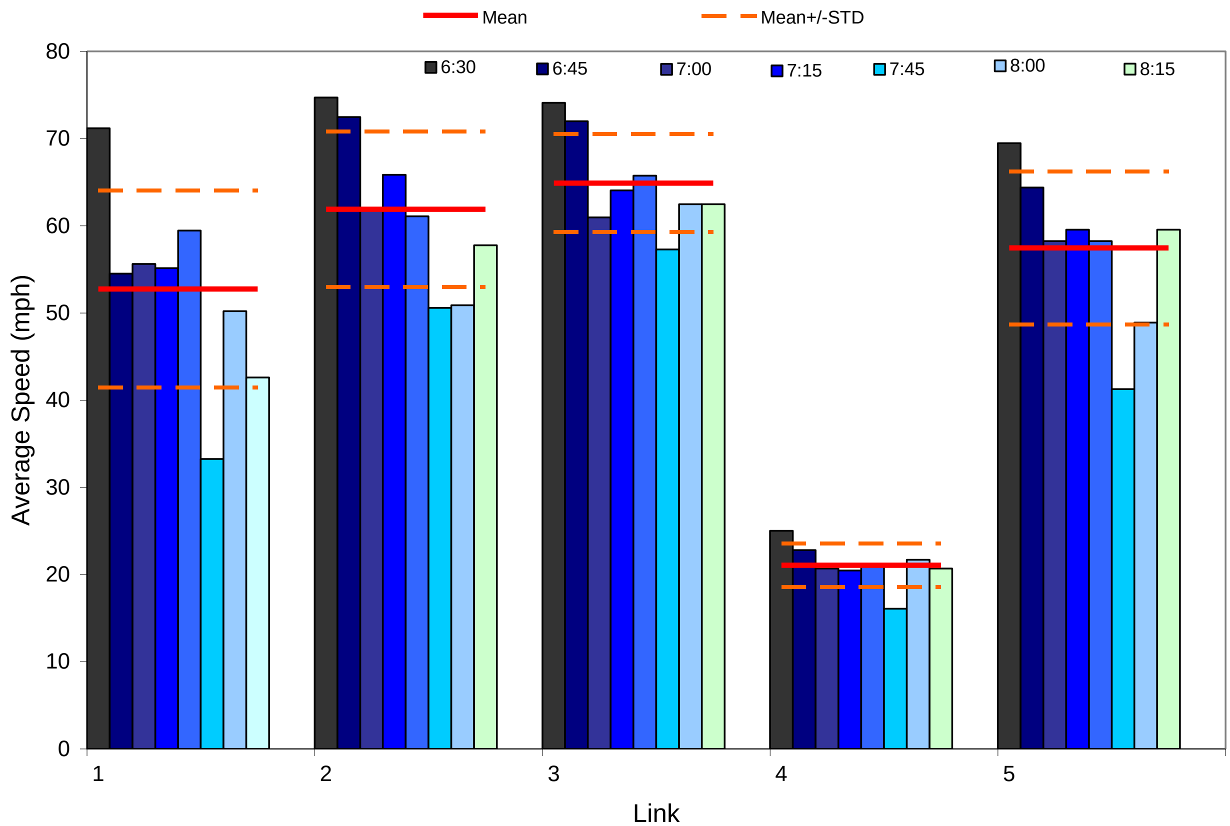


Figure 45. Speed Variation vs. Link for Different Departure Time Periods [I-287 (B)]

The path-based travel time records as well as the mean, mean plus or minus standard deviation, and the 95th percentile travel time for all the records are displayed in Figure 46. When considering the 95th percentile travel time as the threshold travel time, the travel time of 11 collected data was found to be greater than the mean plus the standard deviation and five of the collected data were also greater than the the 95th percentile travel time.

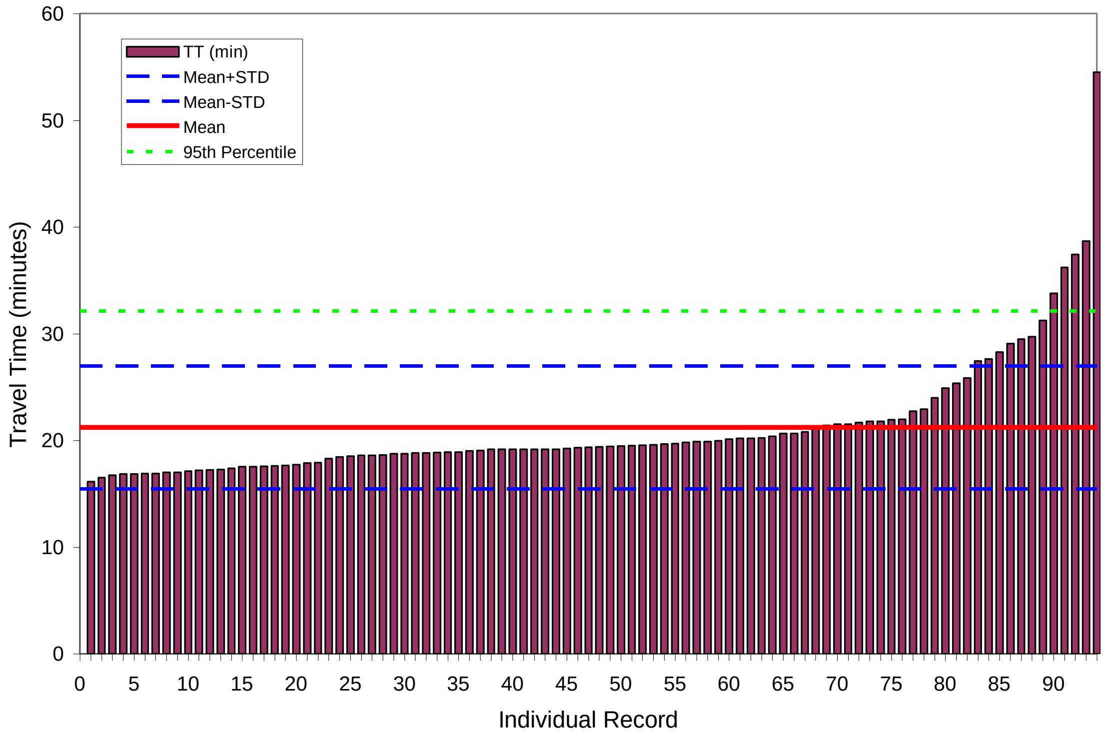


Figure 46. Path Travel Time Distribution [I-287 (B)]

From Figure 47 one can see that the extremely long travel time shown in Figure 46 was observed during a departure time of 7:00 A.M. Travel time variation during the departure time of 8:00 A.M. is greater than that of the other departure time periods. Also, the travel time records greater than the 95th percentile travel time in Figure 46 were originally from the departure times of 6:30, 7:00, and 7:30 A.M.

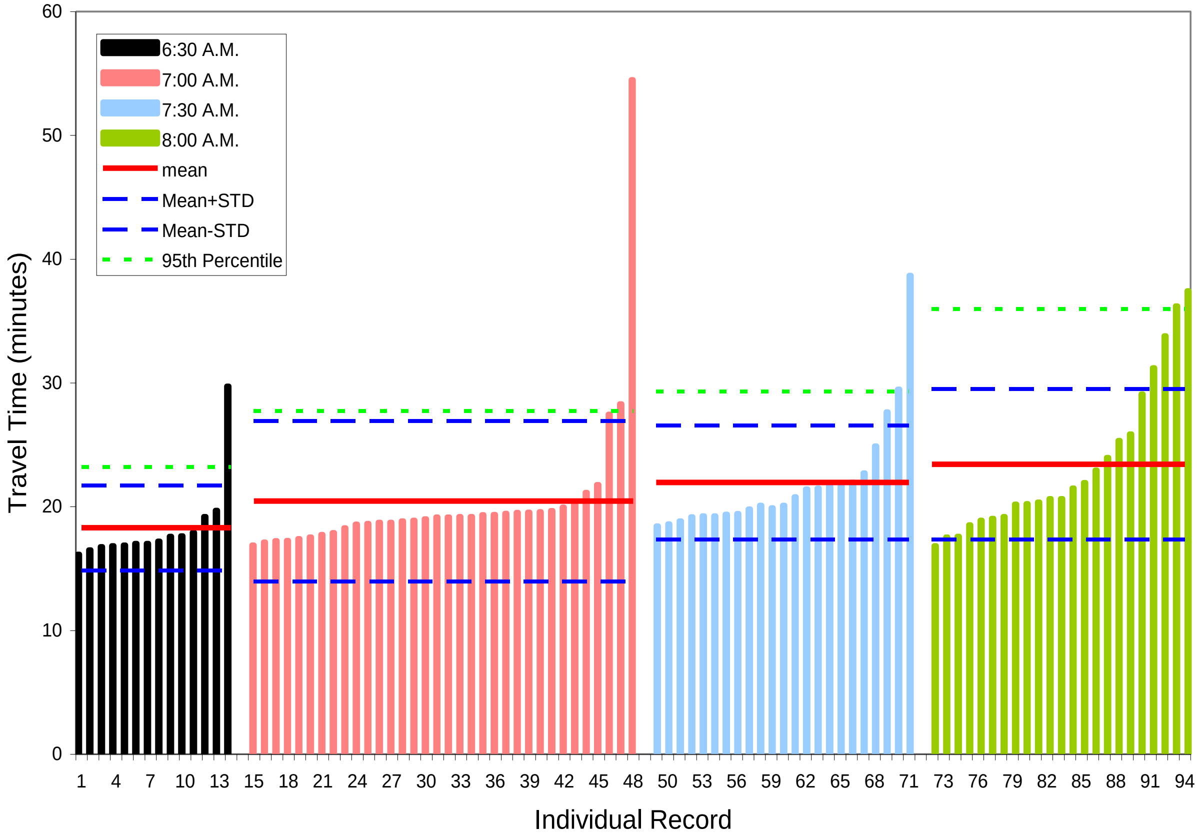


Figure 47. Path Travel Time Distribution by Departure Time Period [I-287 (B)]

The summary of statistical analysis results for I-287(B) is shown in Table 21.

Table 21 - Path Travel Time Reliability Indices per Departure Time [I-287 (B)]

Departure Time (A.M.)	Sample Size	AVG. TT (mm:ss)	STDEV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	24	18:18	3:24	0.19	23:12	26.8	16:06	29:42
6:45-7:15	24	20:24	6:30	0.32	27:14	33.5	16:54	54:30
7:15-7:45	23	21:54	4:24	0.21	29:18	33.8	18:24	38:42
7:45-8:15	23	23:24	6:05	0.26	36:00	53.9	16:48	37:24

Travel Time Analysis for US 1 (C)

The segment of US 1 (C) begins at the interchange of US 1 and I-295 and ends at the interchange of US 1 and US 130. It is 17.88 miles long and consists of 5 nodes. Table 22 presents the characteristics of this segment.

Table 22 - Node Location and Coordinates on US 1 (C) Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 1 (C) (I-295 to US 130)	1	6.76	-	-74.691436	40.287239	near I-295
	2	8.10	1.34*	-74.678777	40.297745	@ CR 533
	3	11.27	3.17	-74.638087	40.331414	@ CR 571
	4	16.47	5.20	-74.571109	40.386518	@ CR 522
	5	24.64	8.17	-74.458659	40.461786	near US 130
Total	-	-	17.88	-	-	-

*: Link distance from node 1 to node 2

Figure 48 shows the mean cumulative travel times for 9 departure time intervals from 6:30 A.M. to 8:30 A.M. with the moving mean method. The mean cumulative travel times ranged between 25 minutes and 29 minutes, showing the time difference slightly between the time periods. The departure time of 8:30 A.M. represented the longest mean travel time of all time periods. In contrast, departures at 7:30 A.M. needed the shortest mean travel time.

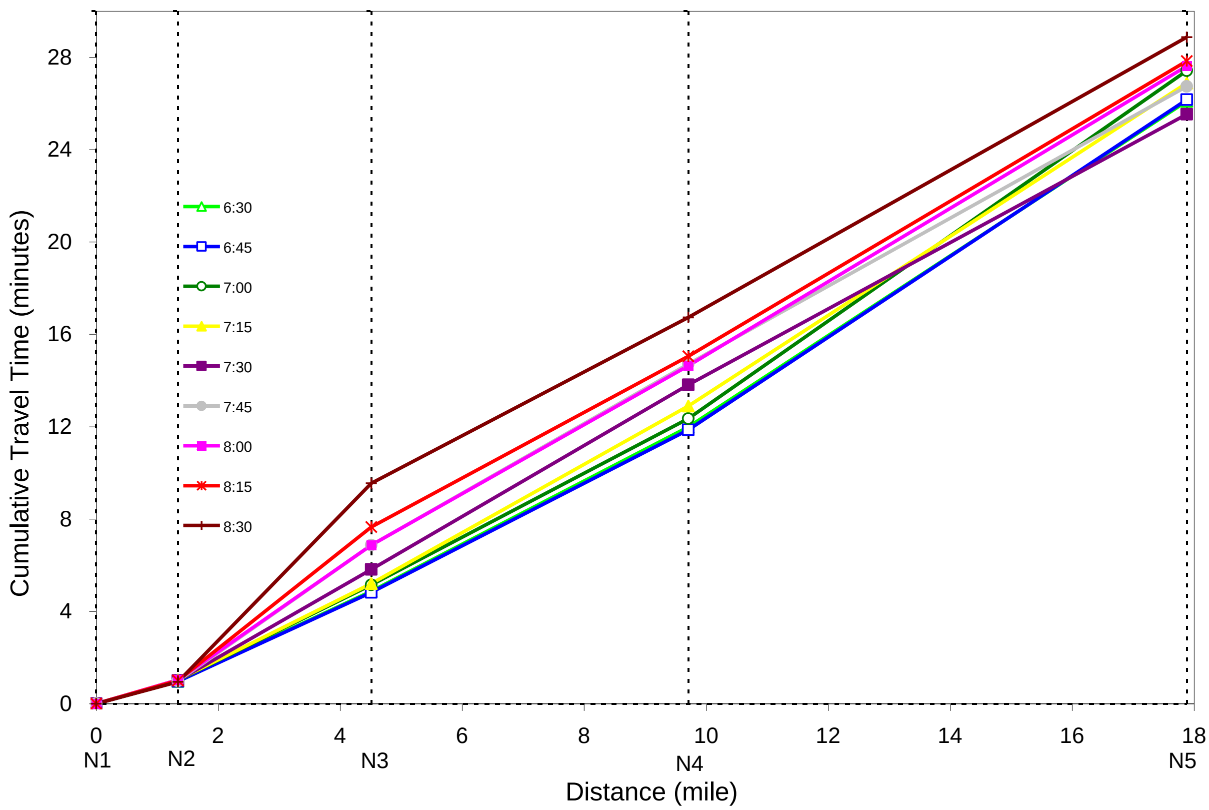


Figure 48. Travel Times for Different Departure Time Periods [US 1 (C)]

The difference between the cumulative path and link-based standard deviations of travel time is presented in Figure 49. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. There was no significant difference between the cumulative path and link-based standard deviations at the beginning of the route up to node 3; however the difference continuously increased after node 3.

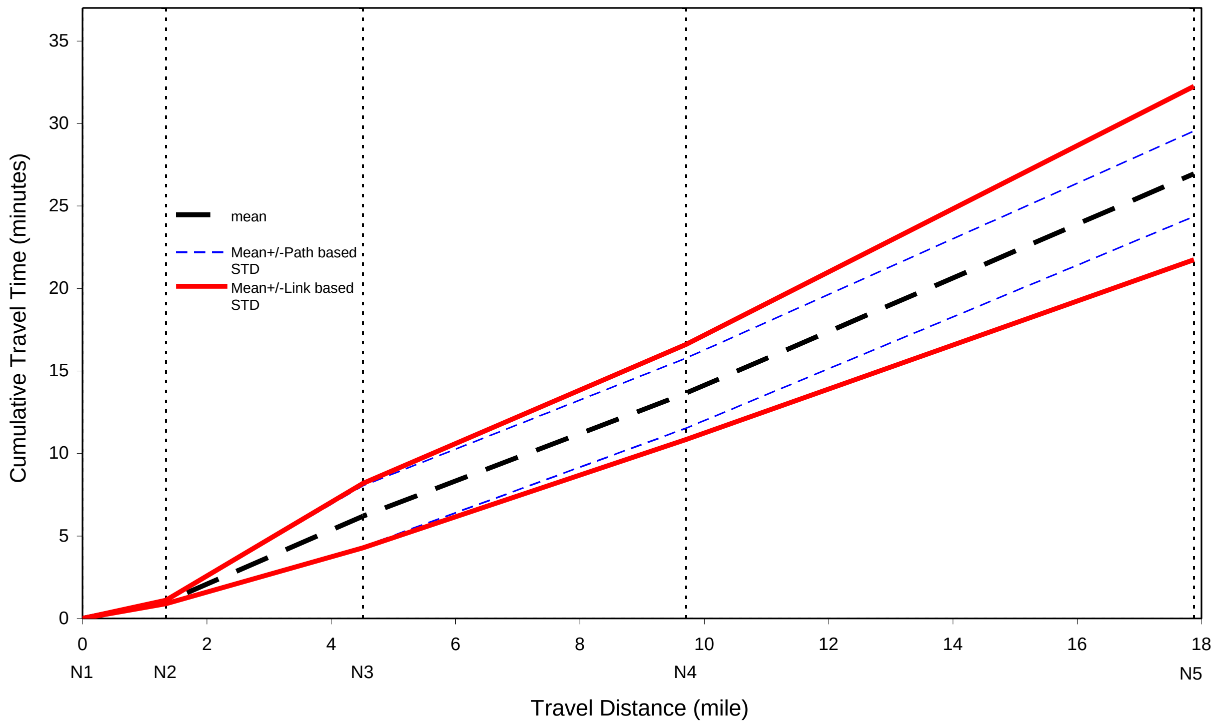


Figure 49.Travel Time Variation with Link-Based vs. Path- Based Data [US 1(C)]

The mean speed of each link for different departure time periods is shown and compared with the mean link speed with standard deviation in Figure 50. Link 1 had significantly high speeds more than 77 mph for every time period while all other links had relatively low speeds between 22 mph and 51 mph. From the figure one can see that late departures showed low speeds on link 2.

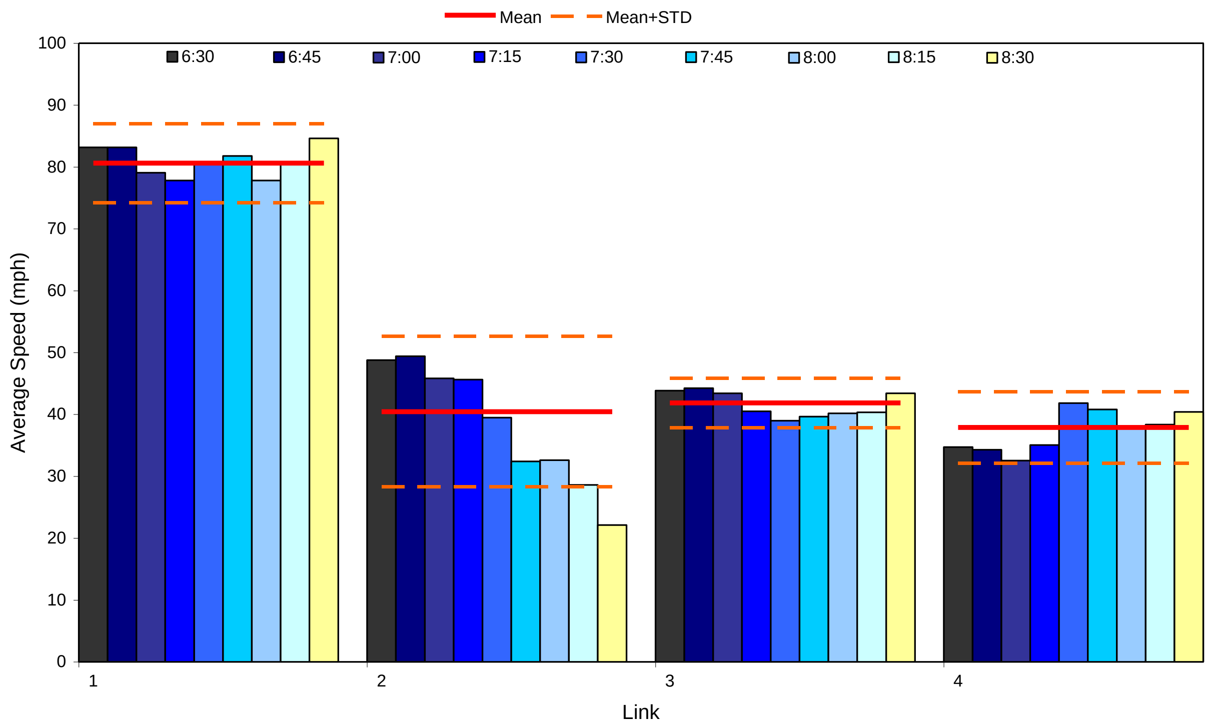


Figure 50. Speed Variation vs. Link for Different Departure Time Periods [US 1 (C)]

Figure 51 represents the path-based travel time distribution for each driver, including mean, mean plus or minus standard deviation, and the 95th percentile travel time. The travel times for 6 records were greater than mean plus standard deviation and 2 records of them were also greater than the 95th percentile travel time. The travel time distribution consisted of data from 23 minutes 4 seconds to 31 minutes 2 seconds.

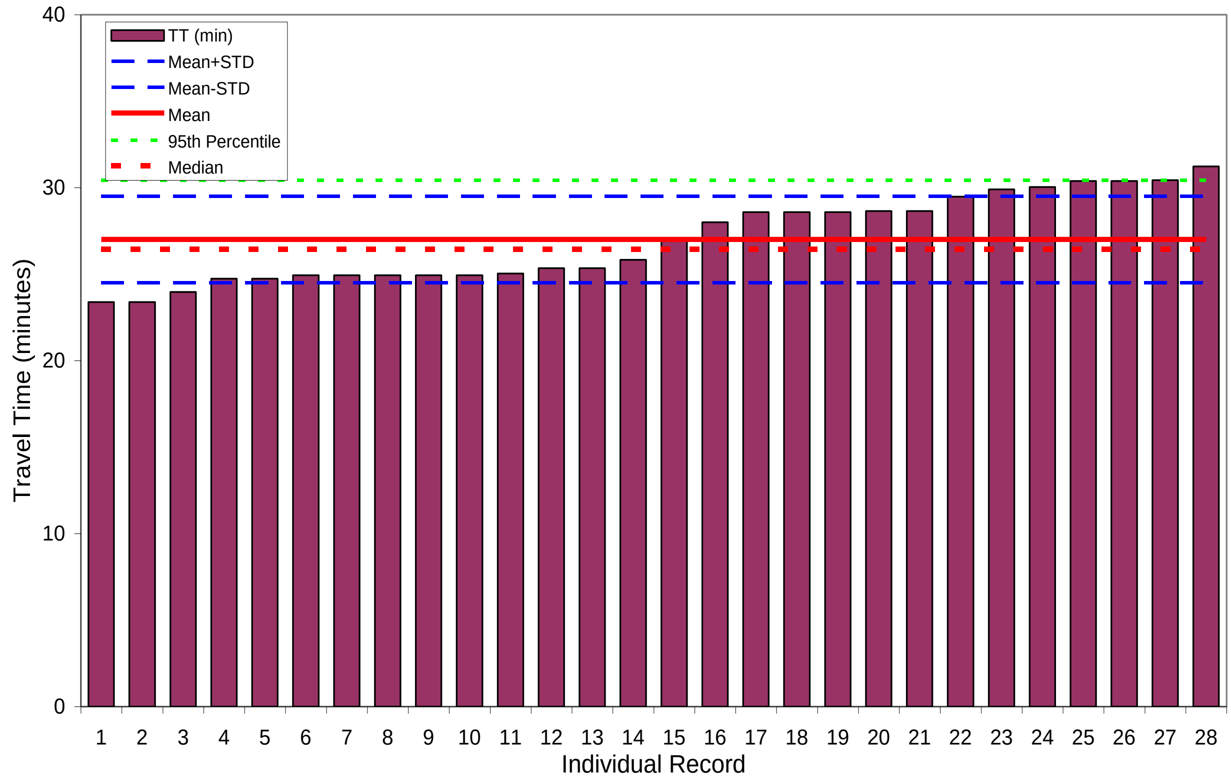


Figure 51. Path Travel Time Distribution [US 1 (C)]

The impact of departure time on the path-based travel time is depicted in Figure 52. Mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and compared for each time period. No substantial path travel time difference was observed for the departure time of 6:30 A.M. The travel time variations were represented slightly for all other time periods.

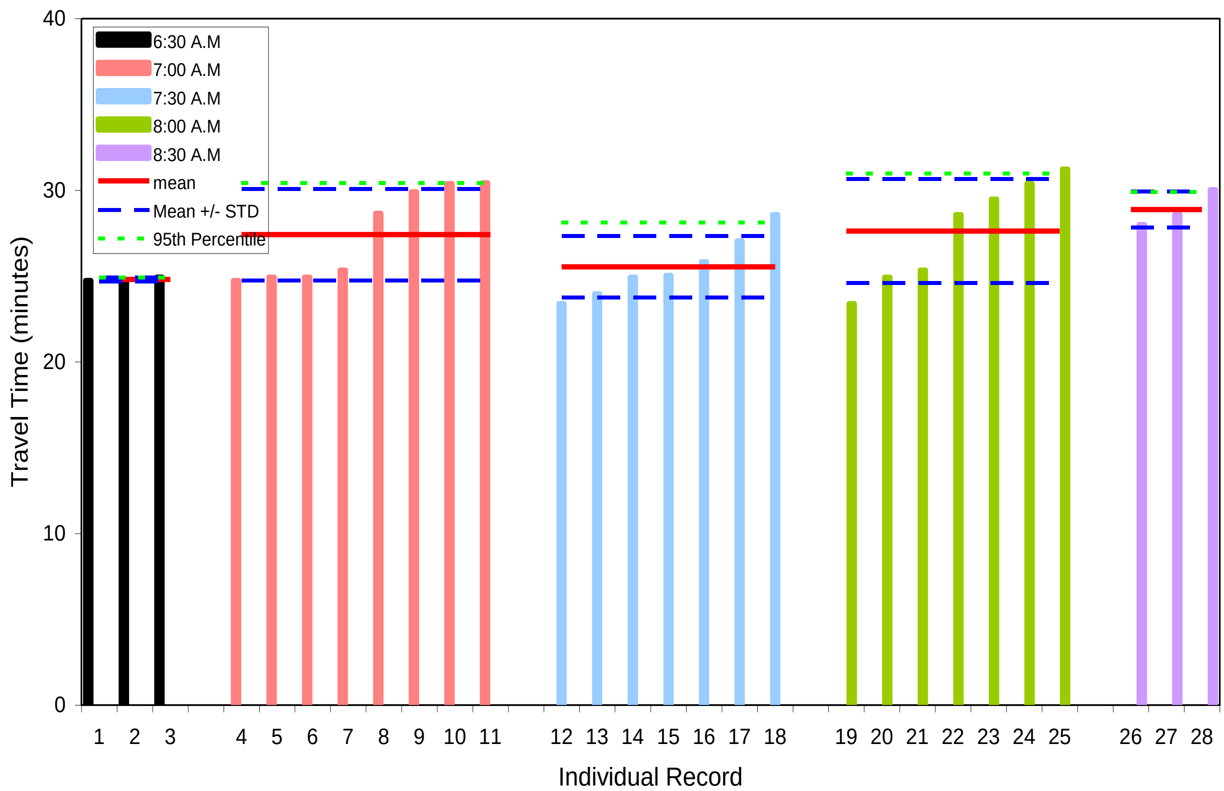


Figure 52. Path Travel Time Distribution by Departure Time Period [US 1 (C)]

A summary of the statistical analysis for US 1 (C) is shown in Table 23.

Table 23 - Path Travel Time Reliability Indices per Departure Time [US 1 (C)]

Departure Time(A.M.)	Sample Size	AVG.TT (mm:ss)	STEDV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	3	26:06	02:12	0.08	28:17	8.4	24:44	28:39
6:45-7:15	8	27:25	02:39	0.10	30:25	10.9	24:44	30:26
7:15-7:45	7	25:32	01:48	0.07	28:07	10.1	23:23	28:35
7:45-8:45*	10	27:37	03:02	0.11	30:59	12.2	23:23	31:14

*: includes 8:15- 8:45 A.M. data

Travel Time Analysis for US 1 (D)

The segment is US 1 (D) begins at the interchange of US 1 and NJ 18 and ends at the interchange of US 1 and US 22. It is 20.2 miles long and consists of 8 nodes. Table 24 presents the characteristics of this segment.

Table 24 - Node Location and Coordinates on US 1 (D) Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 1 (D) (NJ 18 to US 22)	1	27.30	-	-74.416201	40.485635	near NJ 18
	2	28.54	1.24*	-74.406966	40.499829	@ CR 514
	3	31.96	3.42	-74.354389	40.528326	@ I-287
	4	34.52	2.56	-74.317674	40.552445	@ INT-GSP
	5	35.89	1.37	-74.297726	40.564900	@ US 9
	6	36.41	0.52	-74.292986	40.571407	@ NJ 35
	7	43.11	6.70	-74.221227	40.650516	@ NJ 439
	8	47.50	4.39	-74.183572	40.704232	near US 22
Total	-	-	20.20	-	-	-

*: Link distance from node 1 to node 2

Figure 53 illustrates the mean cumulative travel times for 7 departure time intervals from 6:30 A.M. to 8:15 A.M with the moving mean method. The mean cumulative travel times were found to be between 32 minutes and 42 minutes. The departure time of 8:15 A.M. showed the longest mean travel time of all time periods while departures at 6:45 A.M. needed the shortest mean travel time. The mean cumulative travel times increased with the late departures.

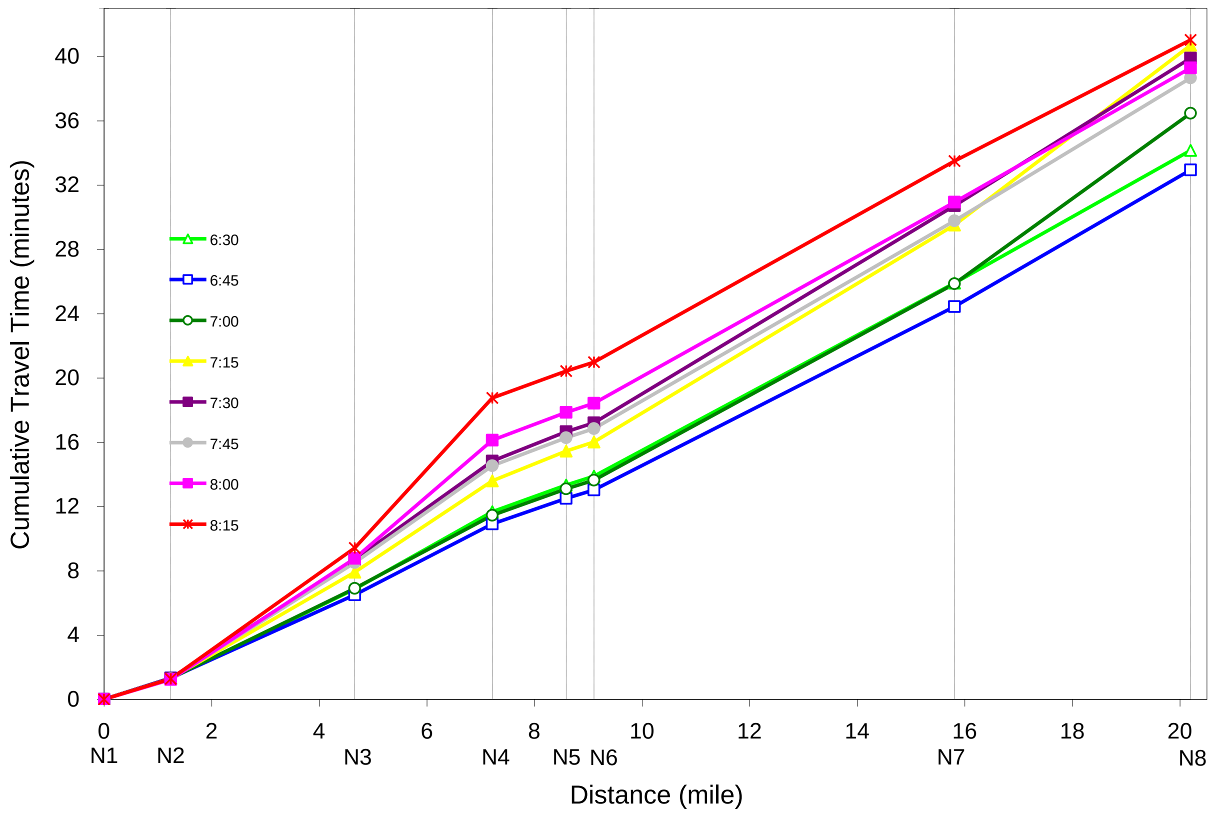


Figure 53. Travel Times for Different Departure Time Periods [US 1 (D)]

Figure 54 shows the difference between the cumulative path and link-based standard deviation of travel time. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. There was no notable difference between the cumulative path and link-based standard deviations from node 1 to node 3; however the difference gradually became larger after node 3.

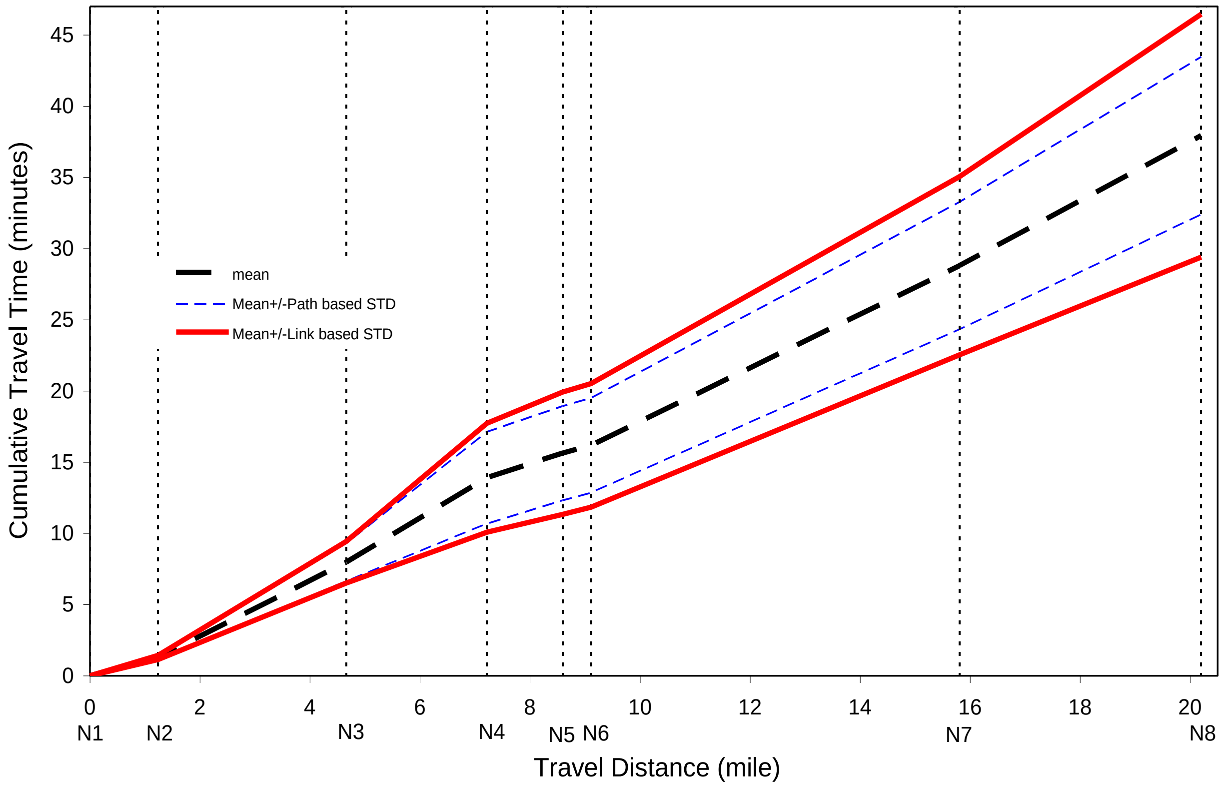


Figure 54. Travel Time Variation with Link-Based vs. Path- Based Data [US 1 (D)]

The mean speed of each link for different departure time periods is shown and compared with the mean link speed with the standard deviation in Figure 55. Link 1, link 4, and link 5 showed significantly higher speeds compared to all other links having speeds less than 43 mph.

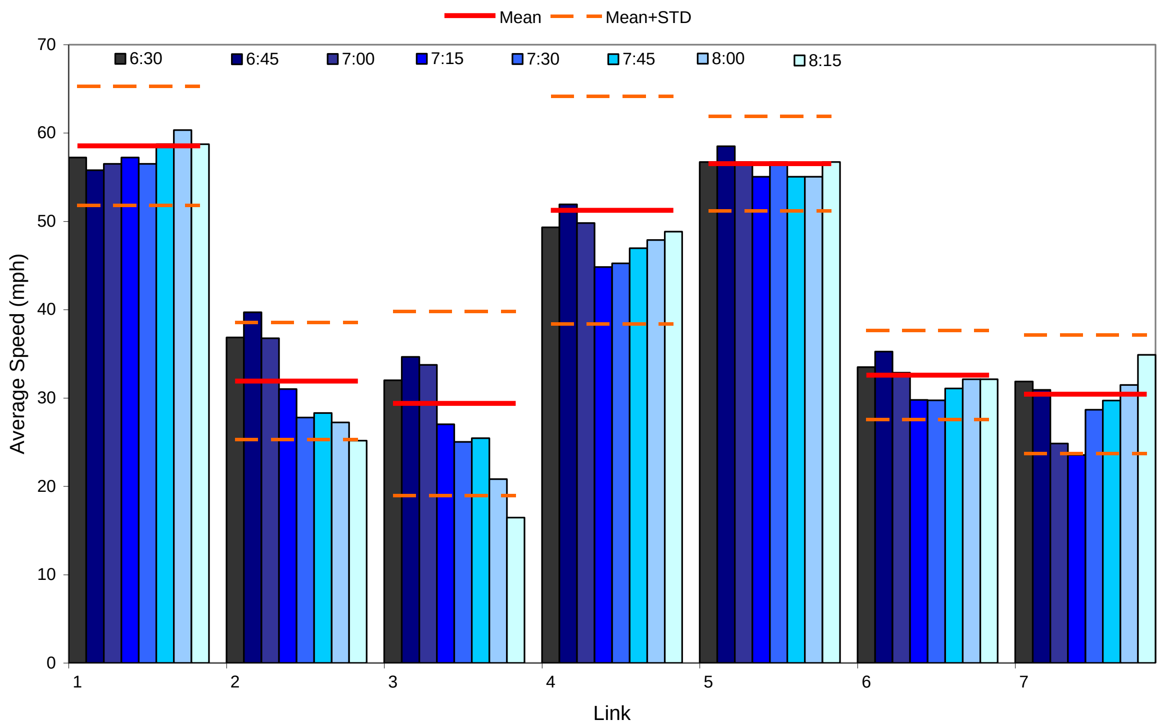


Figure 55. Speed Variation vs. Link for Different Departure Time Periods [US 1 (D)]

The path-based travel time distribution for each driver which includes mean, mean plus or minus standard deviation, and the 95th percentile travel time is shown in Figure 56. The travel times of 10 records were greater than mean plus standard deviation and 3 records of them were also greater than the 95th percentile travel time. The travel time distribution included data from 24 minutes 6 seconds to 49 minutes 5 seconds.

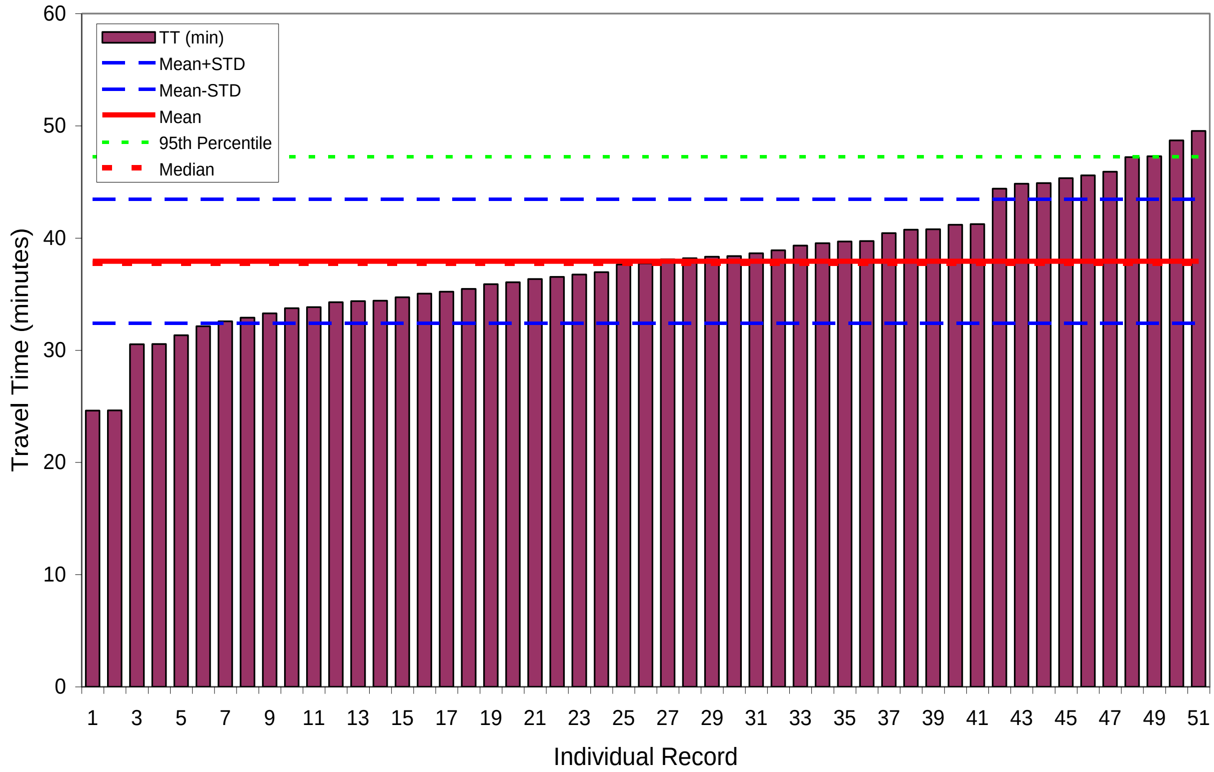


Figure 56. Path Travel Time Distribution [US 1 (D)]

Figure 57 depicts the impact of departure time on the path-based travel time. Mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and compared for each time period. The departure time of 7:00 A.M. showed the biggest travel time variation of all time periods while the departure time of 6:30 A.M. represented the smallest travel time variation.

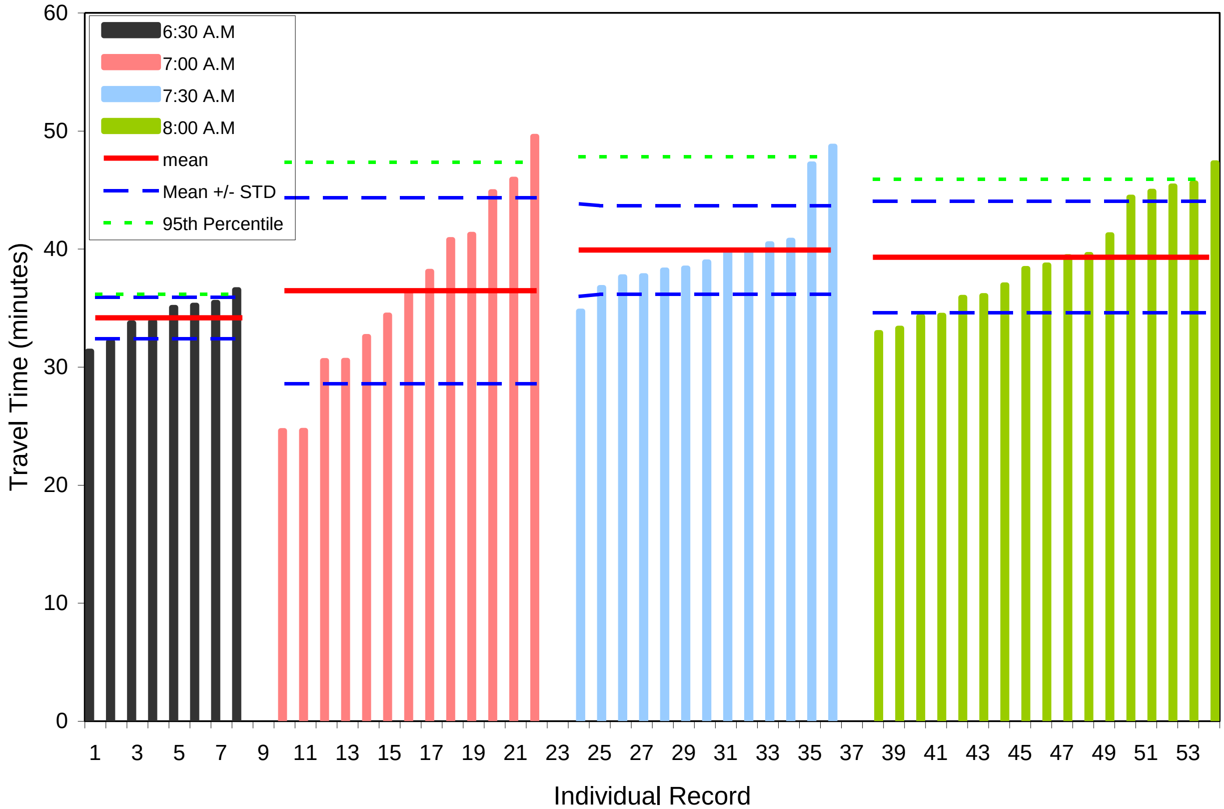


Figure 57. Path Travel Time Distribution by Departure Time Period [US 1 (D)]

A summary of the statistical analysis for US 1 (D) is shown in Table 25.

Table 25 - Path Travel Time Reliability Indices per Departure Time [US 1 (D)]

Departure Time (A.M.)	**Sample Size**	**AVG.TT (mm:ss)**	**STEDV (mm:ss)**	**CV**	**95th percentile (mm:ss)**	**Buffer Index (%)**	**Range (mm:ss)**	
						95th percentile	**t_{MIN}**	**t_{MAX}**
6:15-6:45	8	34:10	01:45	0.05	36:10	5.9	31:20	36:32
6:45-7:15	13	36:28	07:52	0.22	47:21	29.8	24:37	49:32
7:15-7:45	13	39:54	03:55	0.10	47:48	19.8	34:43	48:42
7:45-8:15	17	39:18	04:43	0.12	45:55	16.8	32:54	47:17

Travel Time Analysis for US 1 (E)

The segment of US 1 (E) begins at the interchange of US 1 and US 130 and ends at the interchange of US 1 and I-295. It is 17.88 miles long and consists of 5 nodes. Table 26 presents the characteristics of this segment.

Table 26 - Node Location and Coordinates on US 1 (E) Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 1 (C) **(US 130 to I-295)**	1	24.64	-	-74.450336	40.464064	near US-130
	2	16.47	8.17*	-74.571109	40.386518	@ CR-522
	3	11.27	5.20	-74.638087	40.331414	@ CR-571
	4	8.10	3.17	-74.678777	40.297745	@ CR-533
	5	6.76	1.34	-74.692142	40.286801	near I-295
Total	-	-	17.88	-	-	-

*: Link distance from node 1 to node 2

Note that the valid data from US 1 (E) is only eight after data processing, which resulted from inappropriate navigation device (i.e., Co-Pilot^{TM}) control and careless driving of data collectors. Thus, no statistical analysis is conducted for US 1 (E).

Travel Time Analysis for US 9

The segment of US 9 begins at the interchange of US 9, NJ 166 and the GSP and ends at the intersection of US 9 and CR 522. It is 20.3 miles long and consists of 8 nodes.

Table 27 presents the characteristics of this segment.

Table 27 - Node Location and Coordinates on US 9 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
US 9	1	94.50	-	-74.211416	39.993448	near GSP/NJ 166
	2	98.75	4.25*	-74.221896	40.046801	@ NJ 70
	3	101.71	2.96	-74.216342	40.090067	@ NJ 88
	4	102.86	1.15	-74.219440	40.106220	@ CR 526
	5	107.05	4.19	-74.235756	40.165099	@ I-195
	6	112.91	5.86	-74.278293	40.241697	@ NJ 33
	7	113.75	0.84	-74.286862	40.251814	@ CR 537
	8	114.80	1.05	-74.293812	40.265689	near CR 522
Total	-	-	20.30	-	-	-

*: Link distance from node 1 to node 2

Figure 58 illustrates the mean cumulative travel times for 8 departure time intervals from 6:30 A.M. to 8:15 A.M with the moving mean method. The mean cumulative travel times were observed to be between 30 minutes and 40 minutes, demonstrating difference in travel time for each time period. The departure time of 7:45 A.M. had the longest mean travel time of all time periods while departures at 7:00 A.M. needed the shortest mean travel time. Departures before 7:15 A.M. showed faster mean travel times than departures after 7:15 A.M due to light traffic in the early morning.

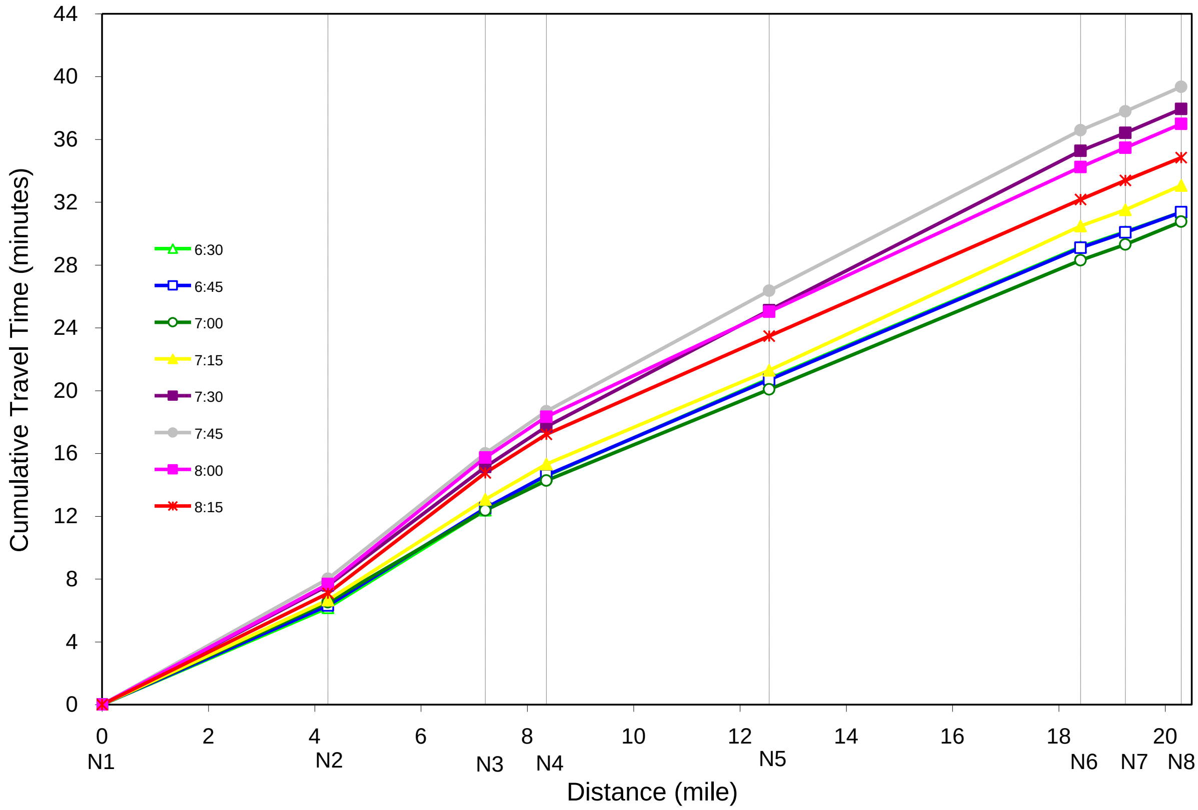


Figure 58. Travel Times for Different Departure Time Periods (US 9)

The difference between the cumulative path and link-based standard deviation of travel time is presented in Figure 59. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. There was no significant difference between the cumulative path and link-based standard deviations at the beginning of the route up to node 3; however the difference between the standard deviations continuously increased after node 3.

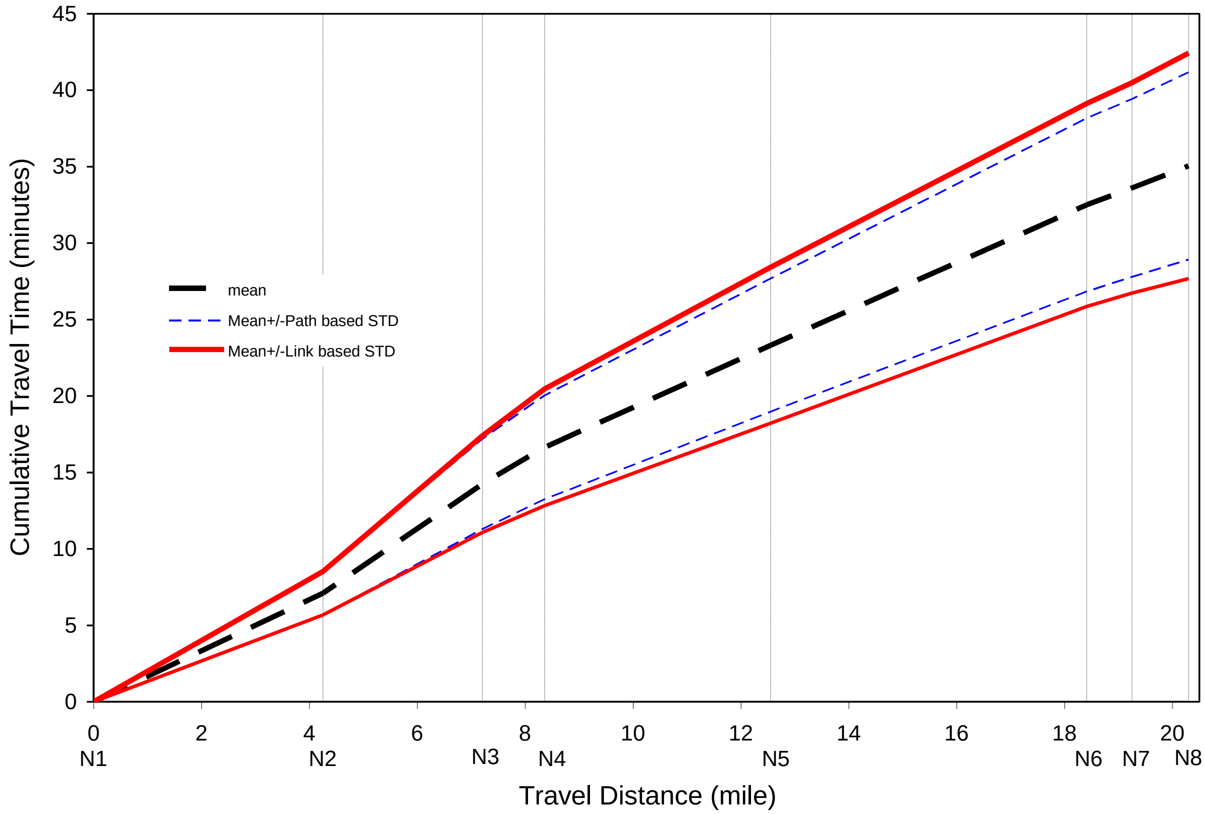


Figure 59. Travel Time Variation with Link-Based vs. Path- Based Data (US 9)

The mean speed of each link for different departure time periods is shown and compared with the mean link speed along with standard deviation in Figure 60. Link 6 and link 7 had the high mean speeds for most of the time periods and link 2 had the lowest speeds for all time periods. From the figure one can see that the mean speeds after 7:30 A.M. were lower than the mean speeds before 7:30 A.M.

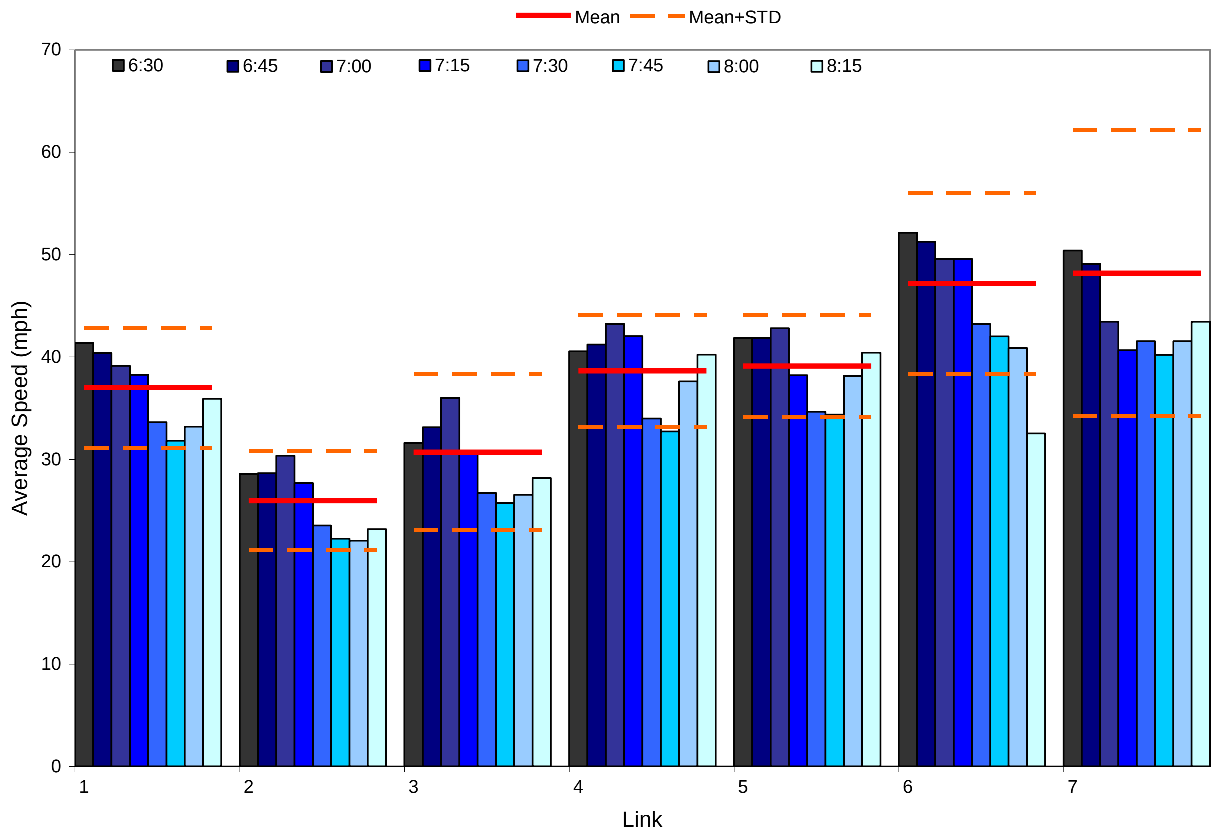


Figure 60. Speed Variation vs. Link for Different Departure Time Periods (US 9)

Figure 61 represents the path-based travel time distribution for each driver, containing mean, mean plus or minus the standard deviation, and the 95th percentile travel time. For 2 records the travel times were greater than mean plus the standard deviation and the same data was also greater than the 95th percentile travel time. The range of the travel time records was from 26 minutes 7 seconds to 61 minutes 25 seconds.

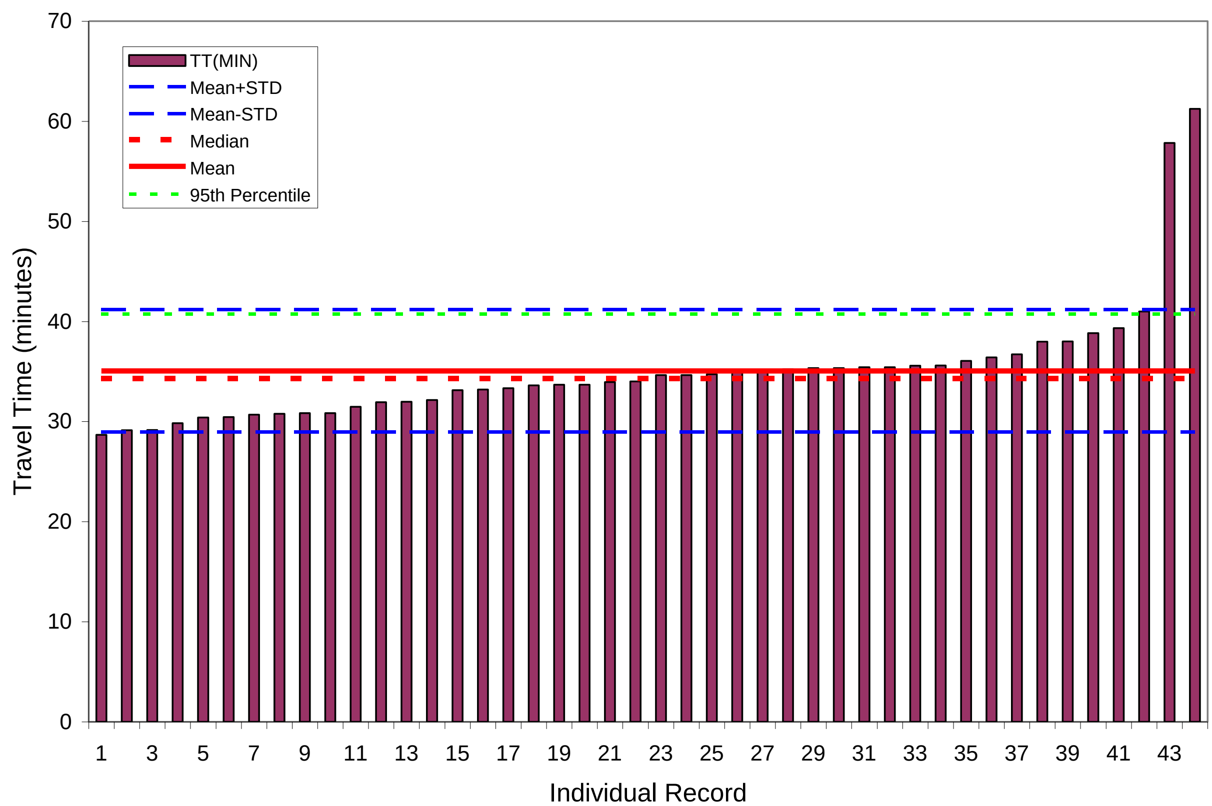


Figure 61. Path Travel Time Distribution (US 9)

The impact of departure time on the path-based travel time is depicted in Figure 62. Mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and compared for each time period. The time distributions for the departure times of 7:30 A.M. and 8:00 A.M. had one driver having a remarkable travel time variation respectively. No substantial path travel time difference was observed for the departure time periods from 6:30 A.M. to 7:00.A.M.

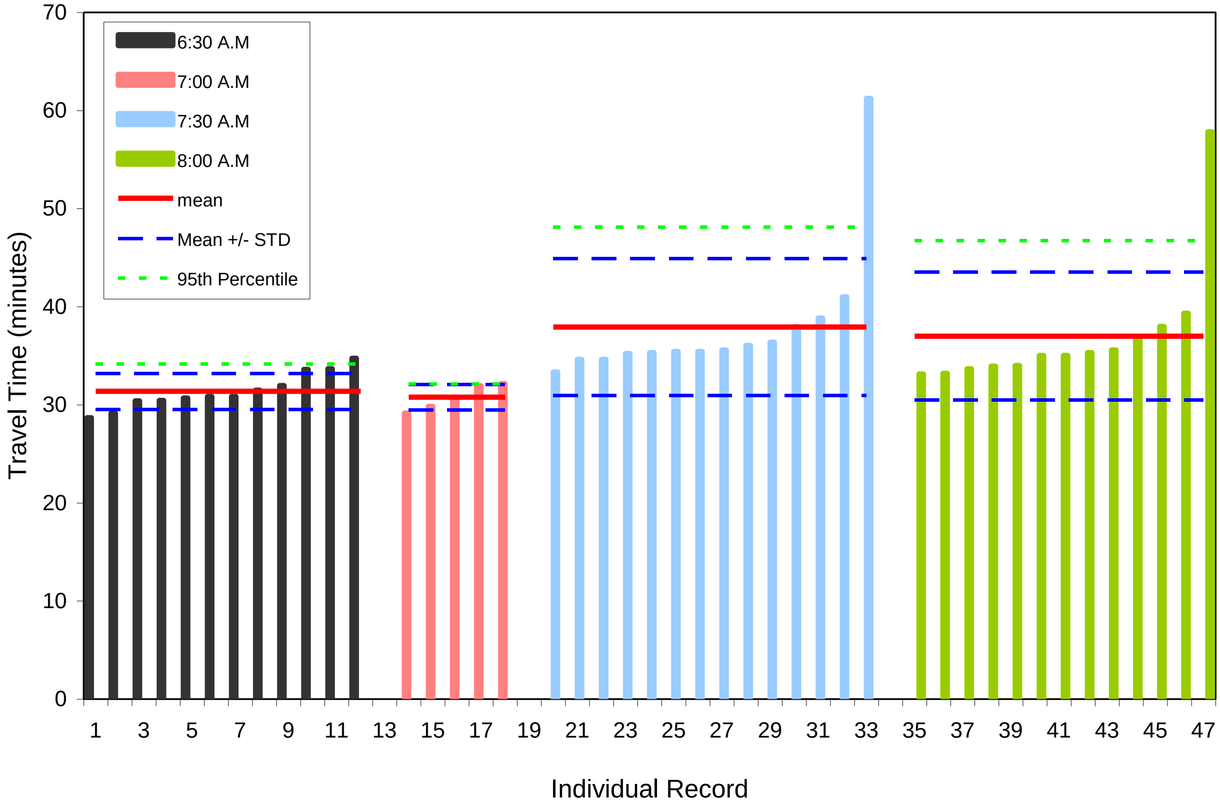


Figure 62. Path Travel Time Distribution by Departure Time Period (US 9)

A summary of the statistical analysis for US 9 is shown in Table 28.

Table 28 - Path Travel Time Reliability Indices per Departure Time (US 9)

Departure Time (A.M.)	**Sample Size**	**AVG.TT (mm:ss)**	**STEDV (mm:ss)**	**CV**	**95^{th} percentile (mm:ss)**	**Buffer Index (%)**	**Range (mm:ss)**	
						95^{th} percentile	**t_{MIN}**	**t_{MAX}**
6:15-6:45	12	31:22	01:50	0.06	34:09	8.9	28:41	34:44
6:45-7:15	5	30:46	01:18	0.04	32:06	4.33	29:09	32:09
7:15-7:45	14	37:56	06:59	0.18	48:05	26.8	33:20	1:01:15
7:45-8:15	13	36:59	06:32	0.18	46:44	26.4	33:08	57:50

Travel Time Analysis for NJ 42 & I-76

The segment of NJ 42 & I-76 begins at the intersection of NJ 42 and US 322 and ends at the interchange of I-76 and I-676. It is 16.8 miles long and consists of 7 nodes. Table 29 presents the characteristics of this segment.

Table 29 - Node Location and Coordinates on NJ 42 **&** I-76 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 42	1	0.00	-	-74.992979	39.689332	near US 322
	2	3.51	3.51*	-75.032914	39.729524	@ CR 555
	3	6.35	2.84	-75.048611	39.767348	@ INT ACE
	4	11.54	5.19	-75.088637	39.830855	@ NJ 41
	5	14.20	2.66	-75.101385	39.867846	@ I-295 & I-76
I-76	6	0.00	0.40	-75.102210	39.873950	@ I-295
	7	2.20	2.20	-75.109348	39.898603	near I-676
Total	-	-	16.80	-	-	-

*: Link distance from node 1 to node 2

Figure 63 illustrates the mean cumulative travel times for 7 departure time intervals from 6:30 A.M. to 8:00 A.M with the moving mean method. The mean cumulative travel times were observed to be between 30 minutes and 40 minutes, showing the difference in the travel time for each time period. The departure time of 7:30 A.M. represented the longest mean travel time of all time periods. In contrast, departures at 6:30 A.M. showed the shortest mean travel time. The longest travel time was observed between node 3 and node 5.

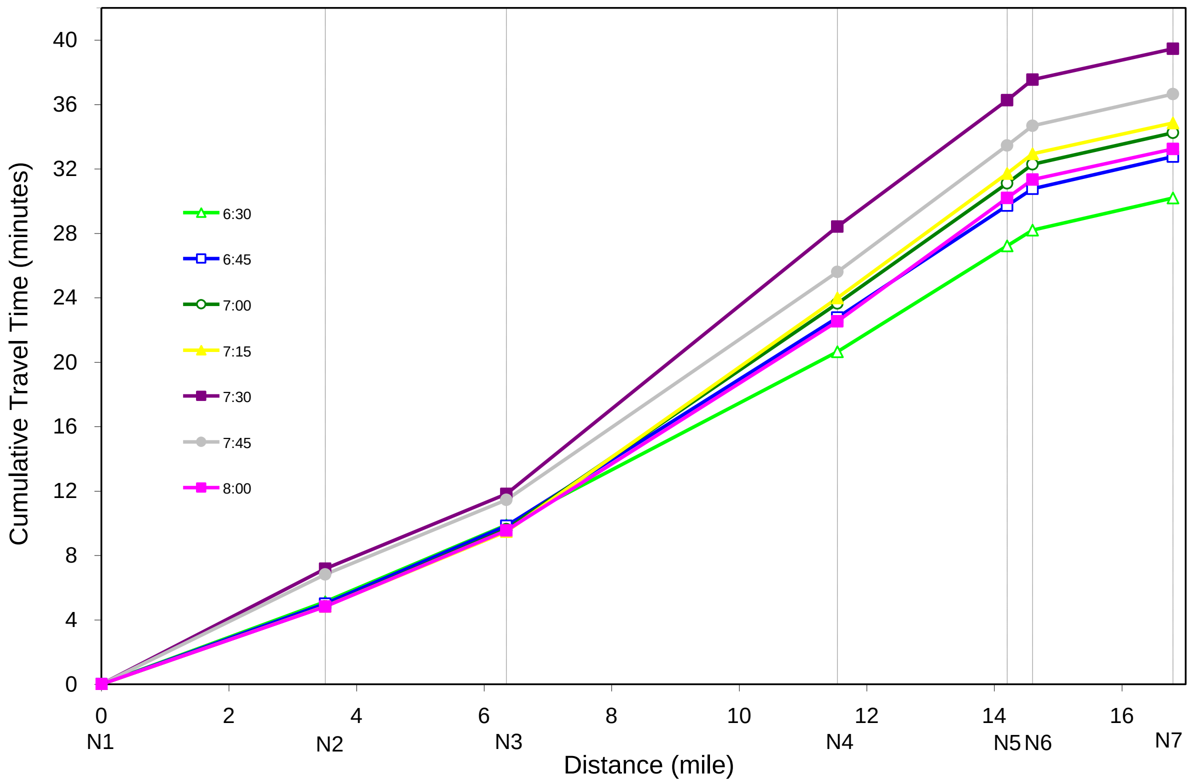


Figure 63. Travel Times for Different Departure Time Periods (NJ 42 & I-76)

Figure 64 shows the difference between the cumulative path and link-based standard deviation of travel time. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. Similar values for the cumulative path and link-based standard deviation were calculated for the segment between nodes 1 and 2; however the difference gradually increased after node 3.

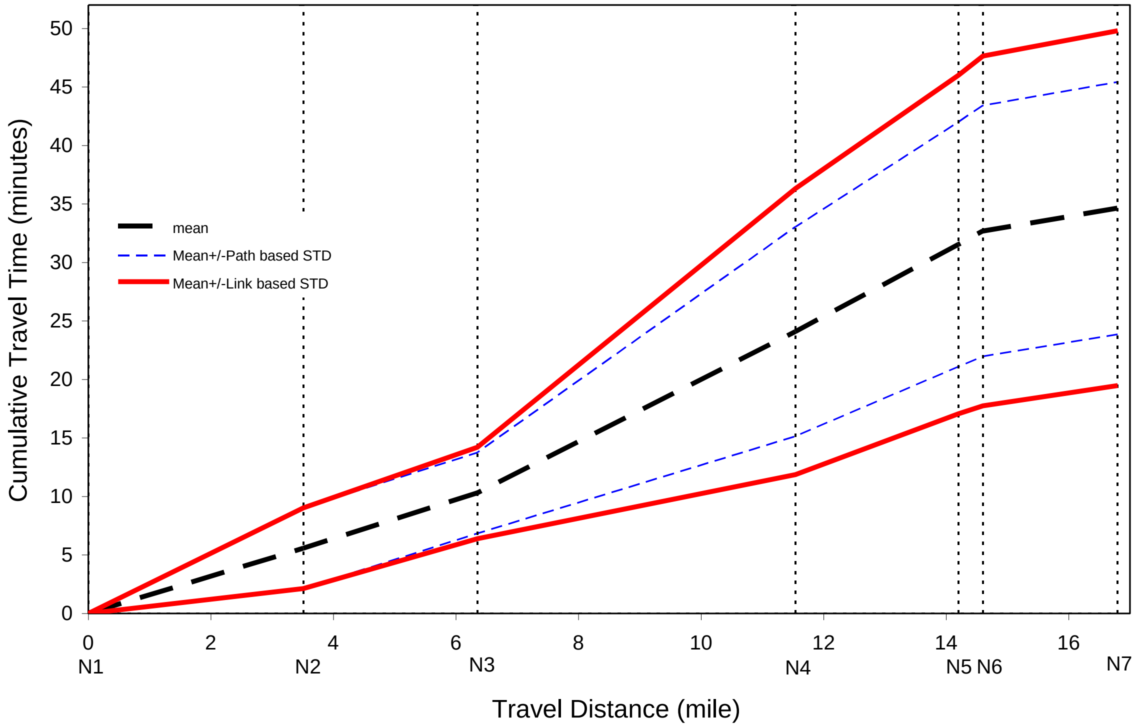


Figure 64. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 42 & I-76)

Figure 65 depicts the mean speed of each link for different departure time periods and compares them with the mean link speed with plus or minus standard deviation. Link 6 had significantly higher speeds than all other links whereas link 4 and link 5 showed much lower speeds less than 29 mph.

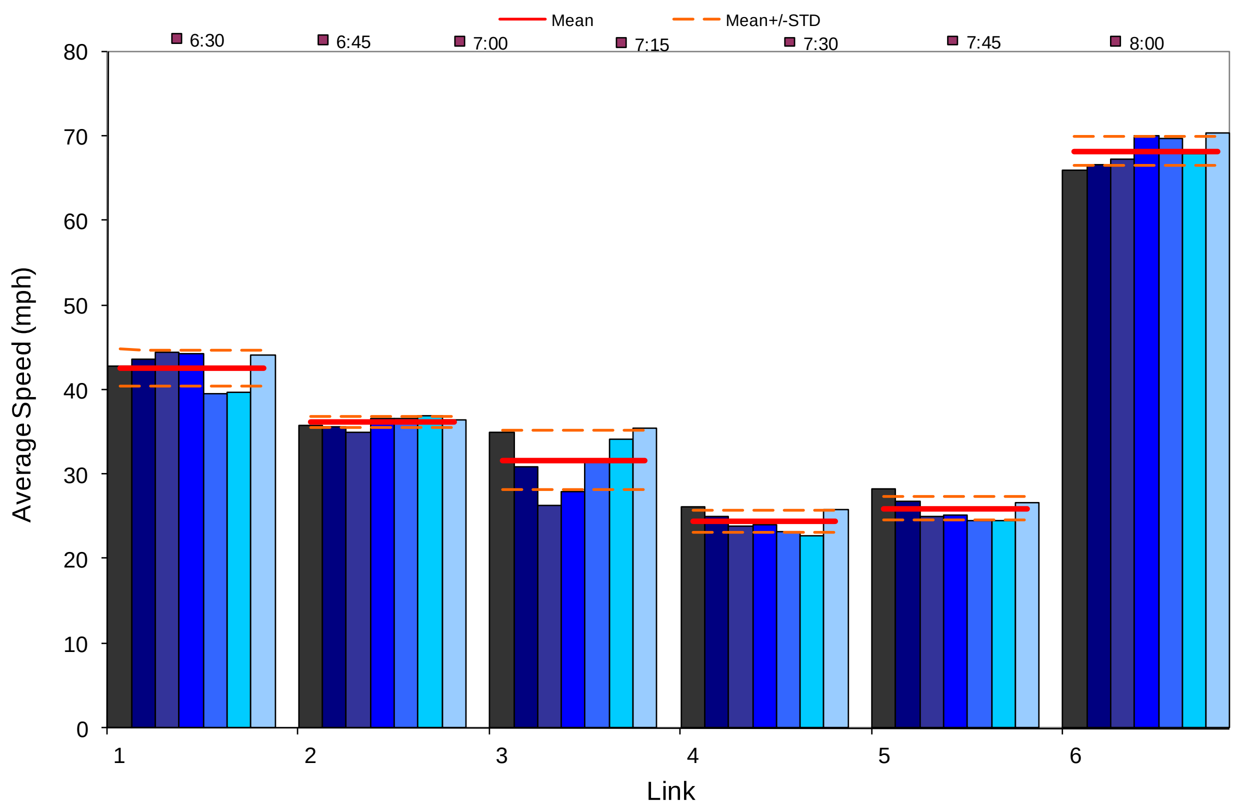


Figure 65. Speed Variation vs. Link for Different Departure Time Periods (NJ 42 & I-76)

The path-based travel time of each driver is shown and compared with mean, mean plus or minus the standard deviation, and the 95th percentile travel time of all the drivers in Figure 66. For 10 records the travel times were greater than mean plus standard deviation and 3 records of them were also greater than the 95th percentile travel time. The travel time distribution included data from 17 minutes 7 seconds to 55 minutes 8 seconds.

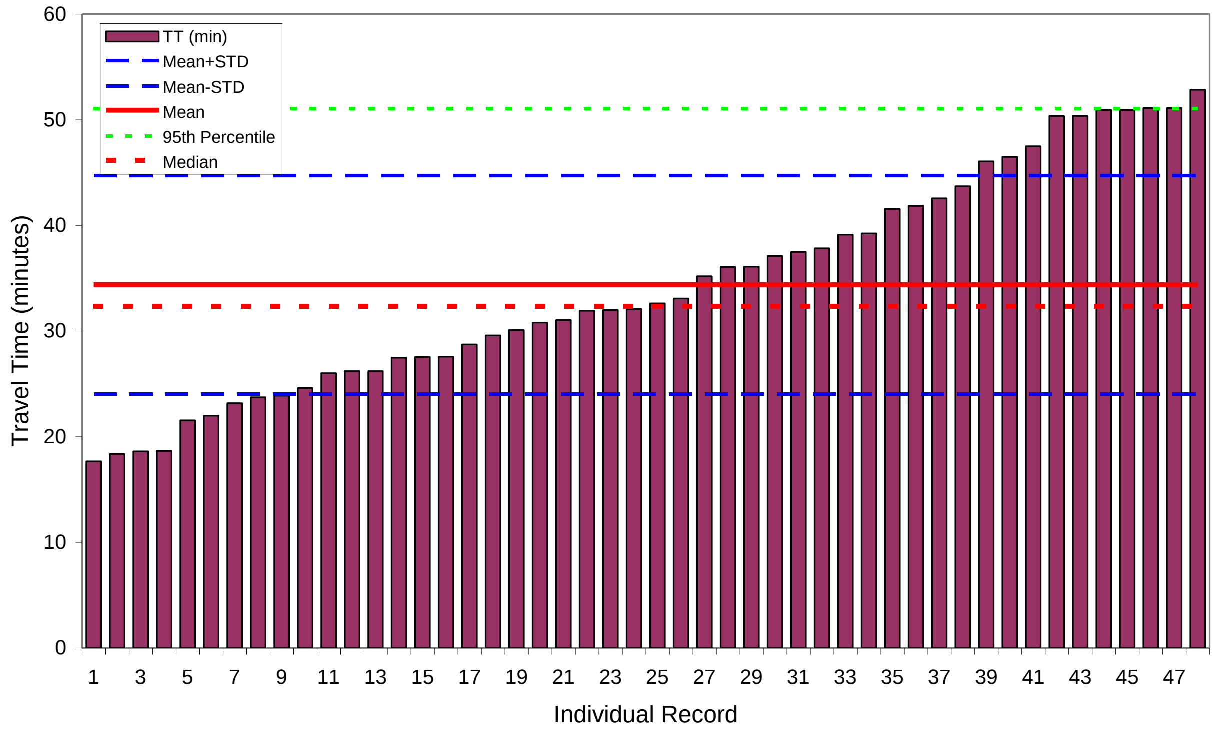


Figure 66. Path Travel Time Distribution (NJ 42 & I-76)

The impact of departure time on the path-based travel time is depicted in Figure 67. Mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and shown for each time period. The biggest travel time variation was observed for the departure time of 6:30 A.M.

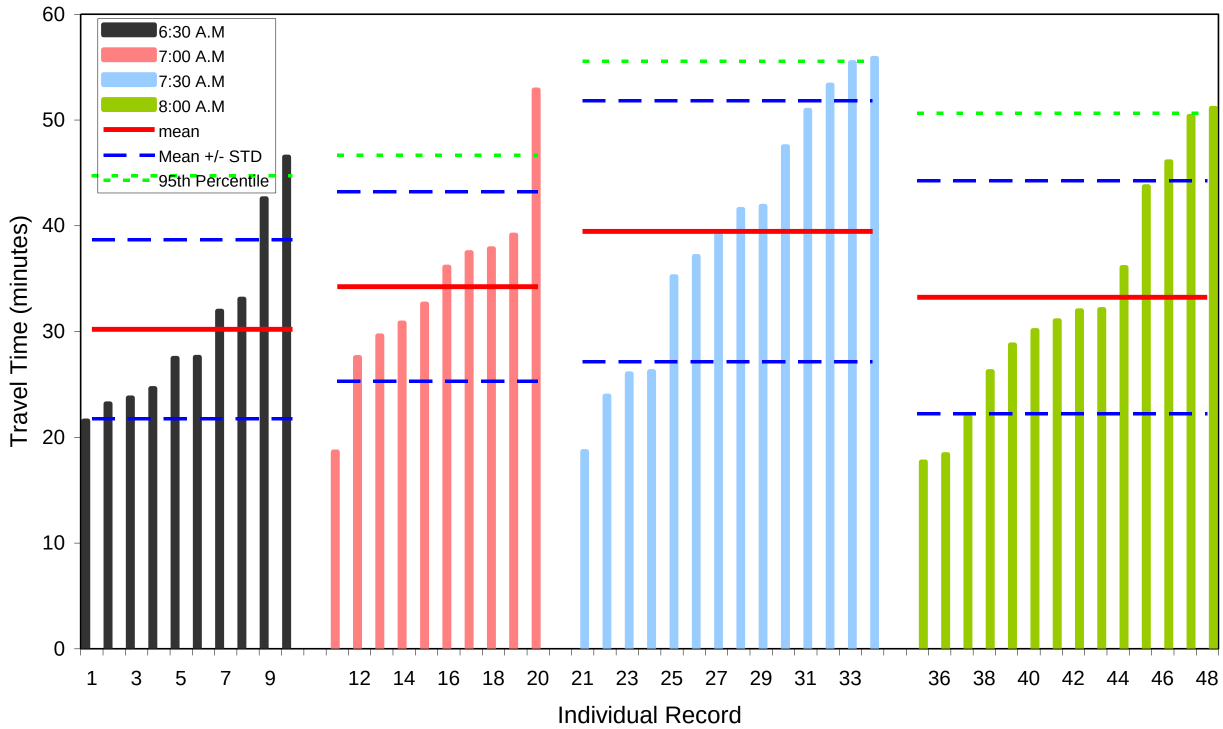


Figure 67. Path Travel Time Distribution by Departure Time Period (NJ 42 & I-76)

A summary of the statistical analysis results for NJ 42 & I-76 is shown in Table 30.

Table 30 - Path Travel Time Reliability Indices per Departure Time (NJ 42 & I-76)

Departure Time (A.M.)	**Sample Size**	**AVG.TT (mm:ss)**	**STEDV (mm:ss)**	**CV**	**95th percentile (mm:ss)**	**Buffer Index (%)**	**Range (mm:ss)**	
						95th percentile	**t_{MIN}**	**t_{MAX}**
6:15-6:45	10	30:12	08:26	0.28	44:43	48.1	21:32	46:29
6:45-7:15	10	34:15	08:57	0.26	46:40	36.3	18:36	52:50
7:15-7:45	14	39:28	12:20	0.31	55:34	40.8	18:38	55:08
7:45-8:15	14	33:14	11:00	0.33	50:37	52.3	18:21	51:06

Travel Time Analysis for NJ 70

The segment of NJ 70 begins with the intersection of NJ 70 and US 206 and ends with the merge with NJ 38. It is 18.53 miles long and consists of 7 nodes. Table 31 presents the characteristics of this segment.

Table 31 - Node Location and Coordinates on NJ 70 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 70	1	18.53	-	-74.742823	39.887334	near US 206
	2	13.91	4.62*	-74.824659	39.904692	@ CR 541
	3	8.33	5.58	-74.927352	39.893833	@ NJ 73
	4	5.07	3.26	-74.984579	39.909097	@ I-295
	5	3.66	1.41	-75.010359	39.913799	@ NJ 41
	6	2.31	1.35	-75.034459	39.919503	@ CR 644
	7	0.00	2.31	-75.068514	39.934111	near NJ-38
Total	-	-	18.53	-	-	-

*: Link distance from node 1 to node 2

Figure 68 shows the mean cumulative travel times for 8 departure time intervals from 6:30 A.M. to 8:15 A.M with the moving mean method. The mean cumulative travel times were between 33 minutes and 48 minutes, representing the large variance. The departure time of 7:30 A.M. had the longest mean travel time more than 47 minutes. However, amongst the other time periods there was only a small range of the mean cumulative travel time distribution from 33 minutes and 25 seconds to 37 minutes and 30 seconds. The longest mean travel times were observed between node 3 and node 5.

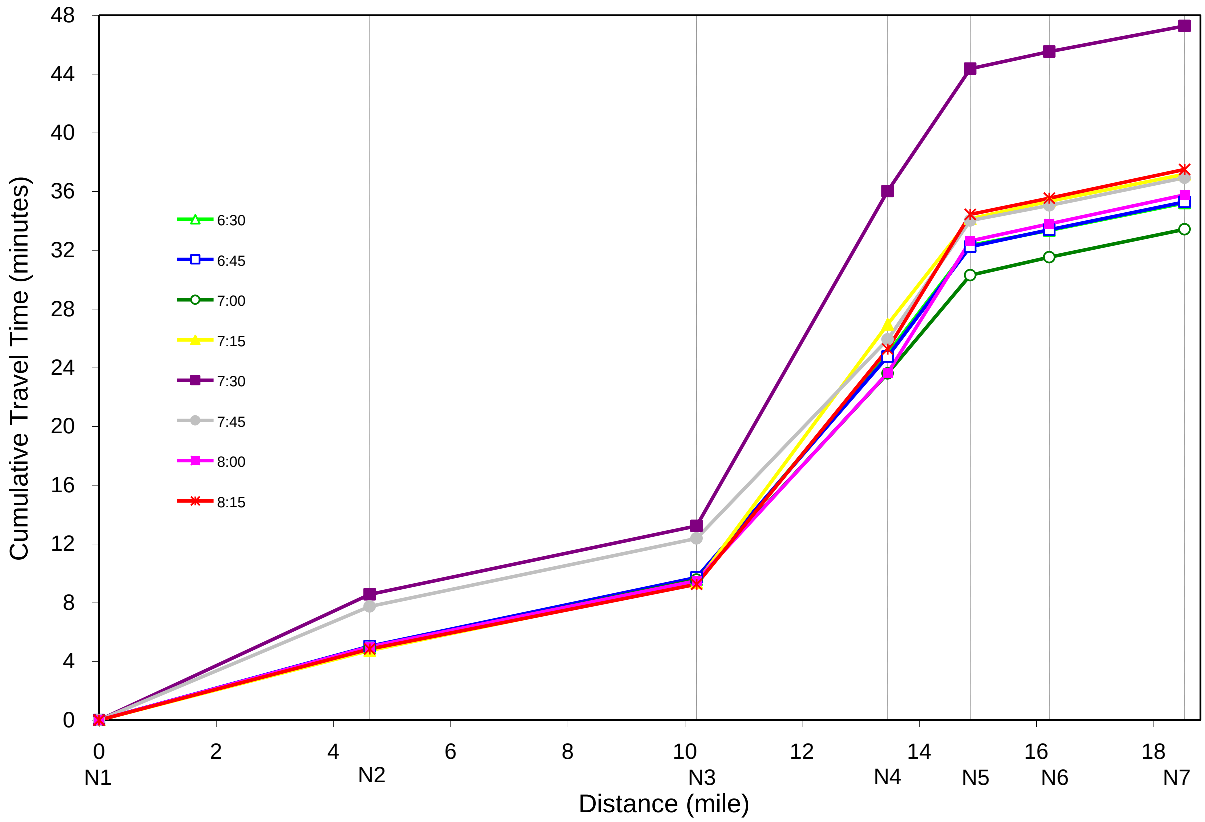


Figure 68. Travel Times for Different Departure Time Periods (NJ 70)

Figure 69 shows the difference between the cumulative path and link-based standard deviation of travel time. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. There was no notable difference between the cumulative path and link-based standard deviation from node 1 to node 3; however the difference became significantly larger after node 3. A significant difference was observed between node 5 and node 7.

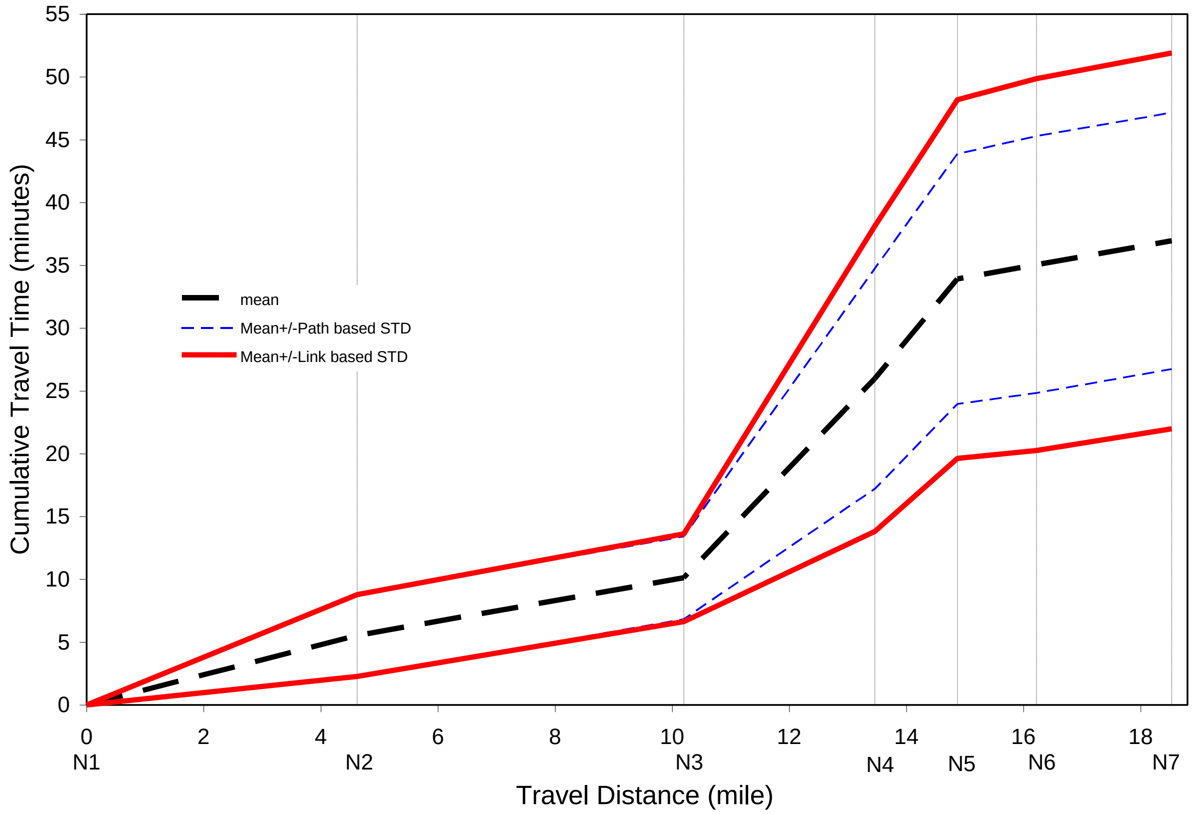


Figure 69. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 70)

The mean speed of each link for different departure time periods is shown and compared with the mean link speed along with the standard deviation in Figure 70. Link 3 and link 4 showed significantly lower speeds less than 20 mph while high speeds more than 70 mph were observed on link 2, link 5, and link 6.

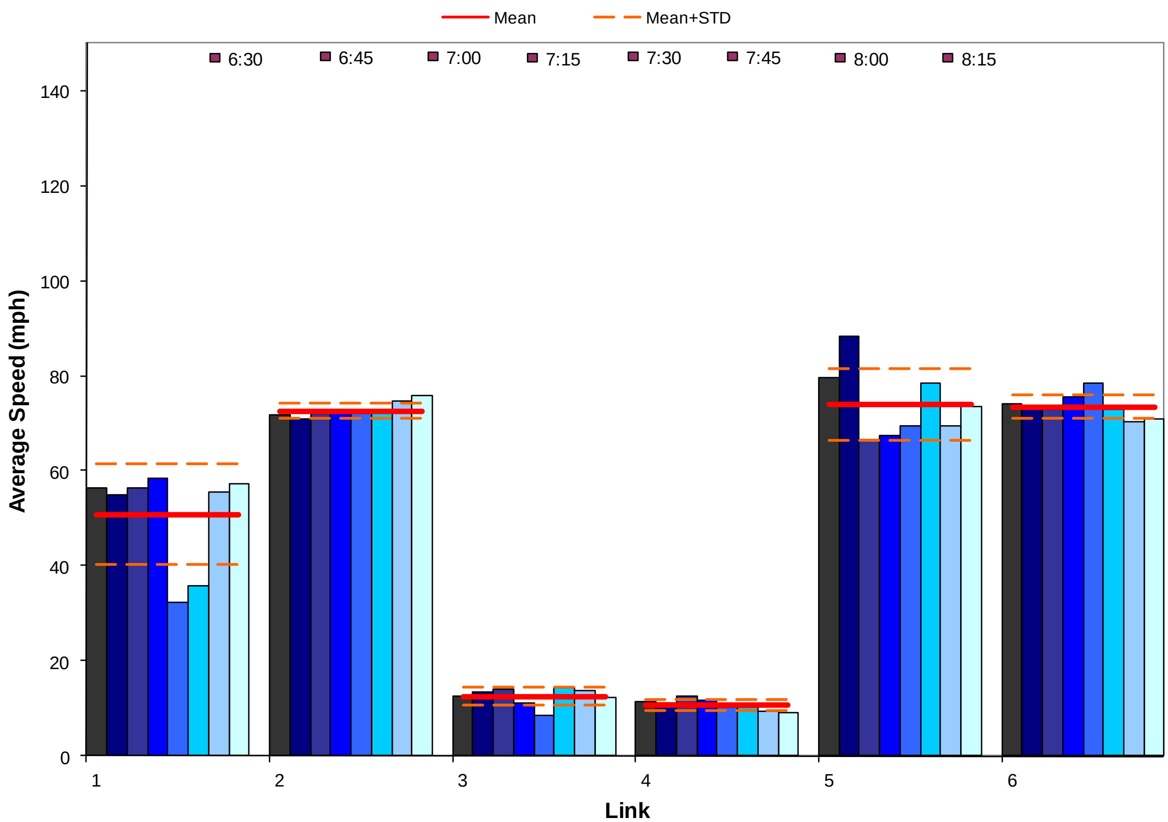


Figure 70. Speed Variation vs. Link for Different Departure Time Periods (NJ 70)

Figure 71 represents the path-based travel time distribution for each driver, and includes the mean, mean plus or minus the standard deviation, and the 95th percentile travel time. The travel times for 7 records were greater than mean plus standard deviation and for 3 records of them were also greater than the 95th percentile travel time. The travel time distribution contained data from 18 minutes 6 seconds to 55 minutes 8 seconds.

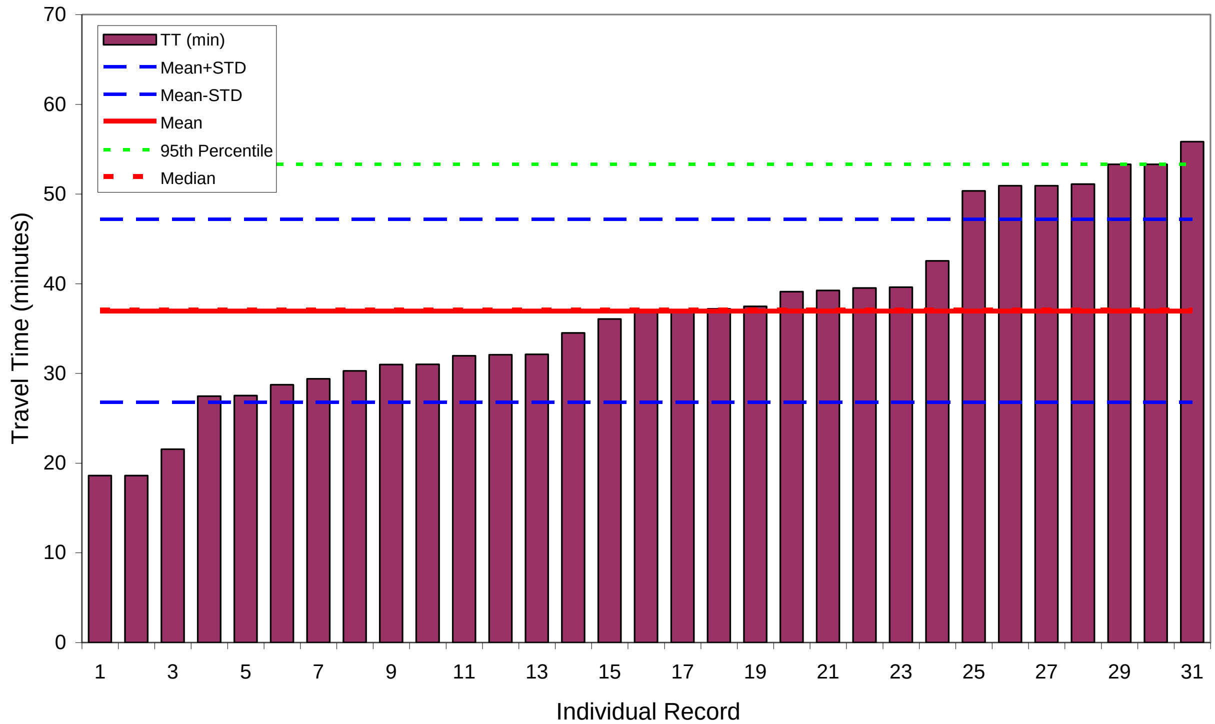


Figure 71. Path Travel Time Distribution (NJ 70)

Figure 72 depicted the impact of departure time on the path-based travel time. Mean, mean plus or minus the standard deviation, and the 95th percentile travel time were calculated and compared for each time period. Every time period had significant travel time variation.

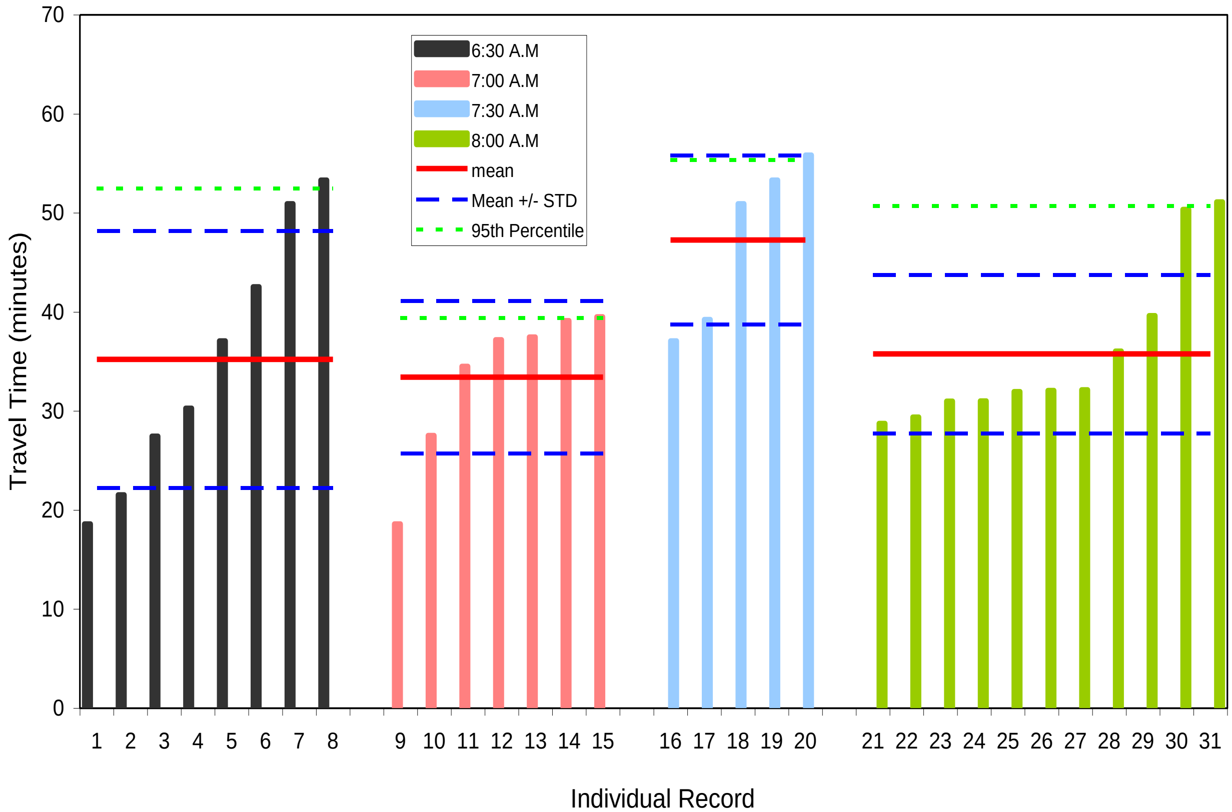


Figure 72. Path Travel Time Distribution by Departure Time Period (NJ 70)

The summary of the statistical analysis for NJ 70 is shown in Table 32.

Table 32 - Path Travel Time Reliability Indices per Departure Time (NJ 70)

Departure Time (A.M.)	Sample Size	AVG.TT (mm:ss)	STEDV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	8	35:13	12:59	0.37	52:28	49.0	18:36	53:18
6:45-7:15	7	33:25	07:42	0.23	39:24	17.9	18:36	39:31
7:15-7:45	5	47:16	08:32	0.18	55:20	17.1	37:05	55:50
7:45-8:15	11	35:46	08:00	0.22	50:44	41.8	28:44	51:06

Travel Time Analysis for NJ 73

The segment of NJ 73 begins at the intersection of NJ 73 and US 70 and ends at the intersection of NJ 73 and Madison St. in Palmyra borough. It is 9.58 miles long and consists of 10 nodes. Table 33 presents the characteristics of this segment.

Table 33 - Node Locations and Coordinates on NJ 73 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 73	1	24.30	-	-74.928632	39.895093	near US 70
	2	25.35	1.05*	-74.939728	39.908836	@ E Greentree Rd
	3	27.00	1.65	-74.956340	39.928360	@ INT-NJTPK
	4	27.68	0.68	-74.965640	39.934730	@ I-295
	5	28.55	0.87	-74.978402	39.943194	@ NJ 38
	6	28.82	0.27	-74.982202	39.945681	@ NJ 41
	7	29.68	0.86	-74.987611	39.956646	@ CR 537
	8	31.39	1.71	-75.009670	39.974180	@ NJ 90
	9	32.18	0.79	-75.017615	39.983633	@ US 130
	10	33.88	1.70	-75.037002	40.002866	@ Madison St.
Total	-	-	9.58	-	-	-

*: Link distance from node 1 to node 2

Figure 73 shows the mean cumulative travel times for 6 departure time intervals from 6:30 A.M. to 7:45 A.M with the moving mean method. The mean cumulative travel times ranged between 12 minutes and 16 minutes, showing the difference slightly. Departures at 7:45 A.M. showed the longest mean travel time while departures at 7:15 A.M. represented the shortest mean travel time.

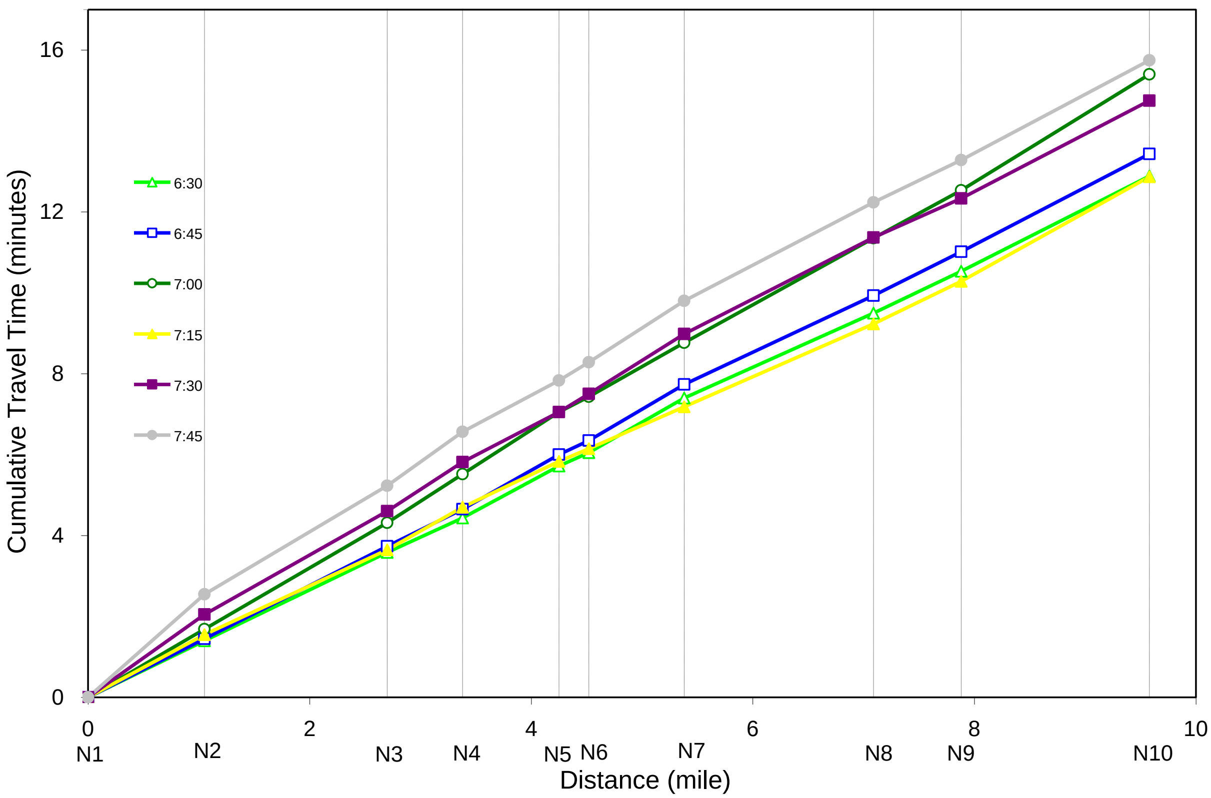


Figure 73. Travel Times for Different Departure Time Periods (NJ 73)

Figure 74 presents the difference between the cumulative path and link-based standard deviation of travel time. As the travel distance increased, the cumulative path and link-based standard deviation of travel time also increased. Similar values for cumulative path and link-based standard deviation were calculated for node 1 and node 2; however, the difference continuously increases gradually after node 2.

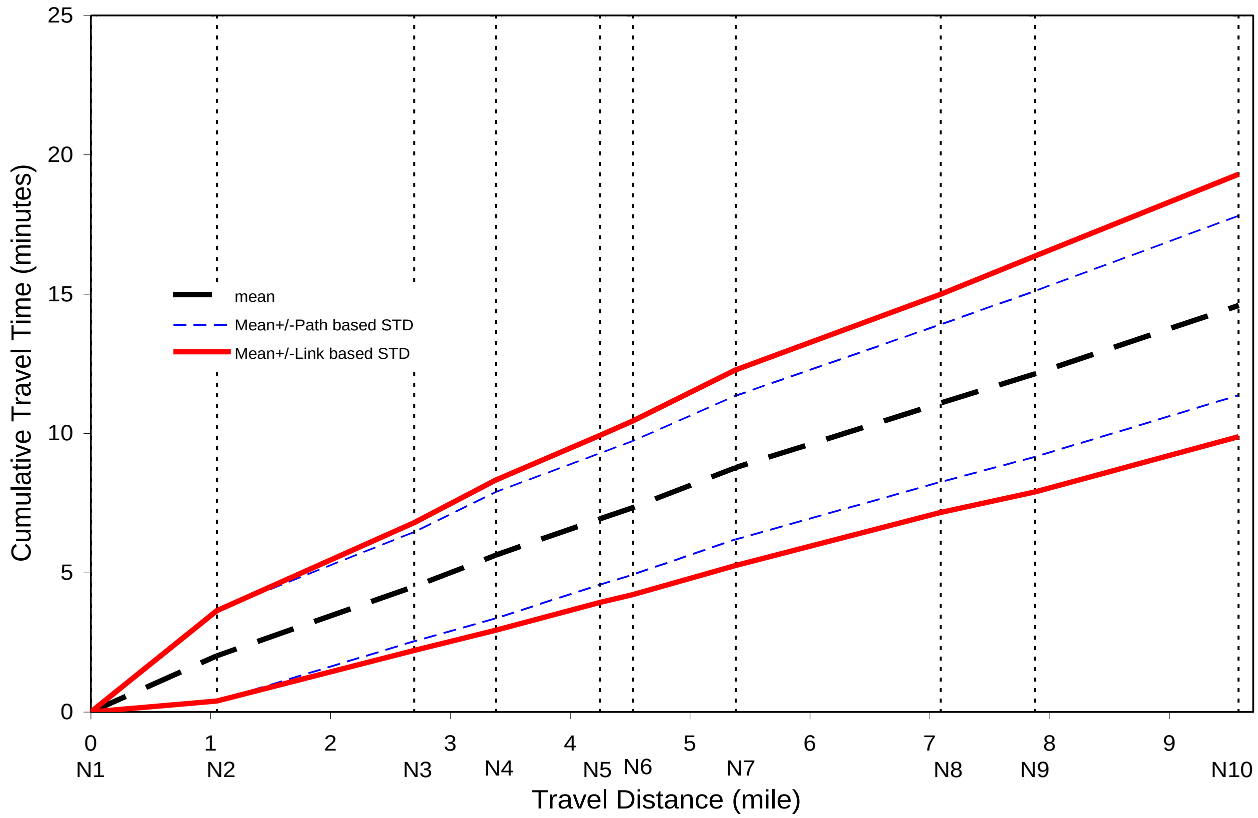


Figure 74. Travel Time Variation with Link-Based vs. Path- Based Data (NJ 73)

The mean speed of each link for different departure time periods is shown and compared with the mean link speed and standard deviation in Figure 75. There was no significant difference in speeds among links, however a distinctive difference in speeds based on the departure times was observed. Late departures after 7:30 A.M. showed lower speeds on link 1, link 2, link 3, link 5, and link 6.

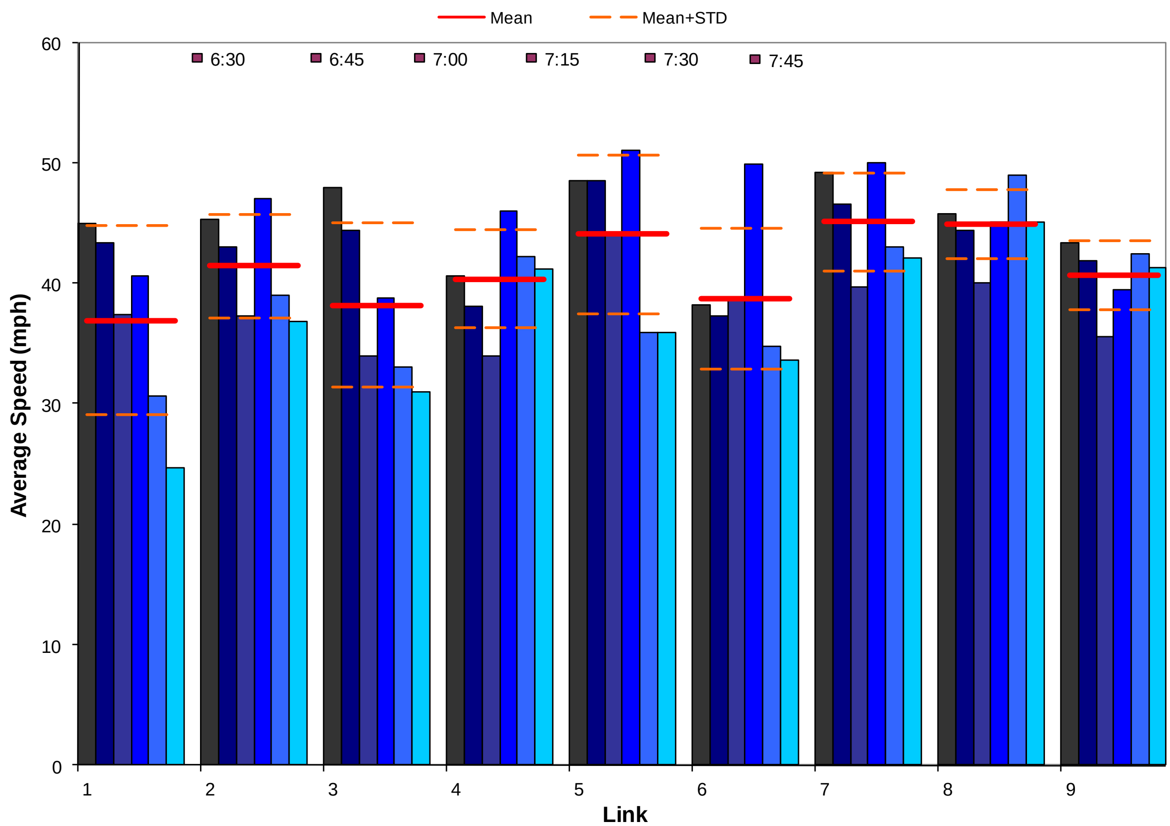


Figure 75. Speed Variation vs. Link for Different Departure Time Periods (NJ 73)

Figure 76 represents the path-based travel time distribution for each driver including mean, mean plus or minus the standard deviation, and the 95th percentile travel time. The travel times for 3 records were greater than mean plus standard deviation, experiencing the higher path travel time than the rest of the group and 2 records of them were also greater than the 95th percentile travel time. The travel time distribution consisted of data from 11 minutes 2 seconds to 26 minutes 1 second.

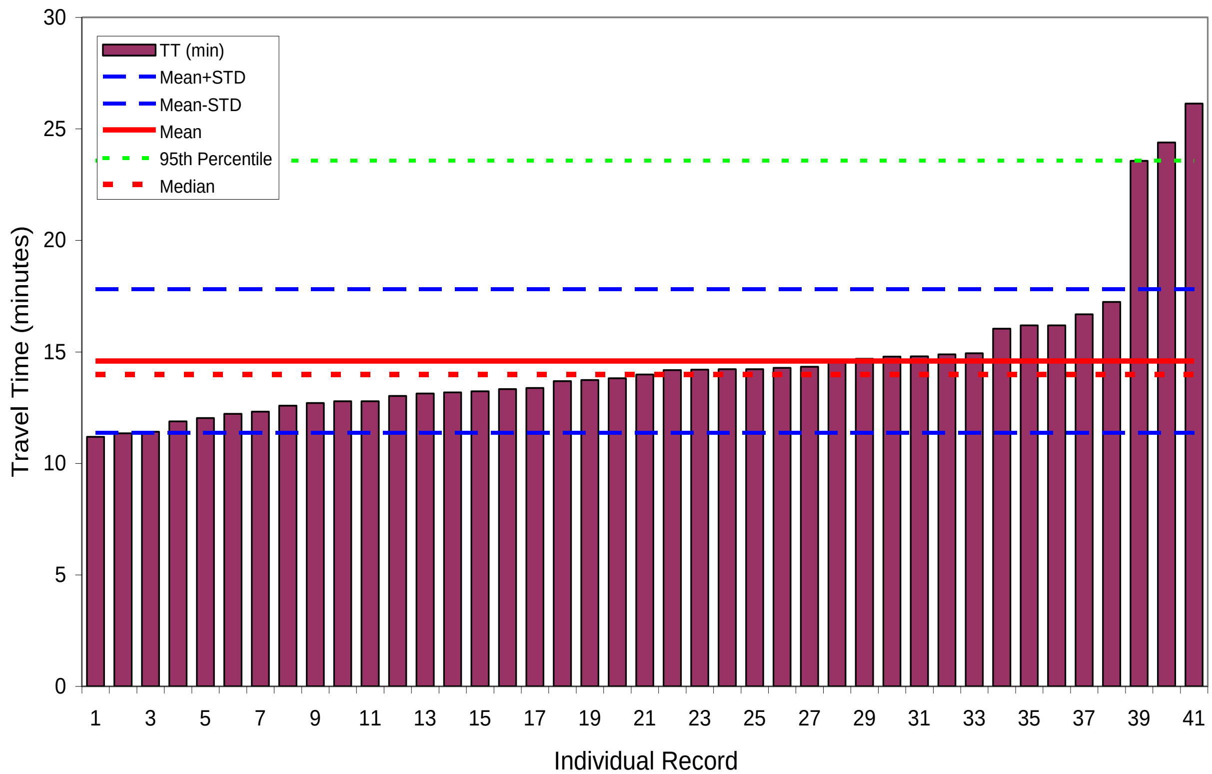


Figure 76. Path Travel Time Distribution (NJ 73)

The impact of departure time on the path-based travel time is depicted in Figure 77. Mean, mean plus or minus standard deviation, and the 95th percentile travel time were calculated and compared for each time period. One diver for the departure time of 7:00 A.M. and two drivers for the departure time of 7:30 A.M. experienced a much higher path travel time than the rest of the group.

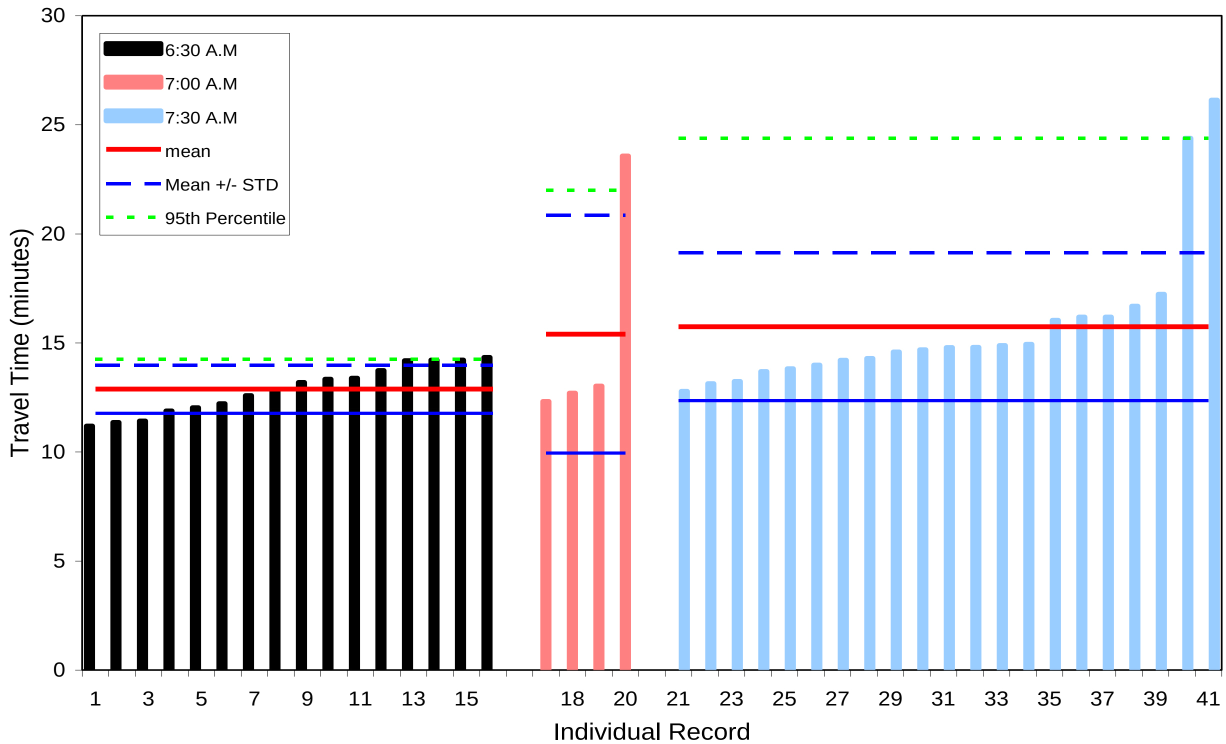


Figure 77. Path Travel Time Distribution by Departure Time Period (NJ 73)

A summary of the statistical analysis for NJ 73 is shown in Table 34.

Table 34 - Path Travel Time Reliability Indices per Departure Time (NJ 73)

Departure Time (A.M.)	Sample Size	AVG.TT (mm:ss)	STEDV (mm:ss)	CV	95th percentile (mm:ss)	Buffer Index (%)	Range (mm:ss)	
						95th percentile	t_{MIN}	t_{MAX}
6:15-6:45	16	12:53	01:06	0.09	14:15	10.6	11:11	14:13
6:45-7:15	4	15:24	05:27	0.35	21:59	42.7	12:19	23:34
7:15-7:45	21	15:45	03:23	0.22	24:23	54.8	12:47	26:08

Travel Time Analysis for NJ 29

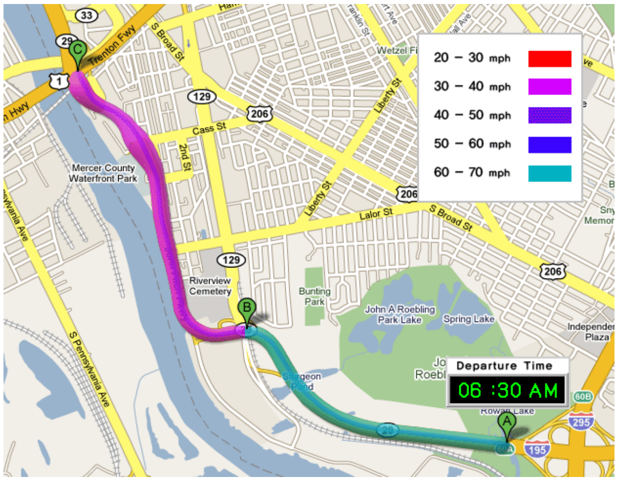
The segment of NJ 29 begins at the interchange of NJ 29 and I-295 and ends at the interchange of NJ 29 and US 1. It is 3.37 miles long and consists of 3 nodes. Table 35 presents the characteristics of this segment.

Table 35 - Node Locations and Coordinates on NJ 29 Segment

Route Name	Node	MP	Distance (mile)	Longitude	Latitude	Description
NJ 29	1	0.00	-	-74.728415	40.184378	near I-295
	2	1.64	1.64*	-74.751270	40.192200	@ NJ 129
	3	3.37	1.73	-74.766109	40.209903	@ US 1
Total	-	-	3.37	-	-	-

*: Link distance from node 1 to node 2

For NJ 29, the results of link travel speed variations over departure time were generated and illustrated on a map. As shown in Figure 78, mean link travel speed per each travel time (e.g., 6:30, 7:00, 7:30, and 8:00 A.M.) is shown in (a), (b), (c), and (d), respectively. It was found that the mean travel speed on each link is quite sensitive to the departure time. Especially, mean travel speed on link 2 is even lower that that on link 1, which resulted from downstream traffic signals. All of the other results of travel time analysis on NJ 29 are shown in Appendix B.



(a) 6:30 A.M.

(b) 7:00 A.M.

(c) 7:30 A.M.

(d) 8:00 A.M.

Source: http://maps.google.com

Figure 78. Link Travel Speed Variations over Departure Time Period on NJ 29

Summary of Co-Pilot™ Data

The complete results of the travel time analysis on all studied location are shown in Appendix B. Overall travel time reliability of all departure time period for all study locations are estimated and shown in Table 36 and the key findings are as follow:

Table 36 – Statistics of Travel Time Data and Measures of Reliability

Locations		NJ 17	NJ 208 & NJ 4	I-80 & I-280	NJ 24 & I-78	US 46 & NJ 3	US 22	I-287 (A)	I-287 (B)	US 1 (C)	US 1 (D)	US 1 (E)	US 9	NJ 42 & I-76	NJ 70	NJ 73	NJ 29[*]
Facility Type[a]		AR[b]	MH[c]	FW[d]	FW	MH	AR	FW	FW	AR	AR	AR	AR	AR & FW	AR	AR	MH
Segment Length (mile)		14.3	17.5	19.4	17.7	13.8	23.4	21.2	20.9	17.9	20.2	17.9	20.3	16.8	18.5	9.6	3.4
AVG. Speed (mph)***		37.0	28.3	48.5	59.9	41.5	40.2	52.5	59.0	40.2	32.4	N/A[f]	35.6	29.4	29.3	40.3	32.0
Speed STDEV (mph)		8.2	8.4	11.2	6.3	11.3	6.5	10.3	10.9	3.6	3.9	N/A	4.3	8.8	7.3	8.9	11.2
Sample Size		73	49	67	82	76	72	94	94	28	51	8	44	48	31	41	111**
AVG. Travel Time (mm:ss)		23:13	37:15	24:06	17:47	19:54	34:57	24:12	21:13	26:40	37:55	N/A	35:03	34:17	36:54	14:35	6:24
Travel Time STDEV (mm:ss)		06:15	09:18	04:54	02:20	8:00	06:23	04:18	05:28	02:25	05:31	N/A	04:09	10:10	9:18	3:18	2:19
Travel Time Median		20:47	37:11	20:38	17:08	17:29	32:57	22:03	19:21	26:26	37:43	N/A	34:18	32:19	37:05	13:56	6:18
Range (mm:ss)	t_{MIN}	16:46	19:00	17:24	15:18	12:23	26:43	17:27	16:06	23:23	24:37	N/A	28:41	18:21	18:36	11:11	2:49
	t_{MAX}	47:29	50:24	58:12	29:17	56:08	52:18	44:17	54:30	31:14	49:32	N/A	61:15	55:50	55:48	26:08	15:47
CV		0.27	0.24	0.21	0.13	0.40	0.18	0.23	0.27	0.09	0.12	N/A	0.12	0.30	0.25	0.22	0.35
Ratio(r)[e]		1.11	1.01	1.16	1.04	1.13	1.06	1.10	1.10	1.02	1.01	N/A	1.02	1.06	0.98	1.04	1.01
Percentage of travel time data less than the mean (%)		61.6	51.0	64.2	69.5	64.4	50.8	64.9	72.3	50.0	50.9	N/A	61.4	54.2	48.4	68.3	50.5
95^{th} percentile (mm:ss)		32:54	47:03	35:36	20:28	23:51	43:13	32:40	29:25	29:27	44:18	N/A	40:16	49:23	49:29	20:12	9:28
Buffer Index (%)	95^{th} Percentile	32.8	29.6	48.7	19.0	73.8	23.5	34.7	38.19	10.9	19.2	N/A	19.2	44.7	34.3	36.4	48.7

a: Roadway types are determined based on HCM 2000, b: Arterial, c: Multi-Lane Highway (traffic signals spaced at 2.0 mi or more), d: Freeway
e: Ratio of mean travel time to median travel time, f: Data not available

(A): I-95 to I-78, (B): I-78 to I-80, (C): I-295 to US 130, (D): NJ 18 to US 22, (E): US 130 to I-295

*: The results of NJ 29 are shown in Appendix B
**: Note that the travel time data collected on NJ 29 were between 6 am and noon
***: Note that the average speed was calculated by taking total travel time divided by total travel distance

- Sample size presents that the total number of travel time data collected and processed. Note that US 1 (Segment C), US 1 (Segment D), US 9, NJ 42 & I-76, NJ 70, NJ 73, and NJ 208 & NJ 4 have a lower sample size compared to the other locations.

- Relatively high coefficients of variance (CV>0.2) were observed on NJ 17, NJ 208 & NJ 4, US 46 & NJ 3, I-80 & I-280, I-287(Segment A), I-287 (Segment B), NJ 42 & I-76, NJ 70, NJ 73, and NJ 29 for which the variations of travel time of these highways were deemed high.

- In terms of 95th percentile buffer index, the highest index was observed in US 46 & NJ 3, while the lowest index was observed in US 1 (Segment C), which means prediction of travel time on US 1 (Segment C) is more precisely than other studied routes.

- In terms of range of travel time, difference between the maximum and the minimum of travel time, the highest range of travel time was observed in US 46 & NJ 3, while the lowest range of travel time was observed in US 1 (Segment C).

TRANSMIT Data

The link-based TRANSMIT travel time data for I-287 N (northbound) was provided by TRANSCOM, which were applied to compare the travel time derived from Co-Pilot™ data. However, the node locations defined in Co-Pilot™ and TRANSMIT data are different. The nodes in TRANSMIT are the locations of EZ-Pass readers. The length of studied I-287N covered by TRANSMIT readers is approximately 42.2 miles long, which includes 7 readers (or 6 links). The length and the identification number of each link are specified in Table 37, and a comparison of Co-Pilot™ and TRANSMIT nodes is illustrated in Figure 79. Link 6 is the longest one with 20.46 miles.

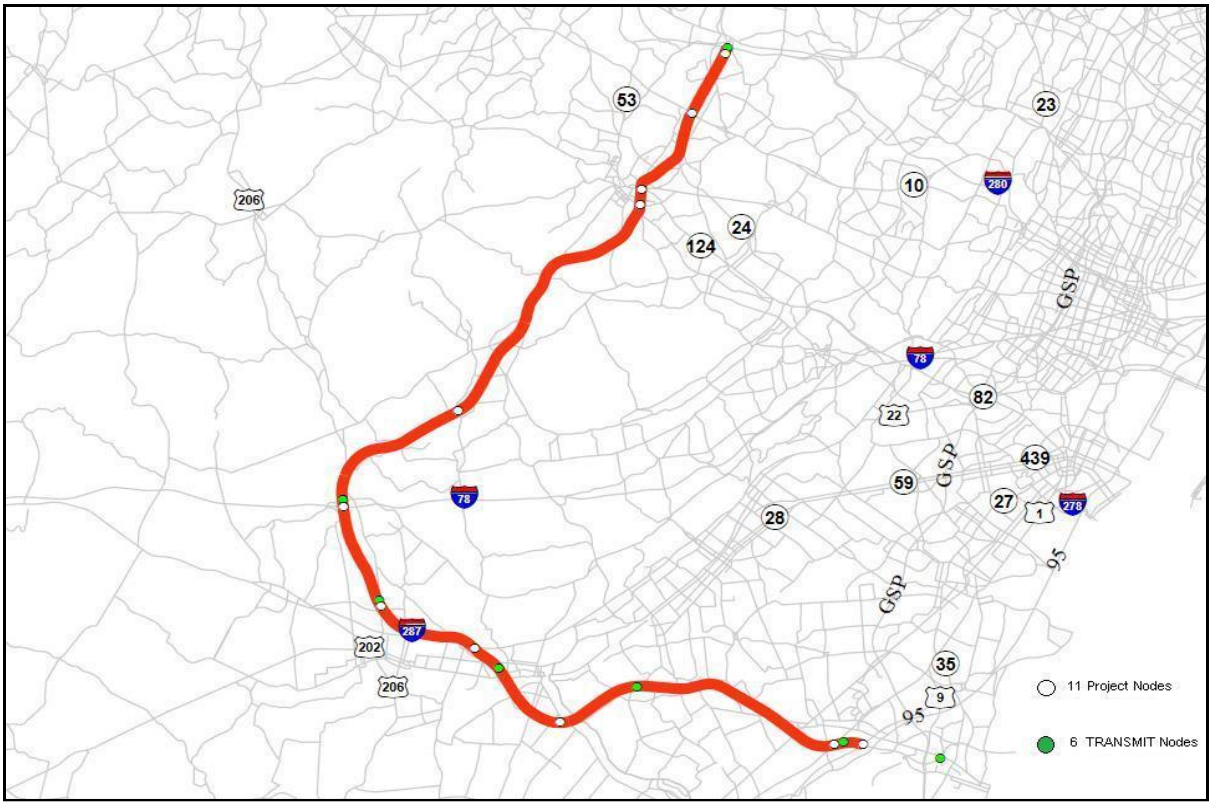


Figure 79. Nodes defined for Co-Pilot™ and TRANSMIT Data

Table 37 - Link Lengths of TRANSMIT Data on I-287

Mile post	Link ID	Length (miles)
0-0.93	5361672	0.93
0.93-7.71	5361673	6.78
7.71-13.50	5361674	5.79
13.50-17.66	5361675	4.16
17.66-21.44	5361676	3.78
21.44-42.20	5361691	20.76

Figure 80 shows the mean cumulative travel time with a 95% confidence interval for 10 departure times ranging from 6:00 to 8:15 A.M. for every 15-minute period. The relationship between travel distance and mean travel time was consistent or uniform for every departure time, and the value of the 95% confidence interval for each departure time was very small.

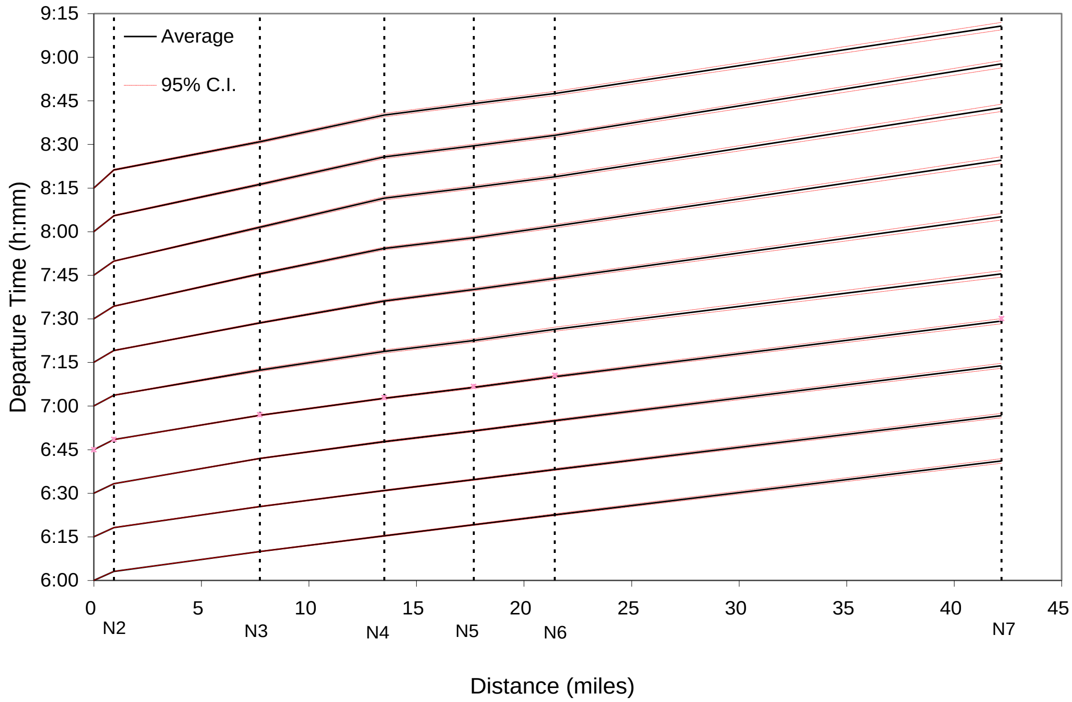


Figure 80. Mean and 95%CI Travel Times for different DPT on I-287 NB

With moving mean approach, the mean cumulative travel time for different departure times are shown in Figure 81. For vehicles departing from 6:00 A.M. to 6:15A.M., the needed travel time to complete the segment were near 41 minutes. However, if vehicle departing after 7:00 A.M., the travel time increased considerably due to recurring congestion.

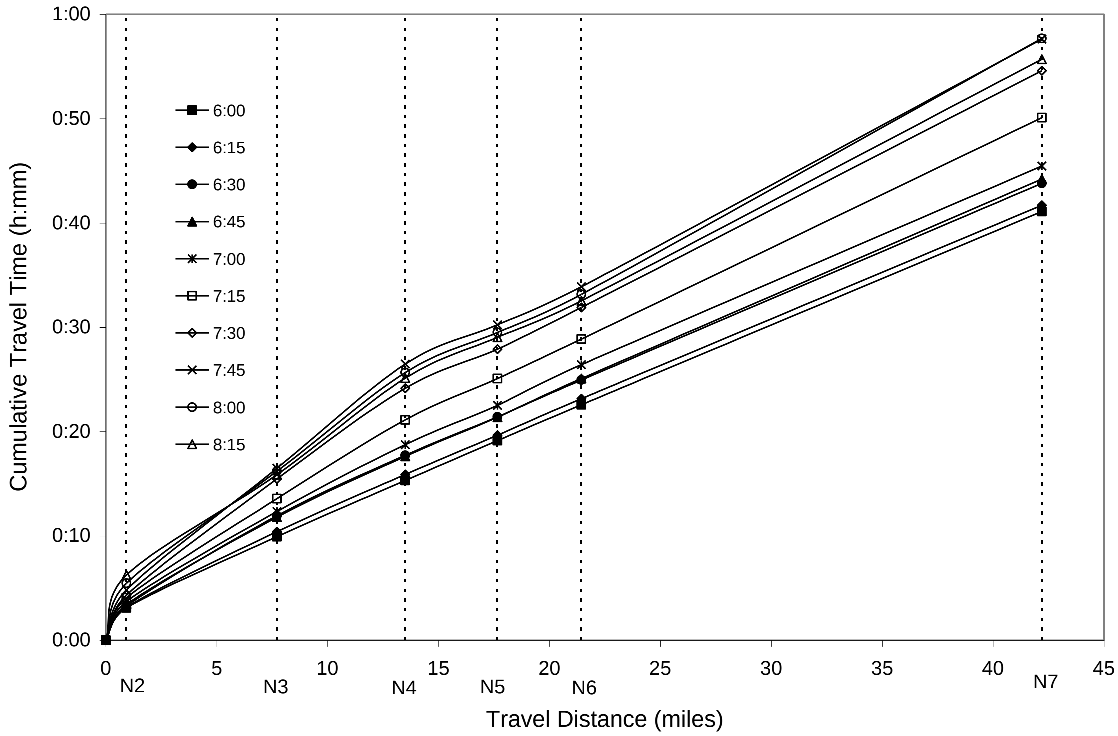


Figure 81. Cumulative Travel Times for Different Departure Times

Figure 82 illustrates the relationship between the mean travel speed and departure time on a link basis. The average link speed significantly decreased on links 1, 2, and 3 as departure time extended from 6 A.M. to 8 A.M., which contributed the longer travel time observed in Figure 81.

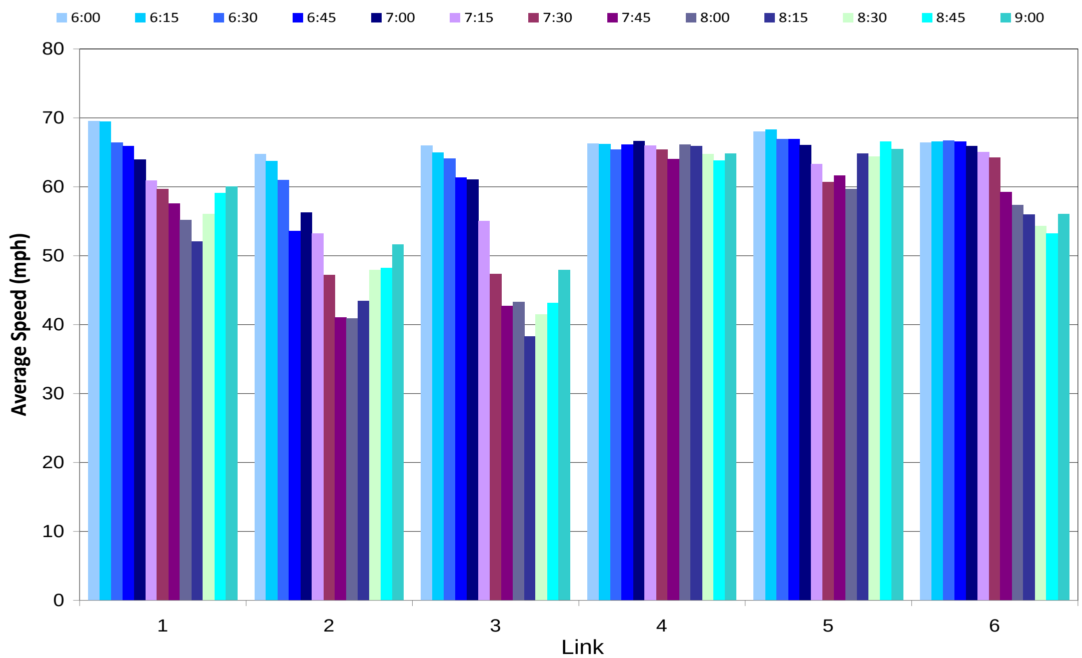


Figure 82. Average Link Speed

The average travel time for each link is shown in Figure 83. The average travel time was proportional to the link length and corresponded to the average link speed shown in Figure 82.

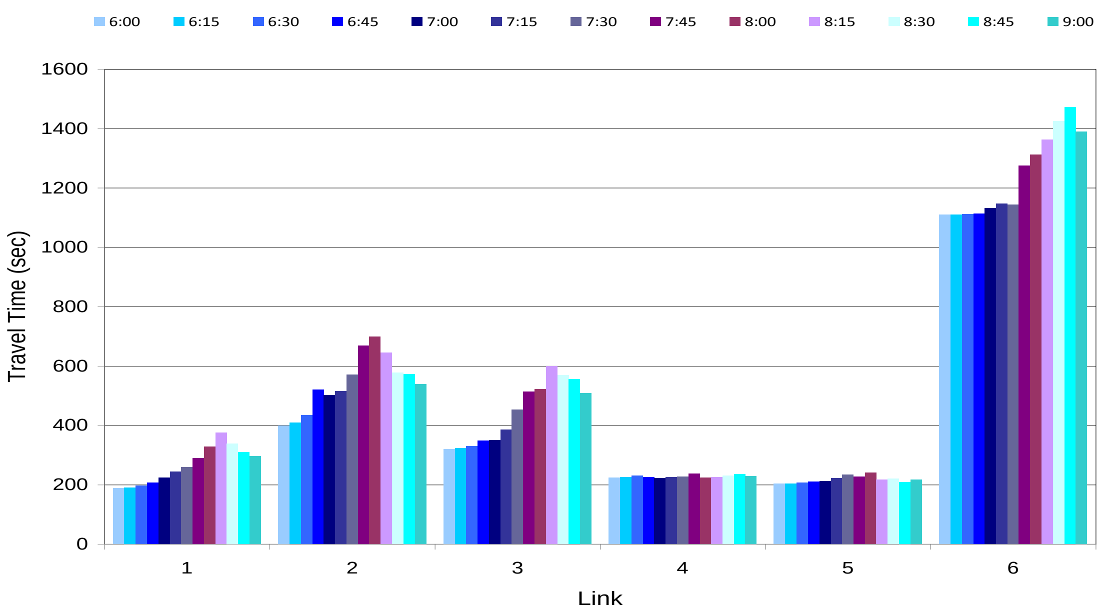


Figure 83. Average Link Travel Time

CONCLUSIONS AND FINDINGS

This report presents a path and link travel time variability study on selected congested highway segments in New Jersey. The estimated variability of travel time (VTT) can be used to determine the reliability of path travel time, which is a performance measure of the predictability of the arrival time at a destination. A set of 30-minute link/path travel time distributions were estimated by time of a day from 6:15 A.M. to 8:45 A.M. for each studied highway segment. The reliability of travel time was estimated using the buffer index based on both the 95th percentile travel time

The travel time data were collected through the use of Co-pilot GPS-enabled vehicle location devices for each of the studied highways for five weeks, which include the segments of NJ 17, NJ 208 & NJ 4, I-80 & I-280, NJ 24 & I-78, US 46 & NJ 3, US 22, I-287 (Segment A), I-287 (Segment B), US 1 (Segment C), US 1 (Segment D), US 9, NJ 42 & I-76, NJ 70, and NJ 73. In addition, the research team analyzed TRANSMIT link travel time (mean travel time and standard deviation on a 15-minute basis) data provided by TRANSCOM for a 40-mile segment of I-287, which were then compared to the data collected by Co-pilot devices.

The travel time data were analyzed at the link and the path level where the link boundaries were defined by NJDOT. The mean and standard deviation of each link and overall path were estimated based on the GPS-based location data.

It is worth noting the following: The variation of path travel time estimated directly through the Co-Pilot data is different from that estimated by adding the variations of individual link travel times. The addition of the link mean travel times plus their corresponding standard deviations overestimated the variation of path travel time due to the covariance between consecutive links such as driving behavior and non-uniformity of link characteristics (e.g., traffic light, access point density, pavement condition, pedestrian movement, etc.). The highest variations on each link generally do not all occur from the same travel time sample. In order to obtain accurate travel time variation, path based travel time data are recommended. If path-based data are unavailable, a method to correct the over-estimated variability using link-based data must be developed - a correction factor can be estimated that will match the corresponding path travel time distribution. This could be an immediate extension of this research project.

Few incidents were observed for most studied highway segments that were surveyed. Therefore, it was difficult to produce any statistically meaningful data on the impact of incidents on traffic conditions. From the limited data collected under incident conditions, it was found that the path travel time is dependent on the traveler's location at the time the incident occurred and the incident duration.

The main outcome of this study is a set of reliability indices and corresponding statistics tables for the studied highways for the morning peak period in 30-minute time intervals 6:15-6:45 A.M., 6:45-7:15 A.M., 7:15-7:45 A.M., and 7:45-8:15 A.M.), the the 95th percentile travel times, and the corresponding buffer index (or reliability index). US 1 (Segment C) (i.e., I-295 to US 130) had the lowest 95th percentile buffer index of travel time while I-287(Segment A) had the highest 95th percentile buffer index of travel time. Thus, the travel time on US 1 (I-295 to US 130) was more reliable than the travel times for other studied highways in the A.M. peak of the weekdays.

The main findings of this study are:

- The highest mean travel speed (59.9 mph) for all records in the A.M. peak was observed on the segment of NJ 24 & I-78, while the lowest speed (28.3 mph) occurred on the segment of NJ 208 & NJ 4. For mean speed of each departure time period, the highest speed (68.4 mph) was found at 6:30 A.M. on I-287 (Segment B). The lowest speed (23.5 mph) occurred at 7:30 A.M. on the segment of NJ 70.

- The highest travel time coefficient of variation (CV=0.4) to the mean for all records in the A.M. peak was found on the segment of US 46 & NJ 3, while the lowest CV (=0.09) was observed on US 1 (Segment C). For CV of each departure time period, the highest CV (=0.49) was observed at 7:00 A.M. on the segments of US 46 & NJ 3. The lowest CV (=0.03) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The highest range of travel time (43 minutes 45 seconds) for all records in the A.M. peak was observed on the segment of US 46 & NJ 3, while the lowest range (e.g. 7 minutes 51 seconds) occurred on US 1 (Segment C). For each departure time period, the highest range of travel time (42 minutes 57 seconds) occurred at 7:00 A.M. on the segment of US 46 & NJ 3, and the lowest range (1 minute 41 seconds) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The greatest buffer index of 95th percentile travel time (73.8%) for records in the A.M. peak occurred on the segment of US 46 & NJ 3, while the smallest buffer index (10.9%) was observed on US 1 (Segment C). For each departure time period, the greatest buffer index (109.1%) occurred at 7:30 A.M. on the segment of US 46 & NJ 3, and the smallest buffer index (4.3%) was observed at 7:00 A.M. on the segment of NJ 24 & I-78.

- The majority of the path travel time distributions were shown – using normality and log-normality tests - to follow a shifted log-normal distribution for the morning period from 6:00 to 9:00 AM. Only the distribution on the segment of NJ 208 & NJ 4 out of the eight that were tested was shown to follow a Normal distribution. For each of these distributions the associated 95% Confidence Intervals were estimated. Due to limited data for each 15-minute time interval the corresponding path travel time distributions could not be estimated.

- The majority of studied highways had a relatively high travel time coefficient of variation to the mean (CV>0.2). This is an indication that the selected highways, all of which were selected due to high amounts of congestion, exhibit high variations in travel times. This indicates that travel times on the more congested highways in the state exhibit a high amount of travel time unreliability.

RECOMMENDATIONS AND FURTHER STUDIES

Future studies should concentrate on the following areas listed below.

1. The travel time variability study could be expanded and enhanced by conducting the following tasks.

    - Identify a set of large corporations and public agencies (e.g. NJDOT, Dow Jones, pharmaceutical companies, UPS, Universities, other) that are large trip generators and request from them to ask their employees to install location based devices into their vehicles (e.g., GPS-enabled cell phones with a data plan, in-vehicle navigations systems integrated with a communication system).

    - Use GPS-enabled devices that also have wireless communication capability and a computer server such that you can view the vehicles in real time, record their data and produce real-time estimates of link and path travel times. This will reduce or eliminate the potential errors associated with manual observations.

    - Create a security routine that will seal a user ID from the system. Do not require from them to follow certain routes – any route for at least three months. This will provide a much larger sample size and allow an unbiased look into the trip making of people (completely anonymous and secure).

    - Retrieve parallel to the travel time study the corresponding traffic counts and speed from automated or manual detectors.

    - Retrieve all geometric and traffic flow data characteristics in order to conduct capacity analyses using real data.

2. The establishment of such a GPS-enabled and combined with roadside detectors traffic monitoring system will have the following benefits:

- Continuous estimation of OD-, path-,and link- based travel time for different vehicle classes (cars, buses, trucks);

- Consistent calibration of transportation and traffic simulators such as transportation planning models, Dynamic Traffic Assignment (DTA), and microscopic traffic analysis; Elimination of traditional traffic monitoring systems such as inductive loop detectors or other similar devices, which will result in substantial cost savings for the State. Given that such GPS system will be met with public resistance the State should provide strong assurances that all data to be stored will be anonymous and secure.

3. The TRANSMIT system provides a set of more comprehensive link travel time data on a 24-hour basis. Yet only aggregate 15-minute data are provided. TRANSMIT data can be further used to produce travel time estimates at the link, superlink or path level. Furthermore, the TRANSMIT system provides an excellent system to produce travel time results for both recurring and non-recurring traffic conditions – thereby a more statistically sound analysis can be carried out at the impact of incidents (capacity reducing events) on traffic conditions for the entire route (upstream and downstream of the incident location). Moreover, the TRANSMIT route data can be used to produce some good estimates of the OD matrix. This task can be given priority due to the fact that the TRANSMIT system is operational and TRANSCOM and its member agencies look for ways to improve their system.

4. Implement a traffic simulator and/or Dynamic Traffic Assignment (DTA) to the underlying network and use the collected GPS data to continuously calibrate the model together with up-to-date traffic counts. A DTA continuously calibrated model with real-traffic counts, roadway occupancy, and/or travel time data will be able to capture the impact of incidents at the network, sub-network, OD pair, path, link and vehicle class level. Comparative analysis between recurring and non-recurring traffic conditions can then be conducted in a systematic and consistent basis through the use of such a continuously calibrated model. A prototype can be developed for demonstration purposes at a NJDOT corridor that has an adequate traffic

surveillance system such as the I-80 or the I-287 (I-287 is also covered by the TRANSMIT system that produces good travel time data).

5. Integrate the continuously calibrated DTA model to the NJDOT's Congestion Management System, the transportation planning model, the traffic operations' signal optimization and traffic flow analysis models, and the PLAN4SAFETY software developed by the Rutgers Traffic Safety Resource center. The integration of a calibrated DTA model with the PLAN4SAFETY software will produce consistent crash rates for all the links of the NJDOT transportation network by producing more accurate traffic link/movement flow rate estimates and speed profiles – especially for links where no actual traffic counts exist.

The mean daily non-recurring delay for a road segment can be estimated by multiplying the daily vehicle miles traveled (VMT), found from the New Jersey Congestion Management System (NJCMS), by the mean time above the threshold time for the road segment. In driver trip making decisions, the variability of travel time might have a greater effect on travel decisions than the mean travel time.

A thorough study needs to be undertaken to estimate the threshold between recurring and non-recurring delay. The threshold estimated in this study was based on very limited number of incidents. In order to produce more robust estimate, a route needs to be surveyed for at least one year. This study should include comprehensive data collection of all the pertinent traffic flow parameters including; roadway capacity, traffic flow rate, link/path travel time, incident characteristics (e.g., type, location, duration, and capacity reduction).

It is recommended that a parameter to measure the reliability or variability of individual travel times should be incorporated into the NJCMS. Such a measure would give a threshold of the percentage travel time over the mean travel time that would not be exceeded 95% of the time. The study proposed above could be used to produce an estimate of the reliability of individual travel times for specific routes.

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APPENDIX A: LITERATURE REVIEW

The primary purpose of the literature review was to identify and review data collection technologies currently used in transportation industry and to study current methods of analysis of travel time variability as this study requires extensive travel time data collection on New Jersey highways. In this section, the results of investigated travel time collection technologies, studied the application of these technologies, and evaluated their applicability to the needs of this study, were discussed and organized into four sub sections, including Travel Time under Recurring and Non-recurring Congestion, Technologies for Collecting Travel Time Data, Methods for Estimating Travel Times, and Travel Time Variability and Reliability.

1. Travel Time under Recurring and Non-recurring Congestion

A congested route has been defined as any type of origin-destination path that experiences travel speeds during the day which are slower than what would be experienced under "free flow" conditions. For planning purposes, this type of definition is broad and far reaching. Under such a definition, most highway or transit links would be classified as experiencing some level of congestion. Instead, congested routes can be identified with the use of performance measures that quantify the congestion of the roadway. The list of potential performance measures is extensive. Some of those considered by the congestion management subcommittee for identification of congested locations include the volume to capacity ratio (V/C), the level of service (LOS), travel speed, and travel time delay. An advantage to using speed and delay are that they are understood by the general public. A disadvantage to both LOS and V/C is that they tend to focus discussion on system improvements, instead of allowing for consideration of demand management as well. Also, LOS cannot detect small changes in performance as well as the other measures.

There are two types of congestion, recurring and non-recurring.

1. Recurring congestion generally occurs on a daily basis and develops in urban

and suburban areas because of excess demand over the available supply. The existence of recurring congestion will cause an increase in the mean travel time if we compare the travel time under recurring congestion with the travel time without traffic congestion. That is to say, recurring congestion can be characterized by the expected travel time value.

2. Non-recurring congestion is caused by planned/unplanned events that disrupt the normal operations of a road network and reduce roadway capacity. Such events include construction, traffic accidents, lane closure, bad weather, and special events. In some routes and areas, such as downtown areas, bridges, highway toll road segments, traffic congestion caused by such uncertain events occurs frequently. Travel time variability is highly dependent and affected by this non-recurring delay. With the impact of non-recurring congestion, the link and path travel time distributions always show obvious asymmetry and long tail on the right side.

Because non-recurring congestion has such a significant impact on the expected travel time, it needs to be included in the travel-time based models to improve decision reliability. With the consideration of uncertain information embedded in the historical travel time distribution, travelers can reduce their risk of selecting a route with a very high variability in travel time.

Several methodologies exist in the literature and have been used for predicting non-recurring delay. These include: (i) Probabilistic Distributions / Conditional Probabilities (Golob et al., 1987; Giuliano 1989; Garib et al., 1997; Sullivan, 1997; Jones et al., 1991, NA.M. and Mannering, 2000; Ozbay and Kachroo, 1999), (ii) Linear Regression (Garib et al., 1997; Ozbay and Kachroo, 1999), (iii) Time sequential modeling (Khattak et al., 1995), (iv) Decision trees (Ozbay and Kachroo, 1999), (v) Classification Trees (Breiman et al., 1984), (vi) Classification and Regression Tree (Breiman et al., 1984; Cios et al., 1998; Salford Systems, 2000), and (vii) Non-parametric regression (Smith. et al., 2001).

Kamga et. al. (2006), utilized a DTA model to produce simulated estimates of incident delay at the network, Origin-Destination pair, path and link level. The following key results were obtained: An incident may increase, decrease or show no change in the overall network travel time; Some OD pairs may see an increase in travel time, some a decrease and some no difference; downstream OD pairs may see improvement in their travel time; even OD pairs upstream of the incident may see a decrease in their travel time unlike conventional belief; the delay experience by travelers should be called "temporal delay" since the Incident delay is the difference of the total trip travel time under incident conditions minus the corresponding trip travel time that would have been experienced by travelers under normal traffic conditions. The resulting incident delay is not the one experienced through the incident zone as any incident causes changes to the traffic conditions both upstream and downstream. For example, if a network operates under oversaturation conditions and an incident occurs it may – depending on the network's topology and traffic flow dynamics – cause the traffic conditions downstream of the incident to improve to within the under saturated regime due to the "metering" effect of the incident.

Sen and Pillai (2001), using the idea of the multi-objective model, developed a mean-variance model for route guidance problems. The model solution helped travelers find a tradeoff between the expected path travel time and the path travel time variability. However, they made an assumption that link travel time is a multivariate normal random variable, which may not be true in real travel time distribution. By making this assumption, the distribution of link travel time can be completely described by the mean and the covariance. The mean-variance model ignores the asymmetry properties of travel time distribution, and may lead to undesirable decisions.

Lu et al. (2005) discussed a method for improving decision reliability through analyzing the moments and central moments of historical travel time data. Because of the existence of traffic congestion, especially non-recurring traffic congestion, travel time is generally a random variable with an asymmetric historical distribution. They applied statistical methods to obtain the higher order moments and central moments of historical travel time, which provided quantitative information on the variability and asymmetry of travel time. The information was useful in making reliable decisions and avoiding potential scenarios that could lead to extremely high costs and the method was based on Advanced Traveler Information Systems, which provide useful historical travel time information for traffic networks. With the development of technology, historical travel time information could be collected more easily than before. Their result showed that the reliability of recommended routes was improved, which in turn can help travelers avoid selecting routes with higher non-recurring congestion was caused by incidents and special events.

Bremmer et al. (2004) discussed the speed and travel time data derived from the loop detector network on Puget Sound urban freeways were used by WSDOT to measure and communicate real-time travel times on 12 major commute routes. Continued work toward analyzing different types of congestion distinguished between recurring congestion caused by inadequate capacity and non-recurring congestion caused by incidents, inclement weather, and other factors such as travel to and from major sporting events. The agency also made progress in measuring what is of most concern to commuters and haulers: travel time reliability.

Chu et al. (2005) estimated the travel time for a highway segment by applying the Adaptive Kalman filter technique that incorporated two data sources, point detector data and area-wide probe data. The traffic system was regarded as a discrete-time dynamic system. The system model was described with a state equation and an observation equation based on the traditional traffic flow theory.

An advantage of the method was its capability to work with the erratic detector data and model errors. The algorithm was tested in a stretch of freeway using a microscopic simulation model. The algorithm outperformed the probe-based method and the double-detector based method under both recurring and non-recurring traffic conditions despite errors in the loop detector using a microscopic simulation model, PARA.M.ICS. Some sensitivity analyses proved the robustness of the method by showing its capability to work with the erratic point detector data at different freeway segments under different probe rates.

Quiroga C.A. and D. Bullock (1999) utilized GPS-based vehicle probes to produce estimates of link and path travel time under a methodology developed called Travel Time with GPS (TTG). The TTG includes a transportation system spatial model that includes freeways and surface streets, a geographic relational database, and a procedure for linearly referencing GPS data using dynamic segmentation tools.

Chen and Chien (2001) performed travel time prediction based on real-time information provided by probe vehicles. Specifically, the mean travel time of probe vehicles at each time period was used as the real-time observation to predict the travel time in the next (or future) time period. They observed that the path-based travel time prediction method has a better performance over the link-based prediction method under the normal flow condition. They suggested that further research is needed in order to explore the relationship between the probe percentage and the prediction error.

Rice and Zwet (2001) demonstrated how knowing the current speed on a corridor also helps in predicting travel time. Their results showed that travel time on a 40-mile corridor could be predicted with a standard deviation of 8 minutes when current speeds are known, compared to a standard deviation of 15 minutes when such information is not available.

Bickel et al. (2004) discussed statistical issues that have emerged with a traffic performance measurement system, PeMS, that currently functions as a statewide repository for traffic data gathered by thousands of automatic sensors. They focused on detecting sensor malfunction, imputation of missing or bad data, estimation of velocity, and forecasting of travel times on freeway networks.

Hallenbeck et al. (2003) presented in a report for WSDOT a research effort to determine the nature and cause of congestion on Seattle-area freeways based on an analysis of available databases of traffic incidents and freeway performance. This research produced a method for analyzing the recurring and non-recurring components of urban congestion; the method is based on a conceptually straightforward approach and utilizes readily available data.

FHWA (1999) performed a study where day-to-day variability in travel behavior was measured using GPS data collected from a sample of 100 households. The specific objectives of the research project were to: explore day-to-day variability in travel behavior with respect to selected variables such as trip chaining, departure time, trip frequency, and path selection; compare day-to-day variability found in the GPS-based data set against that reported in the literature to assess the potential benefits of using a GPS-based data collection methodology; explore variability in trip making characteristics; and compare GPS-based results of the study to other research on day-to-day variability in travel behavior. The report concluded that GPS based travel data sets appear to be able to: better capture short and infrequent trips (Yalamanchili et al., 1999), provide accurate temporal (time-of-day) information without round-off (Murakami and Wagner, 1999), provide multiple days of travel information with plausible measures of day-to-day variability (this study), and offer detailed route choice, spatial location, and travel itinerary information not available in other travel survey data sets. Within the scope of the study, the full potential of GPS based travel data sets was not exploited. Detailed route choice, spatial location, and travel itinerary data present in the data set were not used in the analysis of the study. The authors suggested that further research should examine day-to-day variability in route choice, spatial location, and action space.

Quiroga et al. (2002) described a tool called GPS-Based Evaluation of Travel Time (GETT) that measures travel time and delay along arterial corridors using global positioning system (GPS) and geographic information system (GIS) technologies. GETT uses linearly referenced GPS data and checkpoints along the routes of interest to calculate partial and cumulative travel times, speeds, and delays.

Belliss (2004) presented methods of using low cost, handheld GPS units to obtain accurate near-instantaneous speed data at short intervals. This data allows valid calculations of speed, delay, and acceleration without the need for costly instrumentation and constant recalibration.

Among others, the use of probe vehicles (also known as floating car) to obtain link travel time is considered as one of the most efficient and promising methods. Although research has studied such systems theoretically, few empirical observations have been made of the variables that may affect information accuracy. Brackstone et al. (2001) reported on the initial implementation of a set of experiments, which attempted to assess the effects of differing transmission intervals, sampling frequency and inter driver variability on data quality, for a beacon based probe vehicle system. The authors concluded that information provided by beacon based probe vehicle systems is likely to be fairly robust to microscopic traffic fluctuations and able to provide a good indicator of network status. However, their reliability for use in incident detection has not been established.

One of the major problems of this approach, as presented by Torday (2003), is the determination of the accuracy level with which an aggregated travel time based on sampled data (for a given probe vehicle ratio) can match the aggregated travel time experienced by the overall vehicles data set. To answer this question, the individual travel time measurements evolution between and within the aggregation periods must be well identified. This evolution is significantly dependent on the type of network. Indeed, if the variability of a freeway link travel time data set (within an aggregated period) is generally low, it isn't the case for urban freeway link. Furthermore, bias problems have been highlighted by Sen et al. (1997) for urban network link travel time samples when the probe vehicles ratio is not equal between the different turnings flows leaving the link. Hellinga and Fu (1999) have clearly demonstrated how the influence of traffic signals and platoon effects are basically responsible for these phenomena. The implications of this link travel time data set variability for optimal routes calculation has also been partially described by Sen et al. (1999). These observations have illustrated the disadvantages of using an aggregated mean to describe a data set with a wide variability.

Ziestman and Rilett (2000) have shown the advantages of using a disaggregated-based travel time estimation instead of an aggregated one. Torday (2003) explained how a more detailed definition of network links in urban and signalized areas can lead to a reduction if the variability of travel time datasets and thus improve the accuracy of probe vehicle-based estimations.

Robinson and Polak (2004) presented three statistical criteria for the comparison of models for the estimation of urban link travel time from inductive loop data; accuracy, transferability, and distribution. They show that there is a limit to the accuracy achieved by any urban link travel time model and present a way of quantifying the transferability of a model. Also, they present an alternative approach for estimating travel time using data from single-loop inductive loop detectors, using the method of k-nearest neighbors.

2. Technologies for Collecting Travel Time Data

Travel time data collection technologies listed below will be reviewed.

- Test Vehicle Techniques
- ITS Probe Vehicle Techniques
- The Electronic Toll Collection (ETC) System – EZ Pass
- Probe-Based System – Wireless Location Technology (WLT)

Test Vehicle Techniques

Test vehicle techniques (often referred to as “floating car”) are the most common travel time collection methods and consist of a vehicle(s) that is specifically dispatched to drive with the traffic stream for the express purpose of data collection. The technologies within this category are illustrated below:

- A passenger in the test vehicle can manually record travel times at designated checkpoints using a clipboard and stopwatch, or computer instrumentation may be used to record vehicle speeds, travel times or distances at preset checkpoints or intervals.
- An electronic distance measuring instrument (DMI) attached to the vehicle's transmission can be coupled with a portable computer to record speeds and distances traveled.
- A GPS receiver coupled with a portable computer or personal digital assistant (PDA or cell phone) can be used to record the test vehicle's position and speed at time intervals as frequent as every second.

ITS Probe Vehicle Techniques

ITS probe vehicle techniques utilize passive instrumented vehicles in the traffic stream and remote sensing devices to collect travel times. The ITS probe vehicles can be personal, public transit, or commercial vehicles and often are not driving for the express purpose of collecting travel times. ITS probe vehicles also typically report travel time data to a transportation management center (TMC) in real-time. Probe vehicles may be equipped with several different types of electronic transponders or receivers.

- A signpost-based system, typically used by transit agencies for tracking bus locations, relies on transponders attached to roadside signposts. Similar systems [e.g. Automatic Vehicle Location (AVL) Systems and Automatic Passenger Counter (APC) Systems] can be applied for tracking dynamic information, such as vehicle locations and arrival times. It is worth noting that this project's research team led by Chien, has conducted a research project sponsored by NJDOT to predict NJ Transit's bus travel times under congested conditions using Automatic Passenger Counter (APC) data.
- AVI transponders [e.g. TRANSCOM's System for Managing Incidents and Traffic (TRANSMIT)] are located inside a vehicle and are used in electronic toll

collection applications. This system utilizes antenna readers installed at regular intervals along the highway to identify the time when each transponder-equipped vehicle passes by. The detection of an equipped vehicle at successive readers downstream produces estimates of link travel times. Note that the research team has substantial experience in using TRANSMIT data. Mouskos, et al (1999 and 2000) conducted the evaluation of the TRANSMIT system where Chien, et al (2001) applied the data for predicting travel times. The TRANSMIT system is expected to be installed at various NJDOT facilities, including the New Jersey Turnpike and the Garden State Parkway (GSP).

- Ground-based radio navigation systems use triangulation techniques to locate radio transponders on vehicles, and are used in route guidance and personal communication systems.

- The monitoring of cellular telephone activity is also being tested for potential travel time collection applications. The use of cell phones could be utilized to produce the distribution of travel times along a transportation network. However, it requires partnership with a cellular carrier. Such an agreement may not be feasible to achieve for this project, however NJDOT should be aware of it for a potential future implementation.

- GPS receivers use a network of satellites to determine vehicle position and are becoming common for route guidance and "mayday" security applications. GPS is expected to be part of every cell phone in the future as part of the E911 initiative. Consequently, one potentially could say that transportation agencies might devise a traffic surveillance system that would be GPS based with minimal capital investment. New Jersey Transit (NJT) has installed GPS receivers on some of its buses and stores the GPS data into a database for analysis. Corridors that are covered by NJT buses equipped with GPS receivers will be used to produce bus travel time distributions for the time period of interest. A formal request will be made to NJT to retrieve this data. The research team has extensive experience in working with NJT GPS data within the City of Newark through a research project sponsored by the Great Cities University Consortium (2002). In addition, within the same project, the previously mentioned Co-Pilot™ In-vehicle Navigation System was used to obtain parallel travel time data for automobiles traveling on the same route from the Newark Penn Station to Emmet St. The auto GPS data and corresponding bus data were used to compare the travel times between the two modes of traffic. The research team was among the first to utilize the GPS based Co-Pilot™ system and evaluate its performance through the Transportation Information and Decision Engineering (TIDE) Center (NJIT, Princeton University and Rutgers University) from 1998 (directed by L. Pignataro) to 2003 (directed by S. Chien).

The next section highlights Electronic Toll Collection System, Wireless Location Technology and measuring travel time under a congestion condition.

The Electronic Toll Collection (ETC) System - EZ Pass

ETC tagged vehicles have the potential to provide a wide range of information, such as

- *Basic Traffic Parameters:* Space-mean speed, link travel time, and path travel time (flow can also be roughly estimated by linking tag counts to the proportion of vehicles with tags).
- *Incident Detection:* With the use of algorithms that note when vehicles are “late” in arriving at a reader site, incidents can be automatically detected.
- *In-Vehicle Information:* It is possible to upgrade the communication hardware to allow the driver to receive traffic information.
- *Fleet Information:* Transit and commercial fleet dispatchers could track their vehicles as they move along instrumented highways.

Advantages and disadvantages of ETC Tagged Probe Vehicles are listed below.

Advantages

- Utilize existing vehicles and toll tags*:* The vehicles being monitored are already being driven with working toll tags. Neither the interested agency nor the individual driver has to make any alterations at the vehicle level to implement the system.
- High volume of data: The volume of data depends only upon the market penetration of ETC tags on the link. Therefore, links near or on toll facilities will have large numbers of vehicles, especially as the ETC system matures.
- Wide data range: Data may be collected continually, 24 hours a day and 7 days a week. The times of greatest congestion will usually have the highest percentage of tags.
- Automatic Recording: The travel time data is recorded automatically. This leads to less error than floating car techniques or estimating travel times from estimated speeds based on data collected by road-based detectors.
- Low operating cost: For the volume of data collected, there is a relatively low cost and low staff needs.
- Better Convenience: There is no disruption of traffic while monitoring travel times.
- More Accuracy: ETC tagged vehicles have been found to be accurate-at high speeds and with multiple vehicles. There is less opportunity for bias than with traditional floating car techniques since the probes drive naturally.
- Can provide lane specific data: Antennas can be installed to detect vehicles in only one lane if desired (e.g., HOV or HOT lanes).

Disadvantages

- Startup costs: While startup costs are not high relative to comparable systems, they may still be significant.

- Dependence upon market penetration of tags: The system's utility depends upon how many drivers choose to equip their vehicles with toll tags. In areas far from toll facilities, or on segments bypassing toll roads, there may be an inadequate number of probe vehicles to provide meaningful information.

- Permanent infrastructure: Once in place, it is costly to transfer components to different locations, as opposed to techniques like floating cars, cellular geo-location, or GPS systems.

- Privacy concerns: Agencies using electronic toll tags as travel time probes have to ensure that individuals cannot be tracked; however, the general public may still distrust the technology.

Various research studies and operational tests were conducted in regards to measuring travel times through the use of the electronic toll collection (ETC) system which are discussed as follows:

Wright and Dahlgren (2001) discussed that ETC on the eight bridges crossing San Francisco Bay provided the means for a relatively simple and low cost system for measuring travel times on bridges and roads. The toll tags used for ETC could be recognized by readers at various locations. The time of reading was recorded so that the time difference between when a vehicle passes one reader and another could be obtained. It was found that the application of ETC data improved facilities efficiency and reduced user's delay.

Saka and Agboh (2002) discussed the aggregated impact of ETC (also called M-Tag) deployment at three toll plazas in the Baltimore Metropolitan Area. The toll plazas were treated as multi-server queuing systems. The delay as well as travel time data were used to estimate mean vehicular travel speed at the toll facilities. The analysis involved the development of simulation and deterministic models used to generate traffic flow parameters, including speed and driving cycles for the study areas. The methodology and results presented herein were expected to serve as a guide for making decisions and estimating benefits relating to the use of ETC technology.

Battelle (2002) evaluated the benefits of potential technologies that could be used to collect truck travel time data in place of specialized onsite data collectors at border crossings between the U.S. and its neighbors - Mexico and Canada. The evaluated technologies were focusing principally on sensing technologies. Automatic Vehicle Identification (AVI) referred to the components and processes of a toll collection system in which the equipment was able to determine ownership of the vehicle in order to charge a toll to the proper customer (used for electronic toll collection (ETC)).

Haugen and Wold (2004) discussed the use of ETC tags for a travel time study in Norway. The data collected through the use of the technology proved to constitute a well suited basis for evaluation of traffic flow quality, and therefore was also well suited for traffic information and route guidance systems. It was found that the analyses made of point data versus segment data show that travel speed was a more stable parameter than point speed and therefore better suited as a basis for traffic control and information (travel time and delay are calculated from travel speed).

Mark (2000) discussed the deployment of the vehicle tag project in San Antonio, as a part of the Metropolitan Model Deployment Initiative (MMDI). It was found that vehicle tags and readers were technically able to collect accurate and reliable arterial travel times, but only if an adequate LMP (Low Market Penetration) was achieved. The LMP of the tags was computed by counting the number of tags read at a specific reader divided by the total number of vehicles that passed the reader in the same time period.

Although AVI tags were reliable and accurate for measuring travel times, the low LMP made it difficult to measure travel times consistently throughout the day. San Antonio instead decided to use inductive loop detectors and point-source detectors to capture speeds on arterials and minor expressways.

Probe-Based System - Wireless Location Technology (WLT)

A probe-based system is used to collect a sample of vehicle positions in both time and space. There are two approaches for a probe-based system. The first is the use of wireless location technology (WLT) to automatically and anonymously track wireless devices as they traverse the system and the second is to “recruit” floating vehicles equipped with GPS devices to voluntarily report their location as they travel. Given the challenge of recruiting floating vehicles, the second approach has seen considerably less attention than WLT-based approaches.

In 2005, NCHRP published the report *Private-Sector Provision of Congestion Data Probe-based Traffic Monitoring; State-of-the-Practice Report* which provided a description of ongoing deployments of wireless location technology (WLT) based traffic monitoring systems. In some cases, the information incompletely described the system or its performance and performance claims have not been validated by an independent source.

- Initial deployments did not produce data of sufficient quality or quantity to provide reliable traffic condition estimates.

- In general, the simulation studies have shown that WLT-based systems can conceptually produce good performance for simple networks.

- Most recent WLT deployments rely on cell handoff data, as opposed to “direct” vehicle location determination. Despite this, no published simulation studies have explicitly examined a handoff based WLT system.

- In a number of cases, inadequate sample sizes were generated to produce accurate speed estimates.

- Transportation agencies have historically not defined detailed performance requirements for these systems. Prior to using this technology, a DOT should ensure that requirements are in place to support the transportation applications for which the data will be used.

- Many deployments have lacked a well-developed, independent evaluation that quantitatively assessed the system performance. Future deployments should include an independent evaluator that will examine the availability and accuracy of the data.

- Many of the institutional and legal issues are not clearly defined in past deployments and financial and contractual information is also not often available in the literature.

For each deployment information was provided for the following categories:

- System Coverage**:** A description of the size and type of network monitored by the system. Depending on the data available, the system coverage may be expressed in terms of geographical boundaries or lane-miles of roadway. An indication of the spatial dispersion of roads and whether the monitored region was an urban or rural area is also provided.

- Participants: A listing of the public and private sector organizations involved in the project.

- Relationship with Cellular Service Providers: The number of wireless providers involved in the project, as well as the nature of their involvement.

- Technology: A brief description of the technology used in the deployment.

- DOT Requirements: The performance requirements specified by the transportation agency, if any.

- General Results: The evaluation results of the deployment, if any. This may include discussions of speed estimation accuracy, location accuracy, system availability, and any operational or institutional issues that were encountered.

- Independent Evaluator: This category was an independent evaluator for the project.

Deployment of this study and its related information are summarized in Table A-1.

Fontaine et al. (2007) discussed that traffic monitoring systems based on wireless location technology (WLT) and developed a methodology to estimate sampling parameters based on localized traffic conditions in the network. In WLT systems, the roadway network was disaggregated into smaller areas based on cellular coverage areas.

Prior tests of WLT based systems have been unsuccessful because they have treated the road network as a homogeneous entity. They discussed that two zonal sampling strategies were examined and tested using three simulated networks. For networks with simple geometry or uniform congested traffic conditions, there were no significant differences among the sampling strategies. The results of this research indicate that the homogeneous approach used by earlier deployments has limitations, and results could be potentially improved by tailoring sampling parameters to a more localized level.

They found that both the availability and accuracy of speed estimates were influenced by the sampling approach used by a WLT-based system and the geometric and traffic characteristics of the roadway network played an extremely important role in dictating the accuracy of speed estimates. Three networks were simulated for two zonal sampling strategies that distributed probes under complex road network and improved speed estimation accuracy by 10 percent.

Smith et al. (2003) discussed a monitoring of traffic operations and management that sampled the traffic conditions by tracking a limited number of probe vehicles as they traversed a network. Wireless location technology (WLT) was developed to allow for the geo-location of mobile wireless devices (the cellular telephones). They provided a comprehensive assessment of WLT-based traffic monitoring and evaluated one of the most recent operational tests in 2001.

Virginia Department of Transportation (VDOT), Maryland State Highway Administration (MSHA), and US Wireless Corporation (USWC) conducted research in the Washington, D.C. region that used an early generation WLT-based system that produced link speed estimates of moderate quality that provided an optimistic outlook for the use of this technology in future traffic monitoring applications. They recommended that a basic research program commence that addresses the complex sampling and map matching challenges that must be surmounted to make accurate, reliable WLT-based system monitoring a reality.

There were three major data collections that took place during daylight hours. One collection was for links that are classified as freeway, one for links that are classified as high-speed major arterial, and one for low-volume/speed urban links. The researchers found that the WLT-based system was unable to reliably collect sufficient samples for estimating conditions on low-volume/speed urban links. The early-generation WLT-based traffic monitoring systems were not ready to provide the accuracy and availability needed by modern traffic management systems. Also, the systems measured speeds within an error of 10 percent on major routes points.

Table A-1- Wireless Location Technology (WLT) Based Traffic Monitoring Systems

	Hampton Roads, Virginia Field Test	Baltimore, Maryland Field Test	Missouri Field Test
Deployment Location	Hampton Roads, Virginia.	Baltimore, Maryland and the suburbs of Washington, DC.	Statewide deployment in Missouri.
System Coverage	Freeways and arterials in the Hampton Roads region of Virginia.	Freeways and arterials.	First, a prototype test will be conducted on no less then five freeway miles and five arterial miles. Then, full deployment will provide traffic data for 5500 miles of roadway in Missouri.
Project Period	2003 - Present.	A two-year agreement starting in October 2004.	Request for proposals released in 2005, currently negotiating a final contract.
Participants	Virginia Department of Transportation, Federal Highway Administration, AirSage, and the University of Virginia.	Public-private partnership between Delcan-NET, ITIS Holdings, the I-95 Corridor Coalition, and the Maryland State Highway Administration.	Not finalized.
Relationship with Cellular Service Providers	AirSage has partnered with Sprint on this field demonstration.	ITIS Holdings has a contract with Cingular.	Not known at this time.
Project Goals	Provide travel data, including travel time and speed information on all roadways.	Provide traffic information though CHART on freeways and major arterials in Baltimore.	Obtain and disseminate traffic data for 5500 miles roadway maintained by the Missouri Department of Transportation.
Technology	AirSage is using their technology patented in January of 2005 to estimate vehicle location, speed, travel time, and other performance measures on roadways in Hampton Roads. The technology works by mining data that is already collected by cellular service providers. A cell phone's location is estimated when it leaves and enters a cell within the cellular network using characteristics of the	The system works by mining data from cellular providers that estimate a cell phone's location, for cell phones that are turned on, as they transfer between cells in a network. Once the location of a cell phone has been estimated several times, then an estimate is made about the travel time of road segments that the driver has traveled on. This data is fused with existing RTMS detectors and incident information to determine a final estimate of travel times and speeds. Data is	Not known at this time.

	signal. The data is transferred through a firewall from the cellular provider's system to an AirSage computer after all personal information is stripped and a unique identification number is assigned to each cell phone. The information is then transferred to the main AirSage computer system where information is aggregated and converted to travel time and speed estimates.	aggregated for the road segments and travel times and speeds are calculated.	
DOT Requirements	None.	The Maryland Department of Transportation contract states "The Department may only integrate Fine Data into CHART if it is demonstrated to the satisfaction of the Contractor that the Fine Data will not as a result be made publicly available," but does not cover issues of accuracy and coverage of the system.	Plan and carry out a development test, full deployment, and traveler information services that make the data available to the public.
General Results	The project is currently in the development phase. There are no results yet to report. The project is currently 2 years behind schedule. Field evaluation is scheduled for December 2005.	Not yet available.	To be determined.
Independent Evaluator	Due to setbacks the data from the system has not been made public and the system has not received a comprehensive evaluation. The University of Virginia has been contracted by VDOT to perform an independent evaluation.	University of Maryland	Not known at this time.

Source: NCHRP Project 70-01, "Private-Sector Provision of Congestion Data Probe-based Traffic Monitoring: State-of-the-Practice Report," University of Virginia Center for Transportation Studies: Virginia Transportation Research Council, November 21, 2005

The limitations of WLT-based monitoring shared with other probe-based systems were sampling, speed variance, and WLT-based monitoring. One of the difficulties of using any probe-based system is determining the relationship between the characteristics of the probe sample and the entire population. Another issue encountered by probe-based systems was how to account for changes in population speed variance. WLT-based systems often had a considerable amount of error in the position estimates that could have a direct impact on whether a WLT-based system could match a vehicle to a road. The errors could potentially require larger sample sizes for WLT-based systems than probe systems based on AVI readers.

Yang (2006) discussed the travel time variable that was a measure of the effectiveness of transportation systems including traffic signal timing control coordination, incident detection, traffic assignment algorithms, and economic studies.

The Global Positioning System (GPS) tested vehicle technique, which involved collecting data with the aid of instrumented vehicles capable of receiving GPS signals for position and time information, and was used to collect outbound peak hour traffic data. The vehicle tracking unit monitored a vehicle's location and travel time information and utilized the wireless data network to transmit data to the web server where the data (i.e., test vehicle ID, longitude, latitude, speed, direction, time stamp, date, etc.) could be accessed and the time stamp data was used to calculate segment travel times. They found that the potential and effectiveness of using the time series modeling in the prediction of arterial travel time showed good prediction results.

3. Methods for Estimating Travel Times

Hess et al. (2005), applied the value of travel time savings (VTSS) as an estimate for measuring delay for use in a mixed logit model. The authors demonstrated that the VTTS is an important willingness-to-pay indicator used for measuring travel time reliability, for example, for cost–benefit analysis in the context of planning new transport systems, or for pricing. In discrete choice models, the computation of VTTS measures is relatively straightforward, especially in the case of models using linear utility functions based on fixed taste coefficients. They have raised important issues associated with the estimation of VTTS using Mixed Multinomial Logit Models (MMNL). These issues are related to the difficulty of maintaining consistency between the theoretical assumptions on which the models are based, the actual behavior of decision-makers, and the data collection and model specification constraints. The research emphasizes avoiding the use of unbounded distributions as a means of capturing heterogeneity in estimating time. It also suggests using MMNL models to estimate travel time reliability by taking into account the effects of random taste heterogeneity. Brownstone et al. (2005) discussed that the most important is the “value of time” (VOT), i.e. the marginal rate of substitution of travel time for money in a travelers’ indirect utility function. Another is the value of reliability (VOR), which measures travelers’ willingness to pay for reductions in the day-to-day variability of travel times facing a particular type of trip. In addition, the extent of heterogeneity in VOT and VOR across the population of travelers has been shown.

Yaron et al. (2006) described two distinguishable modeling approaches based on modeling the attitudes of travelers to the unexpected day-to-day variability of travel times. In his study, the direct approach sees the extent of travel time variability (TTV) as the variable that travelers react to, whereas the indirect approach claims that TTV effects are fully explained by trip scheduling considerations. In this, factors affecting bus users’ scheduling behavior and attitudes to TTV are investigated through a survey among bus users in the city of York, England. The survey methodology and its Internet-based design are described. The results confirm that the influence of TTV on bus users is best explained indirectly through scheduling considerations. The indirect approach is commonly referred to as the scheduling approach. Many mean–variance formulations aim at modeling departure time choices, too; but unlike models of the scheduling approach, they do not rely on scheduling variables.

Recker et al. (2005) explained that travel time variability is increasingly being recognized as a major factor influencing travel decisions and, consequently, is an important performance measure in transportation management. The authors provide an analysis of segment travel time variability which is first measured using a traffic database from GIS. The variability is measured from two different aspects, the first is the variability of day-to-day travel time, and the second one is within-day variability. Standard deviation and normalized standard deviation were used as measures of variability. Numerical experiments were carried out to examine the effects of route choice models on network assignment results. By incorporating travel time variability into the route choice models, the predictive capability of the route choice models is enhanced and could potentially lead to better means of reducing traffic congestion, wasteful travel, and loss of productivity, and at the same time, improve network capacity utilization and travel time reliability.

Palma et al. (2005) conducted a study in Paris to determine the route choice behavior when travel time is uncertain. In this case, the user's choice depends both on expected travel time and travel time variability. Data was collected in the Paris area and analyzed on a method based on the ordered probit. This leads to an ordinal as well as to different cardinal measures of risk aversion. Such an approach is consistent with expected and with non-expected utility theory. Econometric estimates suggest that absolute risk aversion is constant and show that risk aversion is largest for transit users, blue collar workers and for those attending business appointments.

Tables 1 and 2 provide a qualitative comparison and the advantages and disadvantages of different travel time data collection techniques.

4. Travel Time Variability and Reliability

Texas Transportation Institute (TTI) (2000) defined reliability and variability separately. Reliability is commonly used in reference to the level of consistency in transportation service; variability is the amount of inconsistency on operating conditions. To quantify the reliability and variability, they defined two measures. A measure of reliability they recommended is the Buffer Time, which is the amount of extra time that must be allowed for the traveler to reach his destination on time in a high percentage of his trips. A measure of variability is the mean travel time plus one or two standard deviations. Lomax et al. (2004) defined the reliability Buffer Time Index as follows:

$$\text{Buffer Index (\%)} = \frac{95^{th}\ \text{percentile confidence travel rate - average travel rate}}{\text{average travel rate}} \times 100$$

Similar to the Florida Reliability Method which is based on the median travel time, this definition is based on the mean travel rate. Then this definition also does not allow the tracking of reliability over time for a given facility.

Florida DOT (2000) developed and documented the Florida Reliability Method. They defined reliability on a highway segment as the percent of travel that takes no longer than the expected travel time plus a certain acceptable additional time. They define three major components of reliability: travel time, expected travel time, and acceptable additional time.

FHWA (2006) investigated travel time reliability, the importance of travel time reliability, and the measurement of travel time reliability. They explored the necessary steps in estimating travel time reliability and included case studies that illustrate the reliability measure's development process. The recommended steps for developing travel time reliability are as follows:

Step 1. Determine how the measure will be used
Step 2. Develop a plan based on uses and users
Step 3. Collect and process required data
Step 4. Calculate reliability measures
Step 5. Communicate measures in a meaningful way

To estimate travel time reliability for a specific route/trip and time period, four different measures were recommended, which are listed below:

- *90th or 95th percentile travel time*: calculate directly with database or spreadsheet function

- *Buffer index*:

$$\text{Buffer index (\%)} = \frac{\text{95th percentile travel time (min)} - \text{average travel time (min)}}{\text{average travel time (min)}}$$

- *Planning time index*:

$$\text{Planning time index} = \frac{\text{95th percentile travel time}}{\text{free-flow travel time}}$$

- *Frequency that congestion exceeds some expected threshold*: calculate by counting the frequency that traffic conditions exceed a preset threshold

For several road segments and time periods, a calculation method using vehicle-miles of travel (VMT) as a weighting factor was suggested:

- $$\text{Mean index value} = \frac{\sum_{i=1}^{n} (\text{Index value}_n \times \text{VMT}_n)_{\text{each section and time period}}}{\sum_{i=1}^{n} (\text{VMT}_n)_{\text{each section and time period}}}$$

Table A-2 - Qualitative Comparison of Travel Time Data Collection Techniques

	Test Vehicle			License Plate Matching				ITS Probe Vehicle[c]				
	Manual	Electronic DMI	GPS	Manual	Portable Computer	Video with Manual Transcription	Video with Character Recognition[b]	Signpost -Based	AVI	Ground-based Radio Navigation	Cellular Phone Tracking	GPS
Initial or Capital Cost	L	M	M	L	M	L	H	H	H	H	H	M
Operation Cost/ unit of data collected	H	M	M	H	M	M	L	M	L	L	L	L
Require skill or knowledge Level	L	M	M	L	M	M	H	H	H	H	H	H
Data Reduction/ Processing	P	G	G	P	G	F	G	G	G	F	F	F
Route Flexibility	E	E	E	G	G	F	F	P	P	G	G	G
Accuracy and Representative[a]	F	G	G	F	G	E	E	G	E	G	G	G
Sampling Rate												
1. Time	L	L	L	L	M	H	H	M	H	M	H	M
2. Space	M	H	H	L	L,	L	L	L	L	M	M	H
3. Vehicle	L	L	L	M	H	H	H	L	M	M	M	M

Source: Travel Time Data Collection Handbook, FHWA, http://www.fhwa.dot.gov/ohim/start.pdf
Rating scales are relative among the techniques: [High (H), Moderate (M), Low (L)] or [Excellent (E), Good (G), Fair (F), Poor (P)].
Notes: [a] Assumes that adequate quality control procedures are used, [b] Assumes that necessary equipment is purchased (as opposed to contracting data collection services), [c] Assumes that vehicle-to-roadside communication infrastructure does not exist

Table A-3 - Comparison of Travel Time Data Collection Technologies

	TECHNOLOGIES	ADVANTAGES	DISADVANTAGES
TEST VEHICLE	Manual	• low initial cost • low required skill level	• high operating cost per unit of data • limited travel time/delay information available • limited sample of motorists
	Electronic DMI	• moderate initial cost • very detailed speed/delay data available	• lacks geographical referencing (e.g., GIS) • limited sample of motorists
	GPS	• moderate initial cost • data easily integrated into GIS • detailed speed/delay data available • can provide useful data for travel surveys	• reception problems in urban “canyons”, trees • limited sample of motorists
LICENSE PLATE MATCHING	Manual	• low initial cost	• high operating cost per unit of data • accuracy may be questionable • data reduction time-consuming
	Portable Computer	• low operating cost/unit • travel times from large sample of motorists • continuum of travel times during data collection	• accuracy problems with data collection, spurious matches • limited geographic coverage on single day
	Video with Manual Transcription	• travel times from large sample of motorists • continuum of travel times during data collection	• data reduction time-consuming • limited geographic coverage on single day
	Video with Character Recognition	• low operating cost/ unit • travel times from large sample • continuum of travel times during data collection	• high initial costs (if equipment purchased) • limited geographic coverage on single day
ITS PROBE VEHICLE	Signpost-Based	• low operating cost per unit of data	• typically used for transit vehicles (includes loading/unloading times) • sample dependent on equipped vehicles
	AVI	• low operating cost per unit of data • very accurate	• very high initial cost for AVI infrastructure • limited to instrumented locations • sample dependent on equipped vehicles
	Ground-based Radio Navigation	• available consumer product	• typically used for transit vehicles • sample dependent on equipped vehicles
	Cellular Phone Tracking	• widely available consumer product	• accuracy questionable for detailed applications • privacy issues
	GPS	• increasingly available consumer product • low operating cost per unit of data	• sample dependent on equipped vehicles • privacy issues

Source: Travel Time Data Collection Handbook, FHWA, http://www.fhwa.dot.gov/ohim/start.pdf

APPENDIX B: ANALYSIS RESULTS

NJ 17

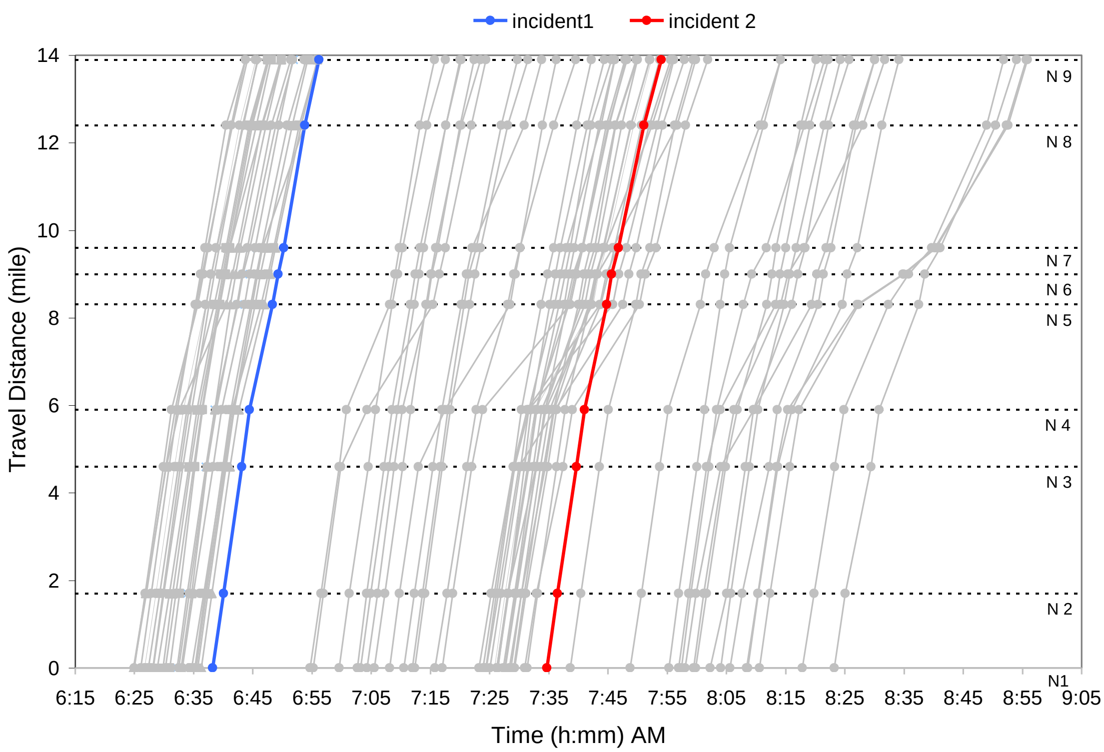

Figure B-1. Probe Vehicle Travel Profiles on NJ 17 vs. Departure Time

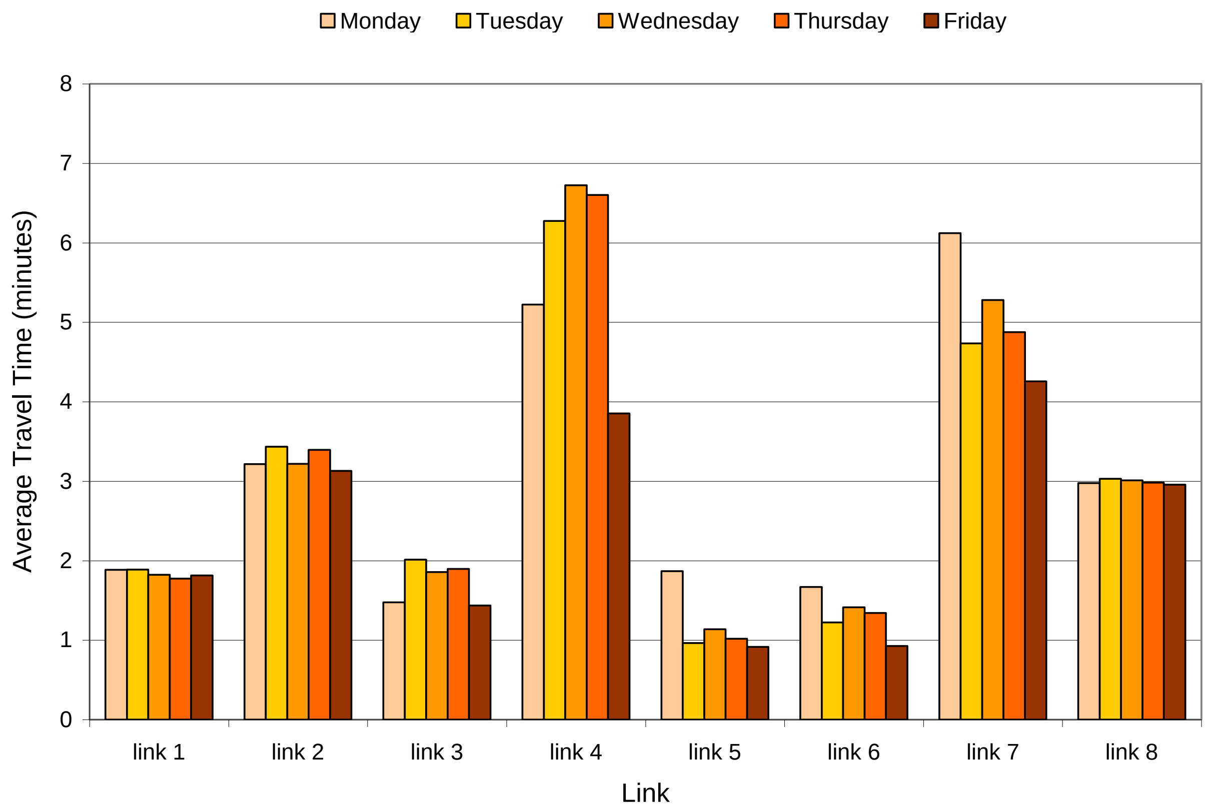

Figure B-2. NJ 17 Mean Travel Time vs. Link and Day of the Week

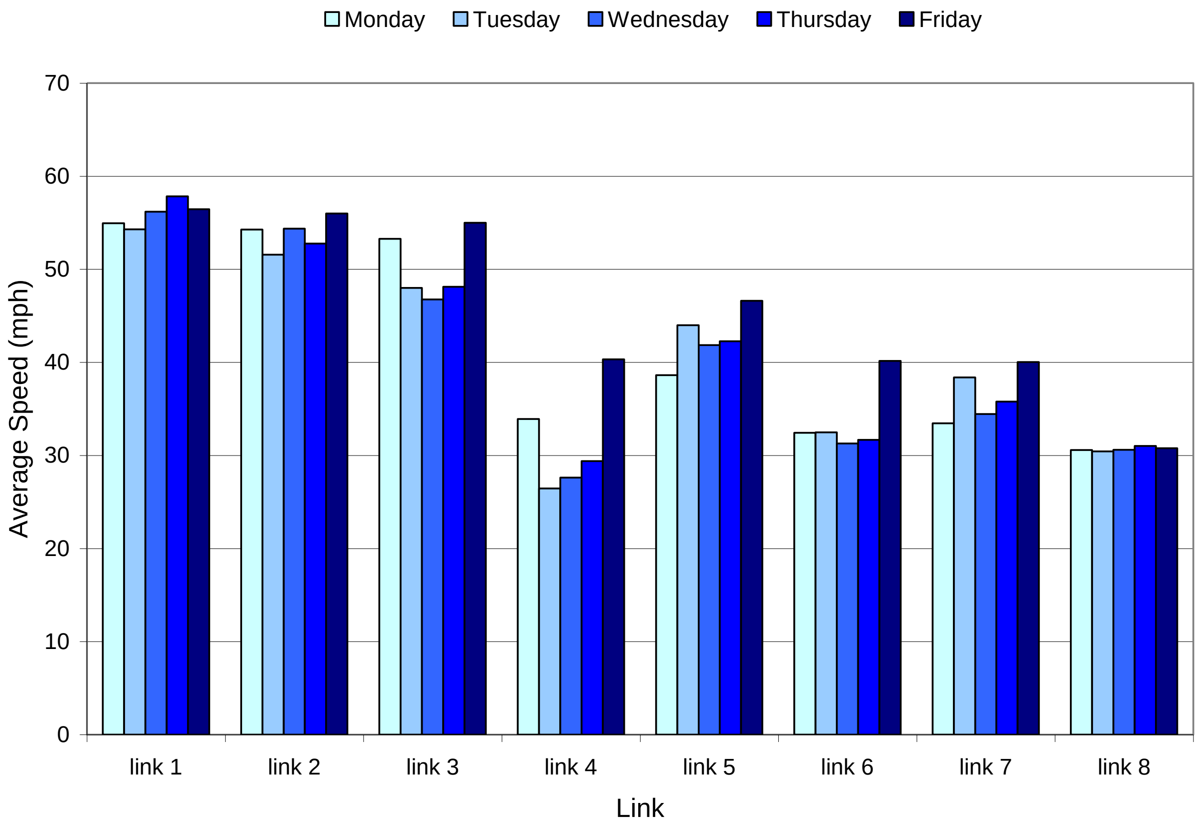

Figure B-3. NJ 17 Mean Travel Speed vs. Link and Day of the Week

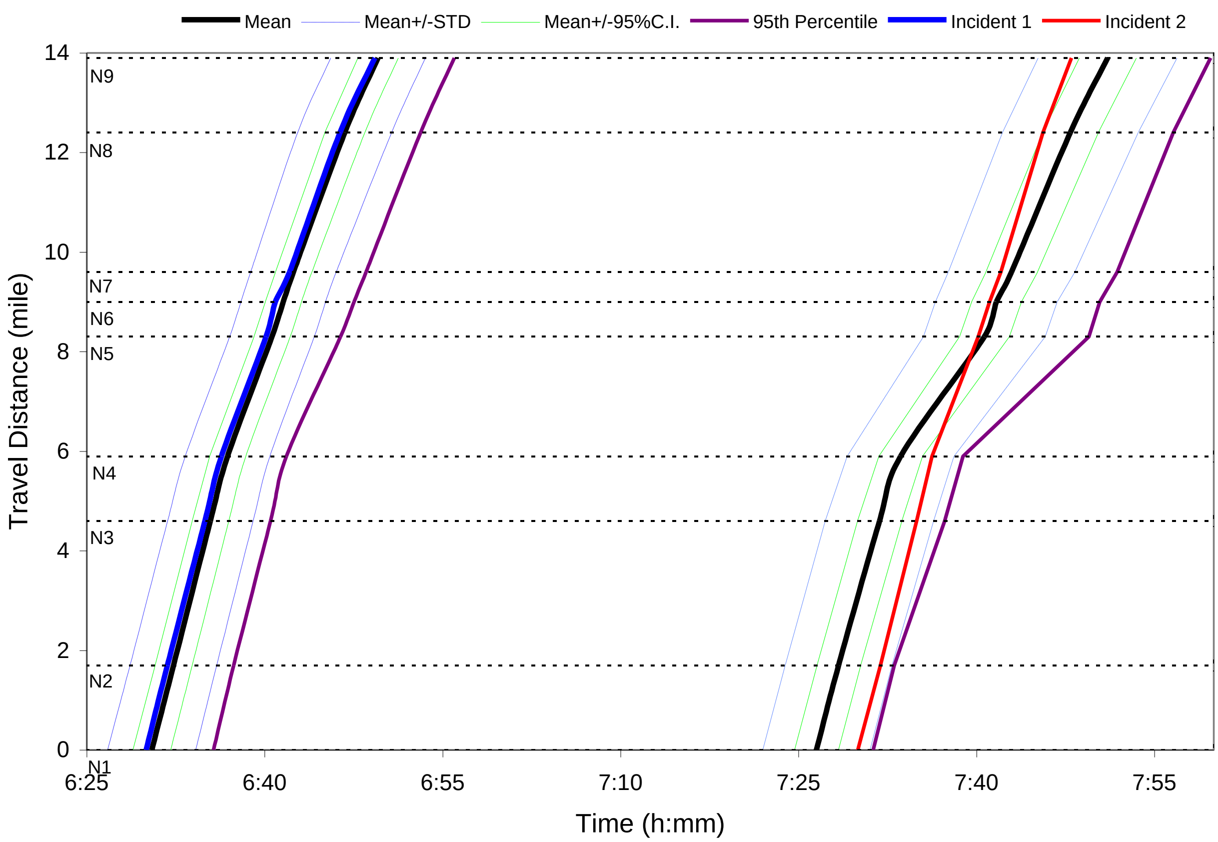

Figure B-4. Incident Impact – NJ 17

NJ 208 & NJ 4

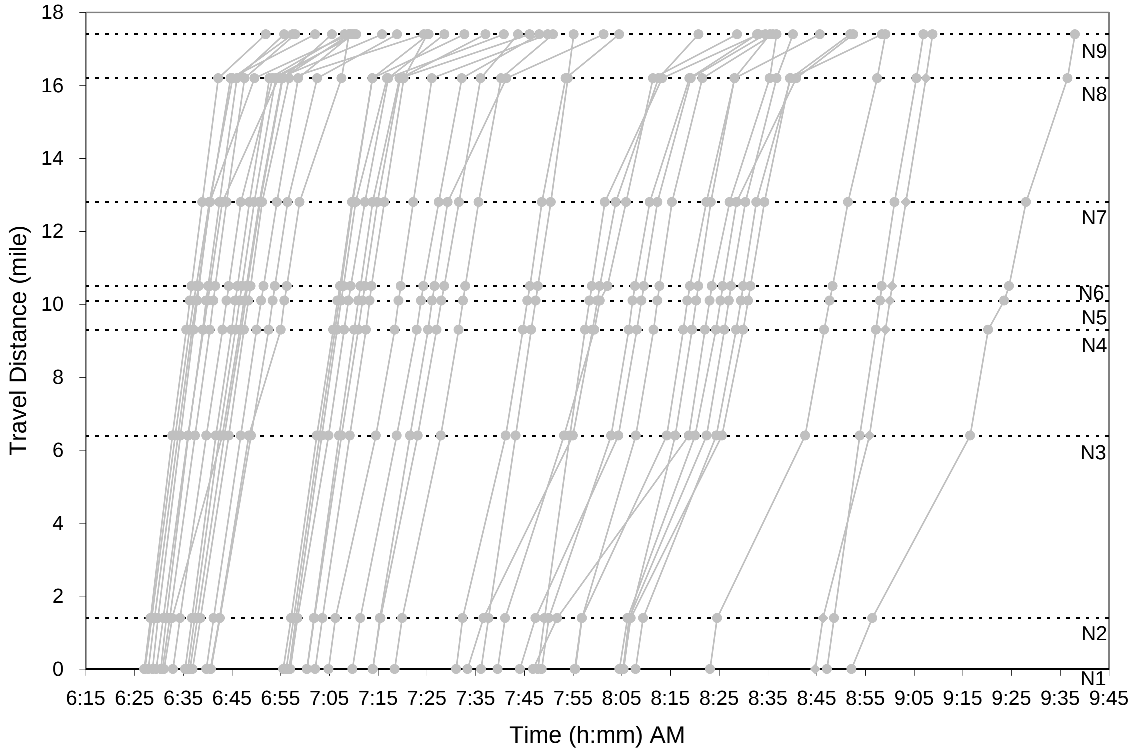

Figure B-5. Probe Vehicle Travel Profiles on NJ 208 & NJ 4 vs. Departure Time

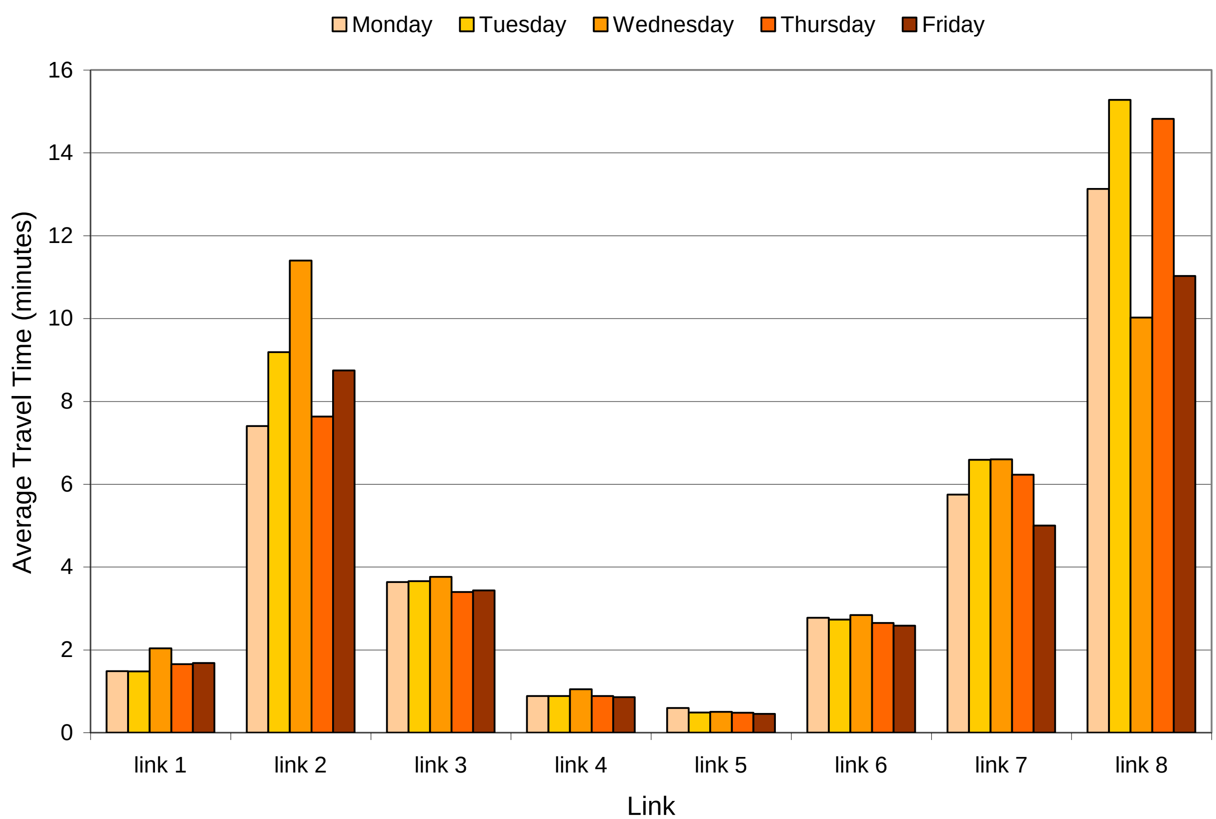

Figure B-6. NJ 208 & NJ 4 Mean Travel time vs. Link and Day of the Week

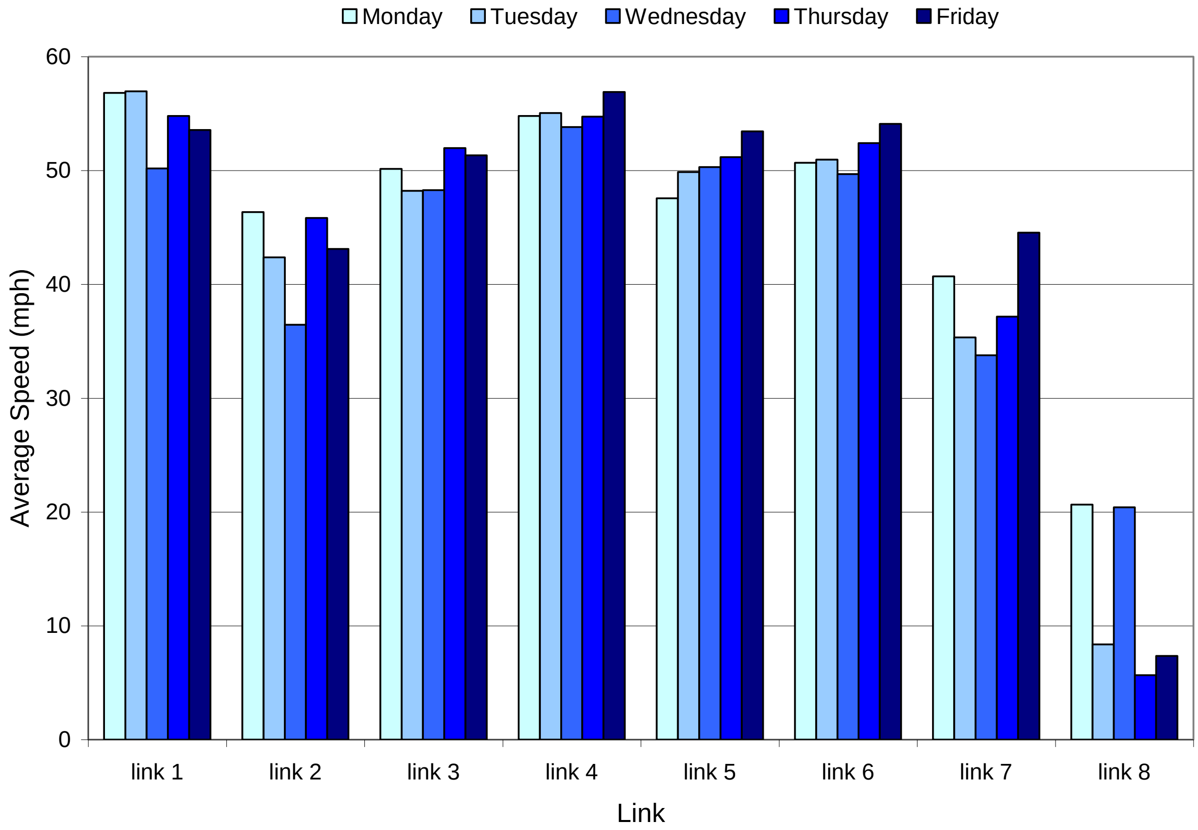

Figure B-7. NJ 208 & NJ 4 Mean Travel Speed vs. Link and Day of the Week

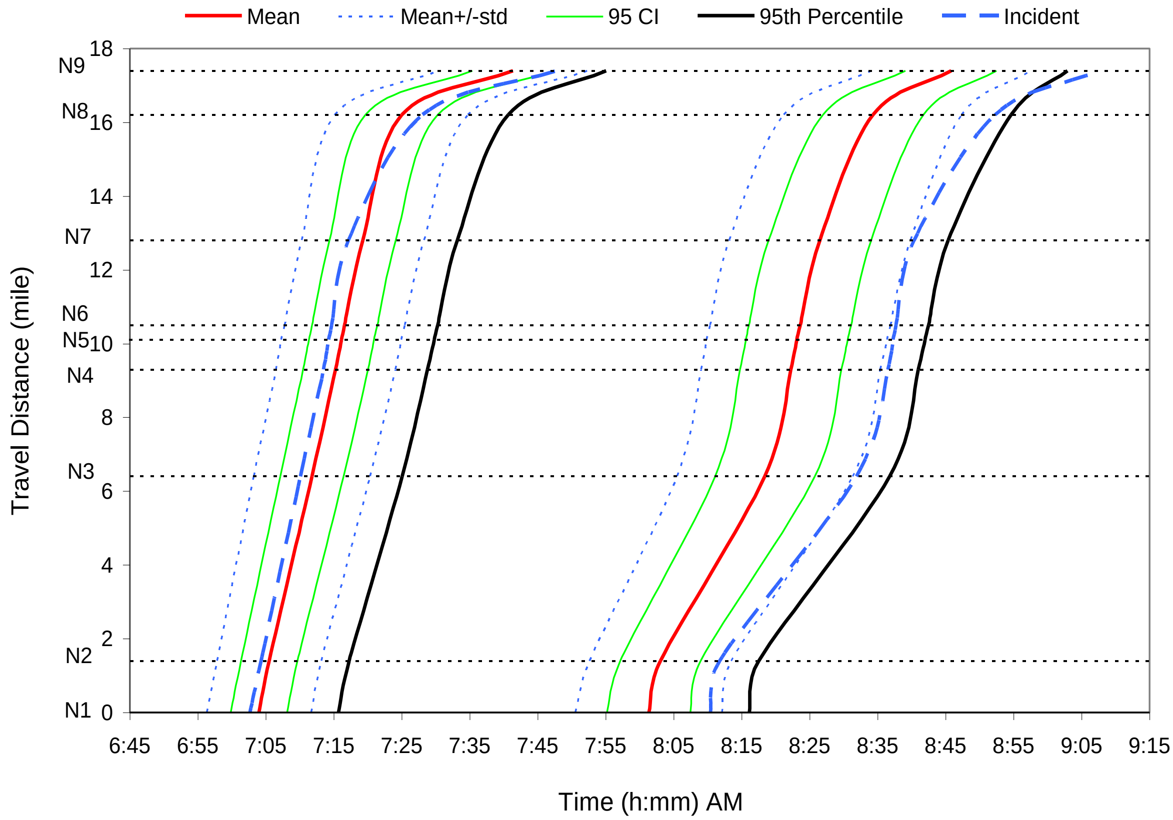

Figure B-8. Incident Impact – NJ 208 & NJ 4

I-80 & I-280

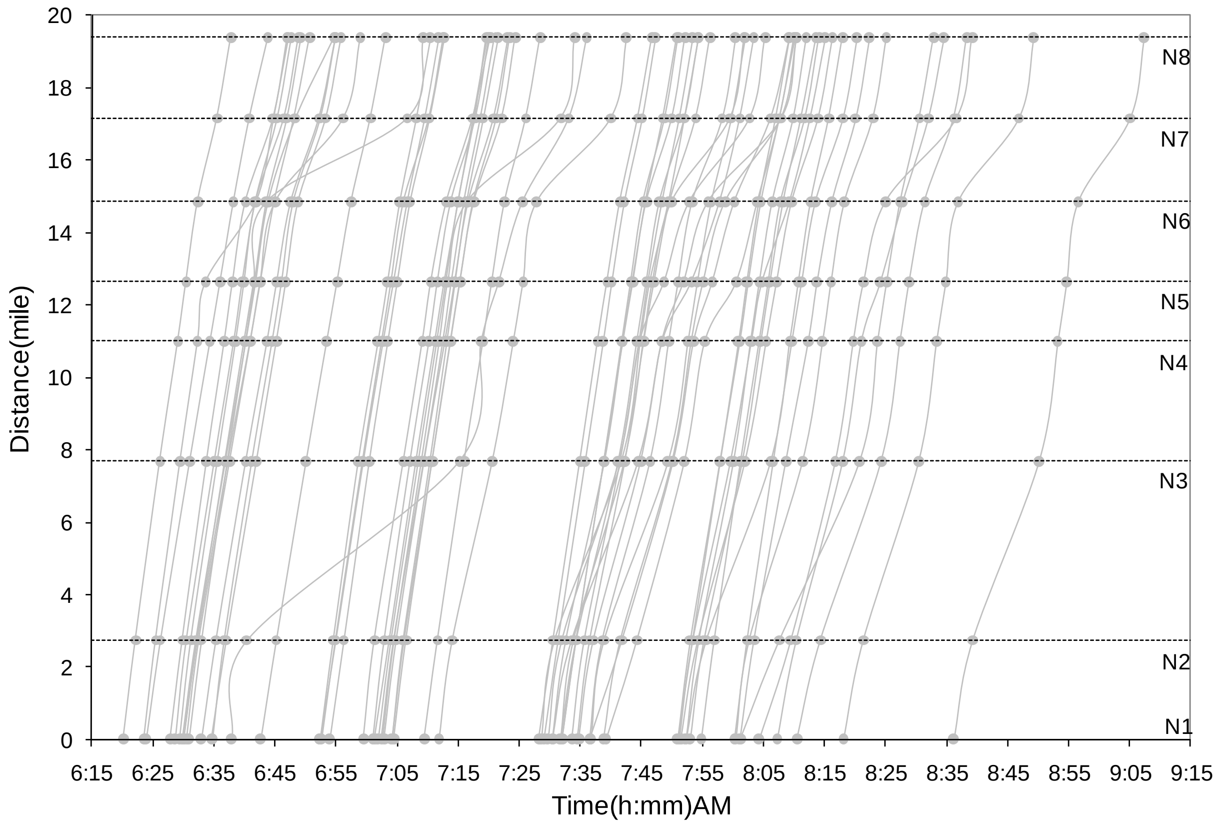

Figure B-9. Probe Vehicle Travel Profiles on I-80 & I-280 vs. Departure Time

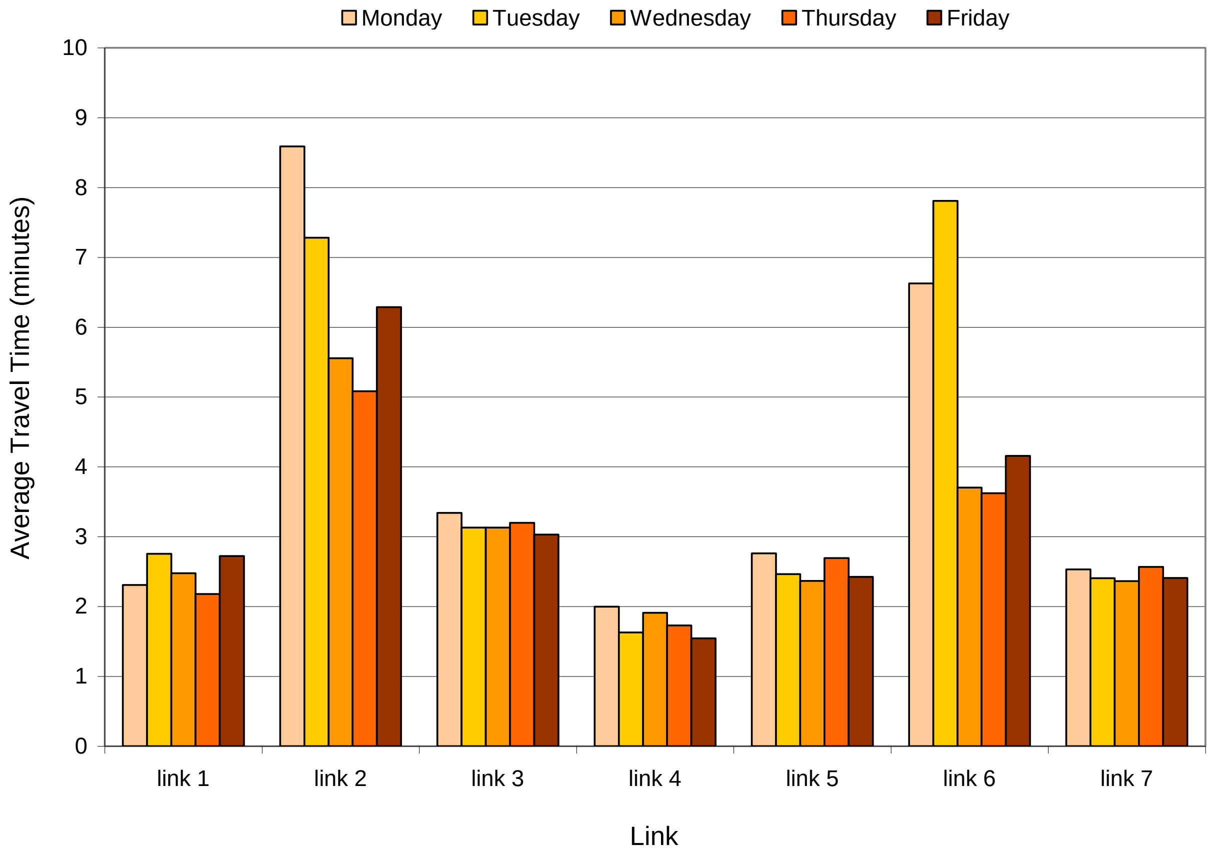

Figure B-10. I-80 & I-280 Mean Travel Time vs. Link and Day of the Week

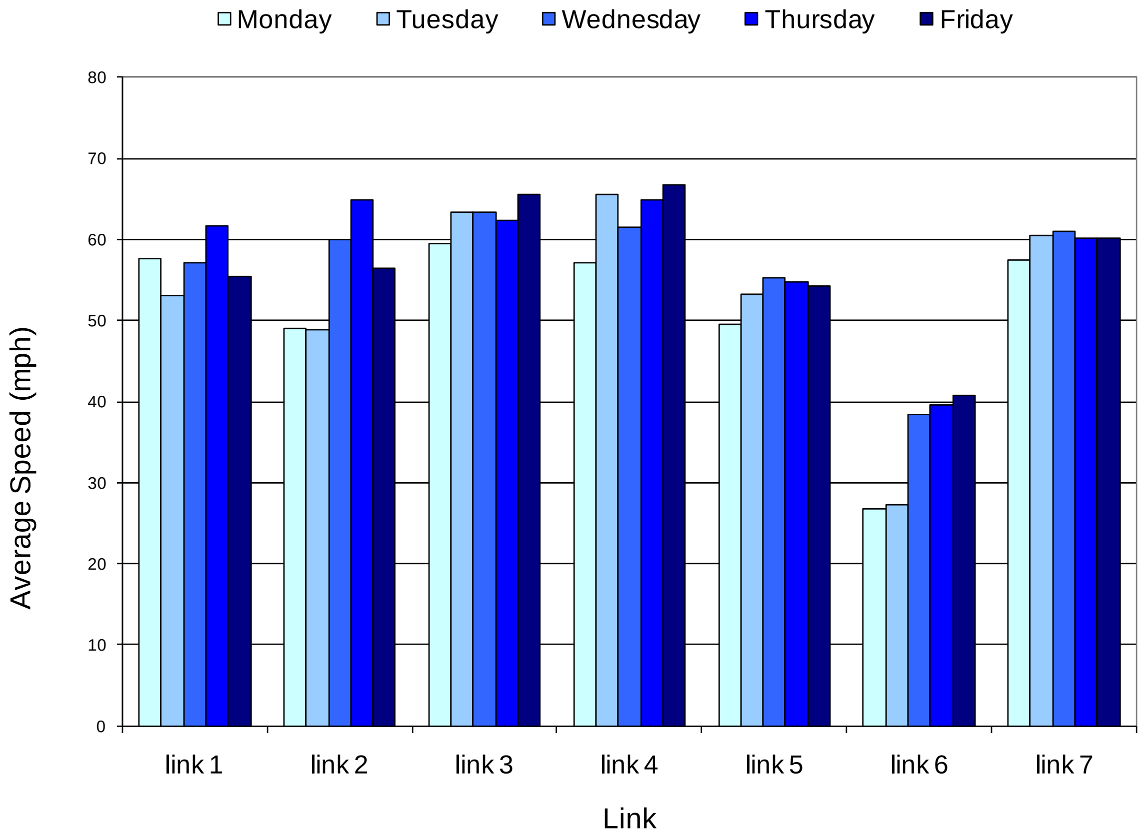

Figure B-11. I-80 & I-280 Mean Travel Speed vs. Link and Day of the Week

NJ 24 & I-78

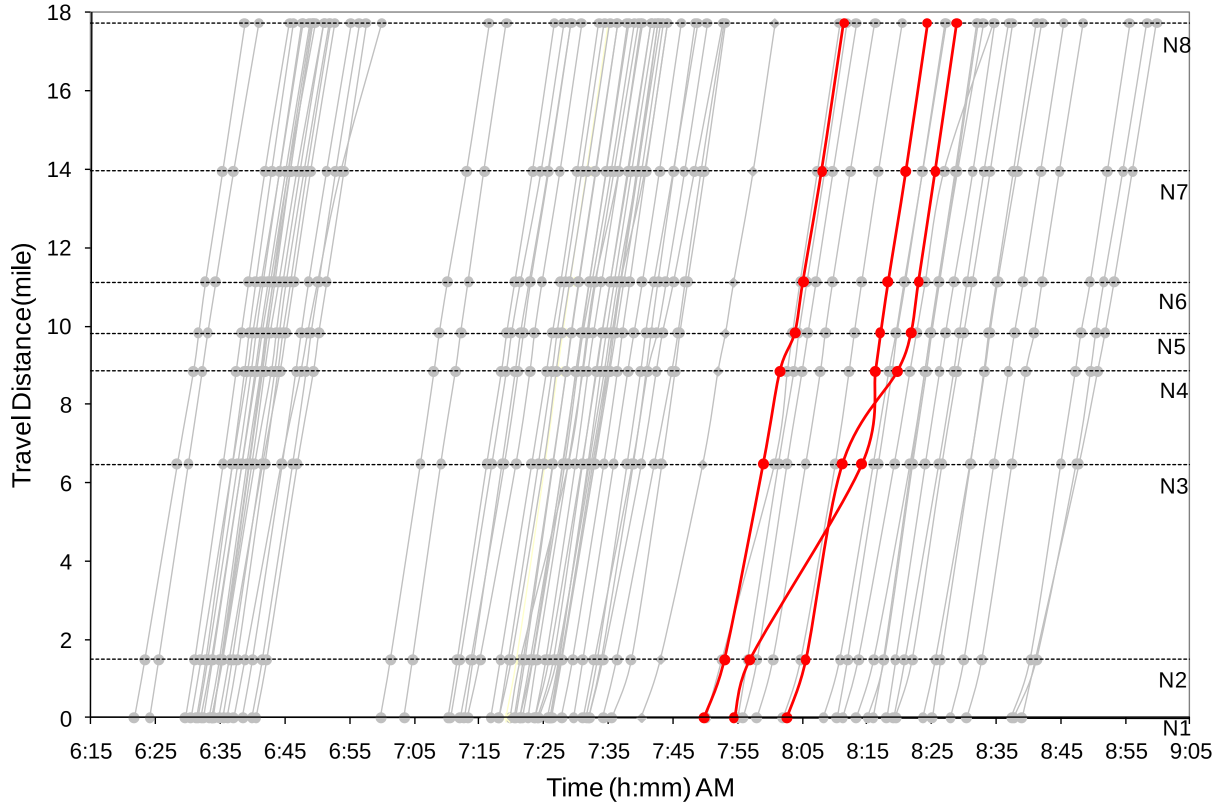

Figure B-12. Probe Vehicle Travel Profiles on NJ 24 & I-78 vs. Departure Time

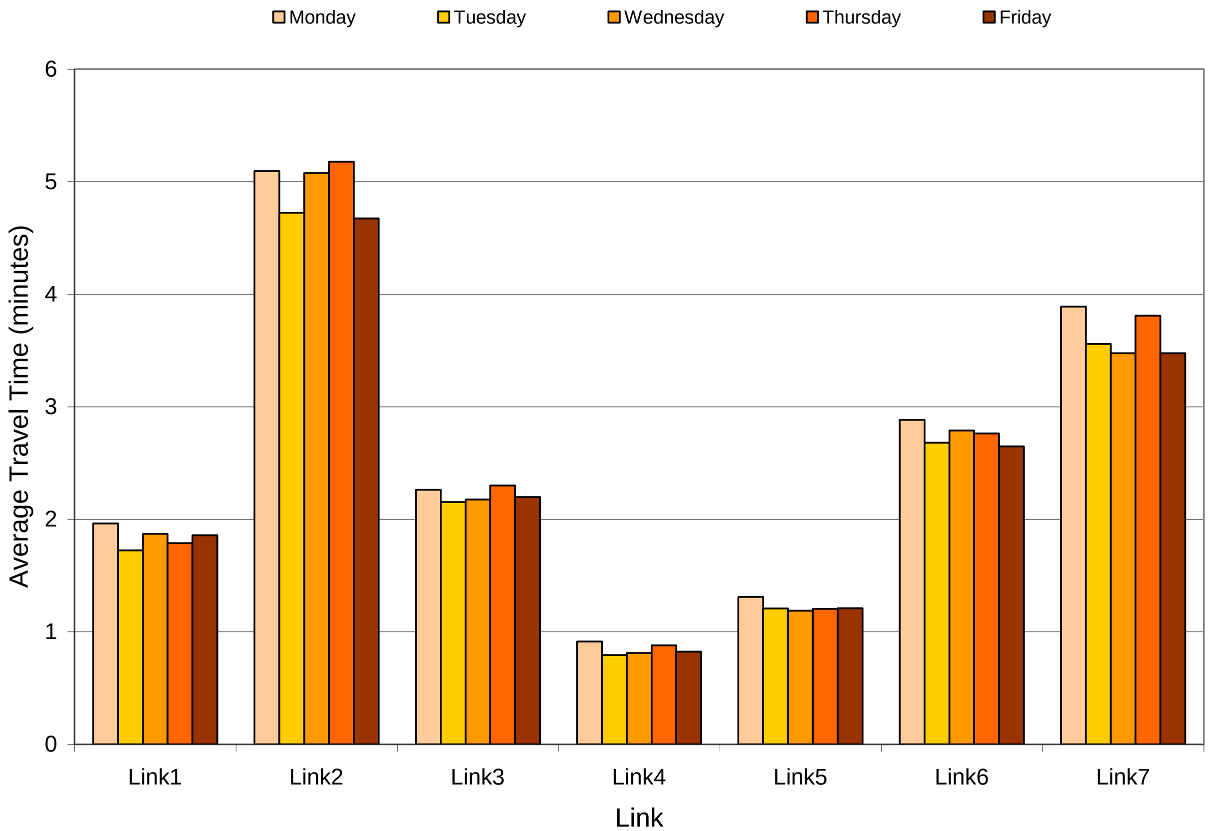

Figure B-13. NJ 24 & I-78 Mean Travel Time vs. Link and Day of the Week

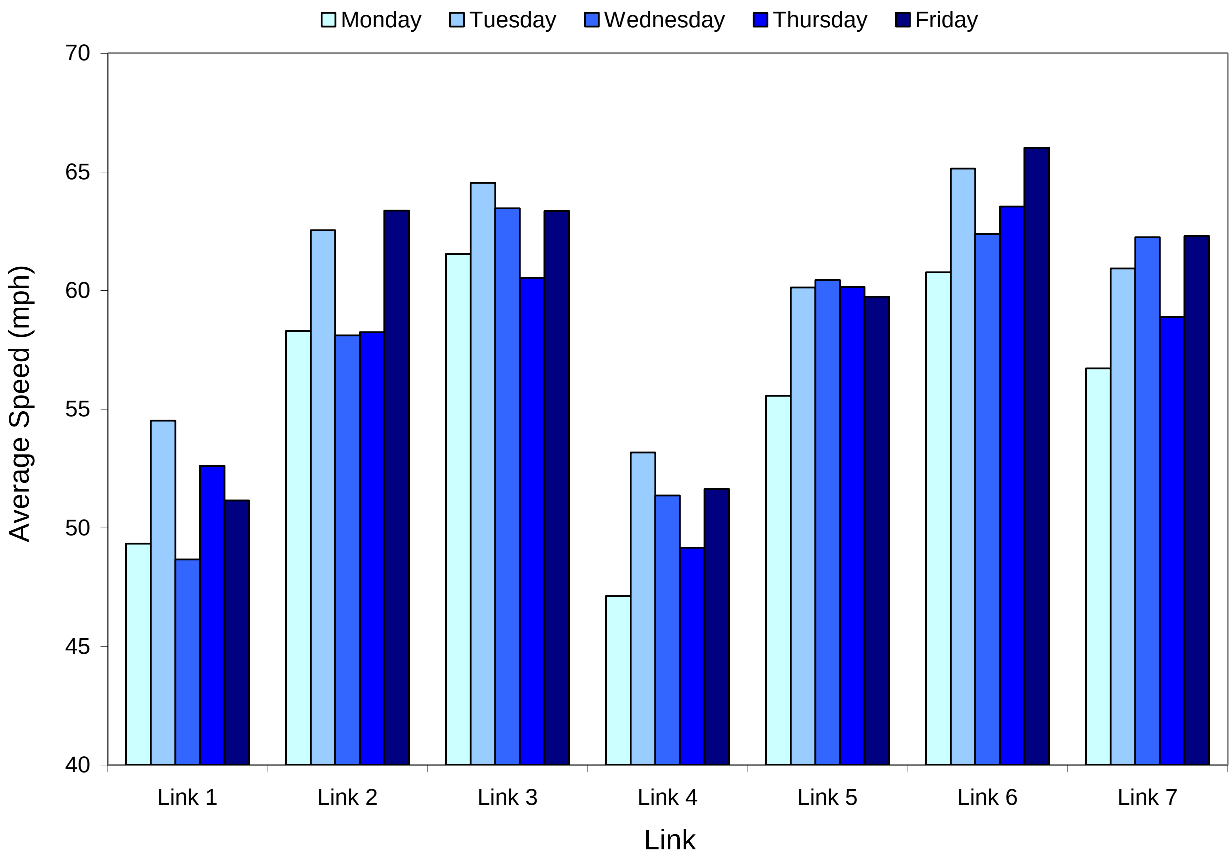

Figure B-14. NJ 24 & I-78 Mean Travel Speed vs. Link and Day of the Week

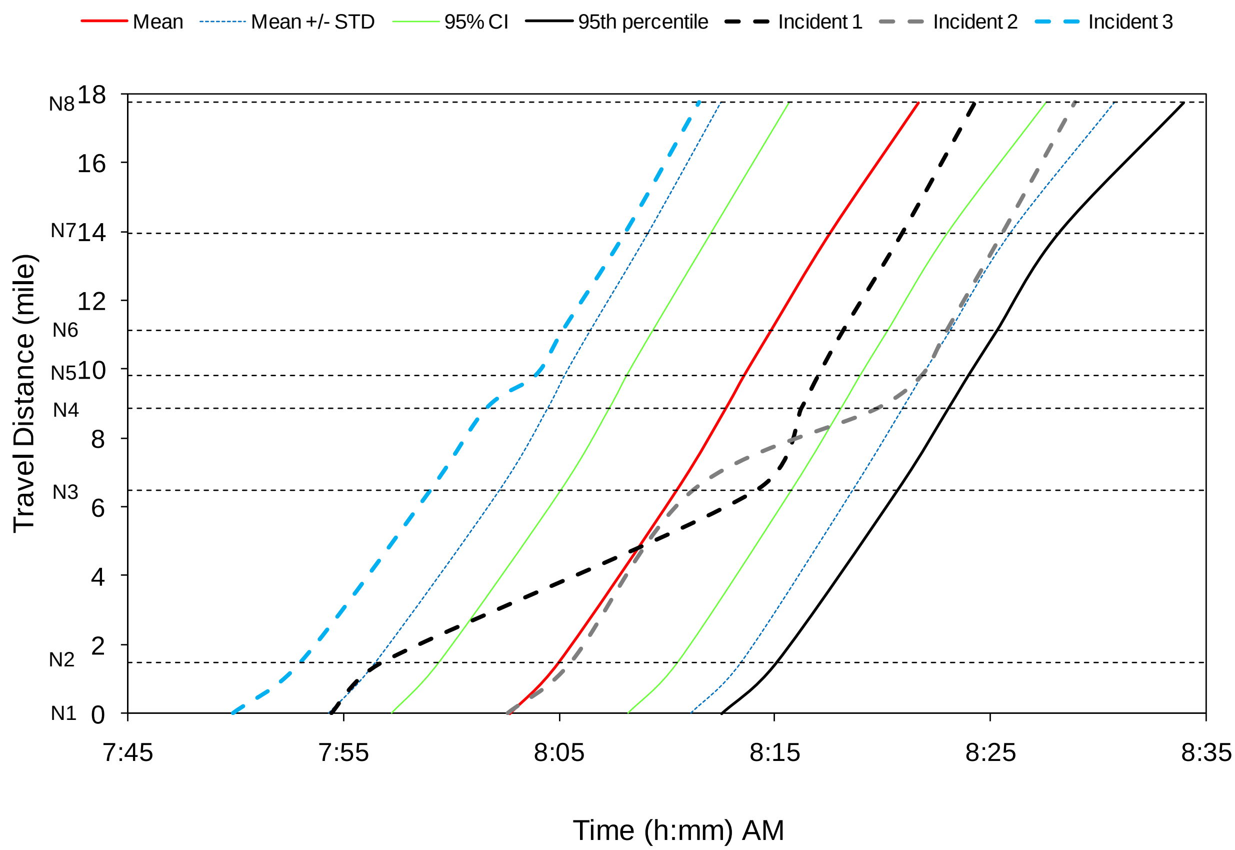

Figure B-15. Incident Impact – NJ 24 & I-78

US 46 & NJ 3

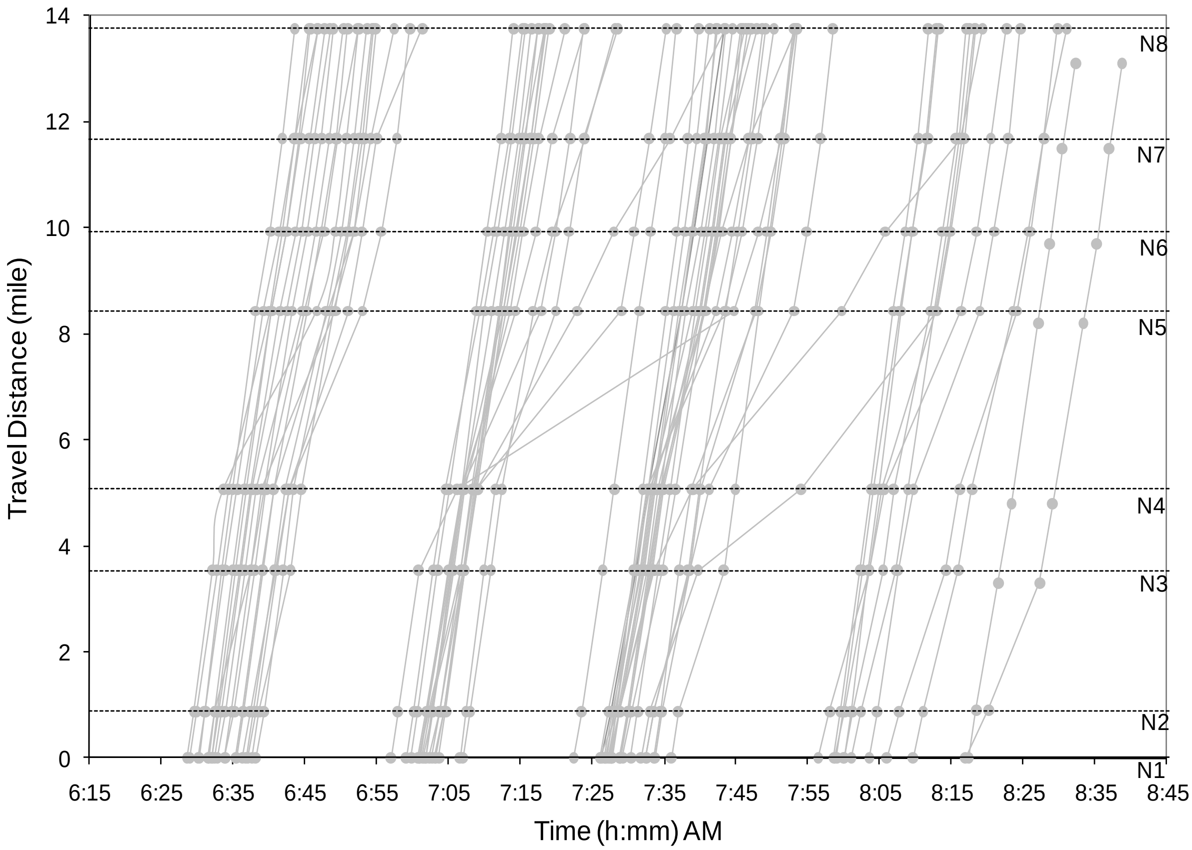

Figure B-16. Probe Vehicle Travel Profiles on US 46 & NJ 3 vs. Departure Time

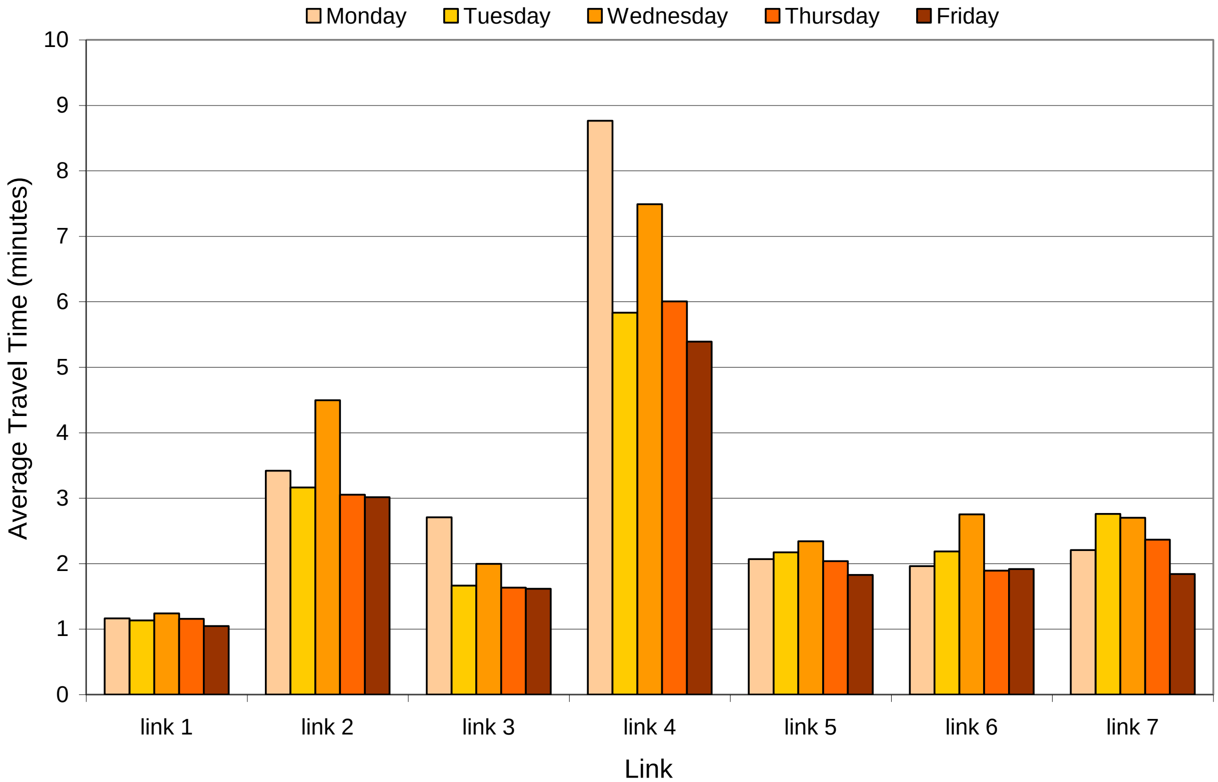

Figure B-17. US 46 & NJ 3 Mean Travel Time vs. Link and Day of the Week

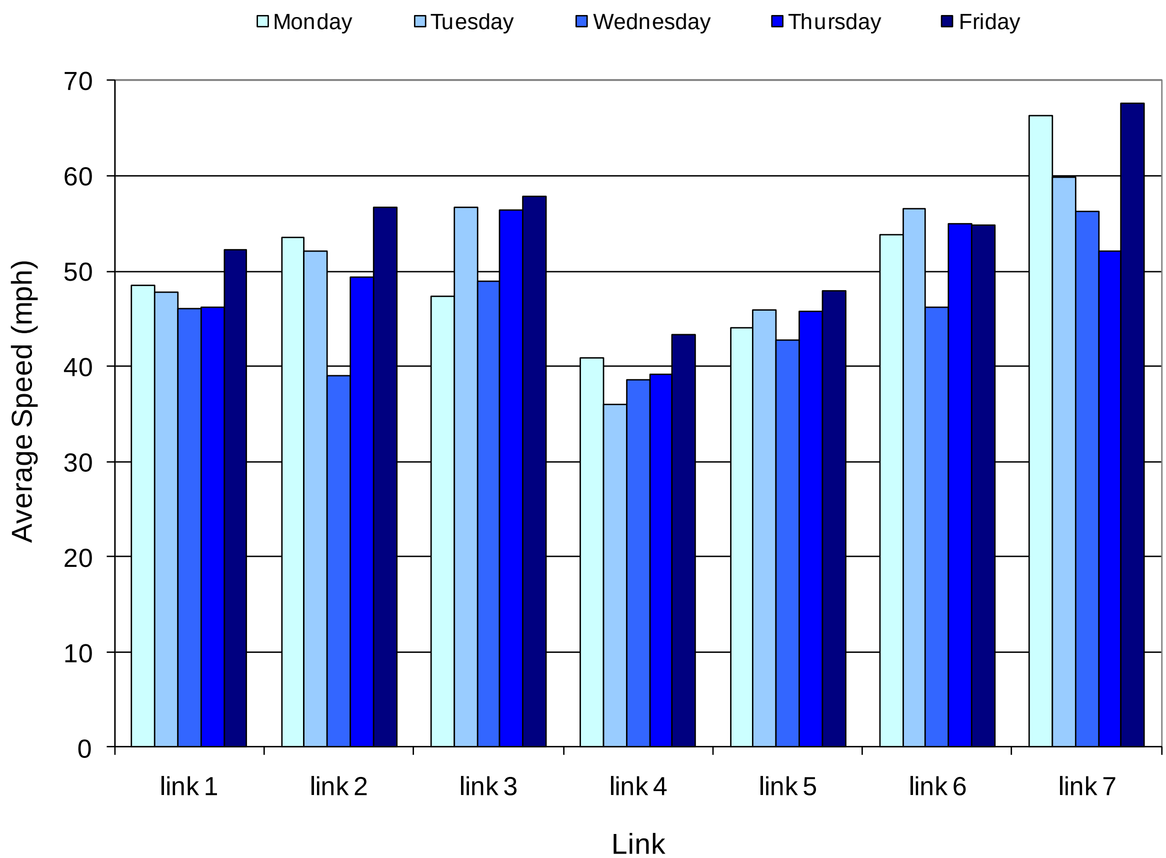

Figure B-18. US 46 & NJ 3 Mean Travel Speed vs. Link and Day of the Week

US 22

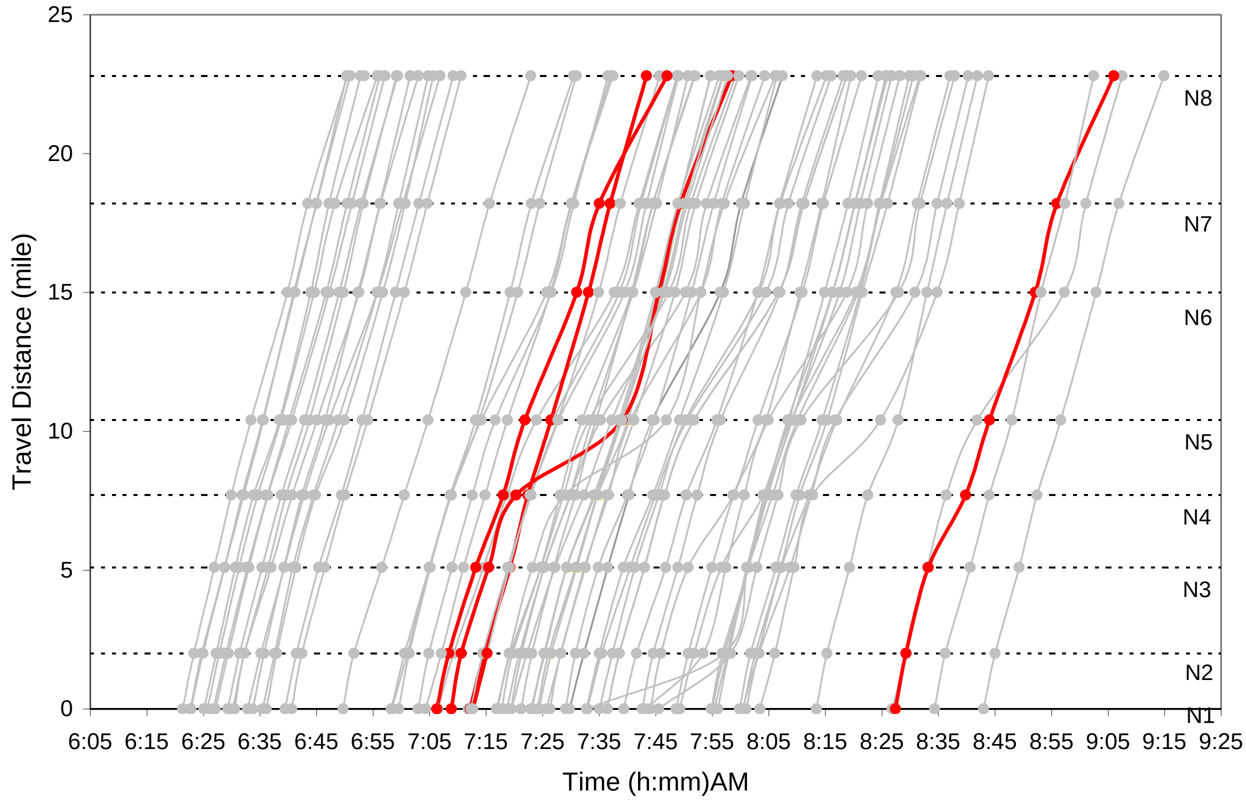

Figure B-19. Probe Vehicle Travel Profiles on US 22 vs. Departure Time

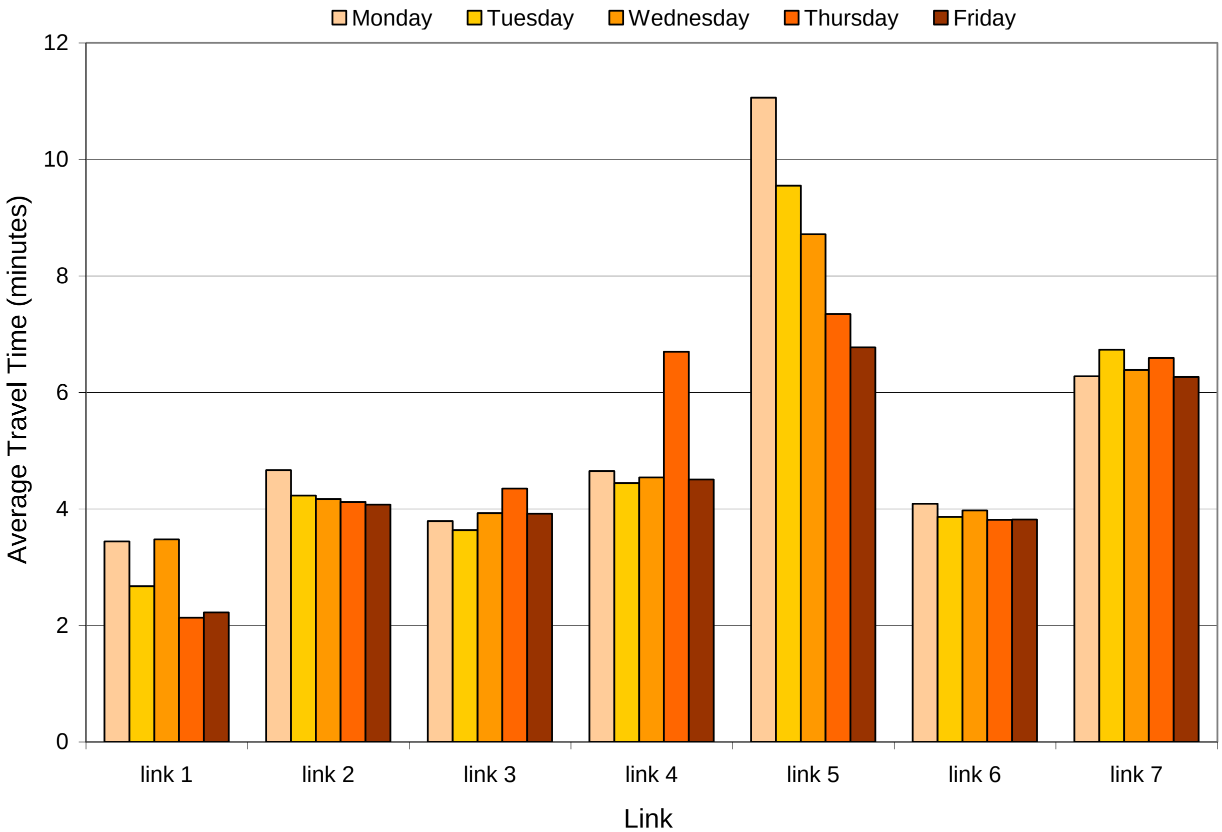

Figure B-20. US 22 Mean Travel Time vs. Link and Day of the Week

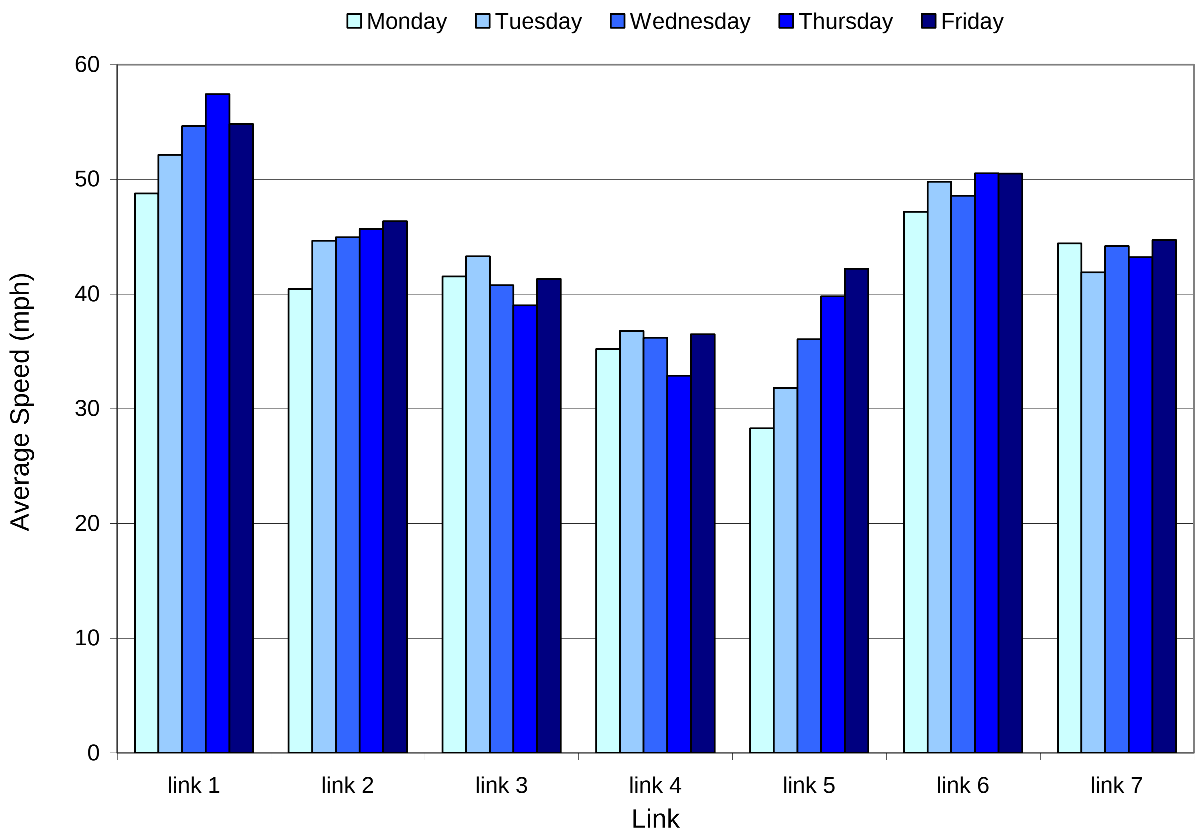

Figure B-21. US 22 Mean Travel Speed vs. Link and Day of the Week

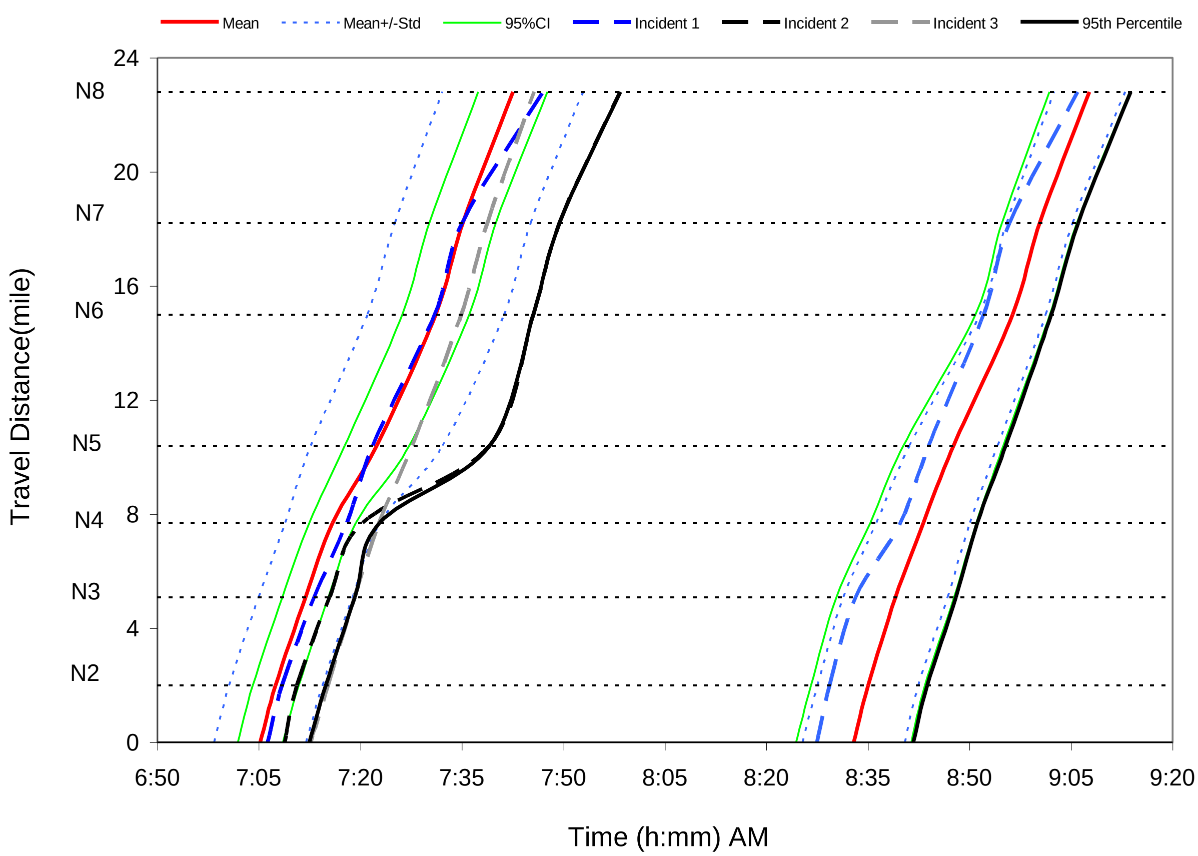

Figure B-22. Incident Impact – US 22

I-287 (A)

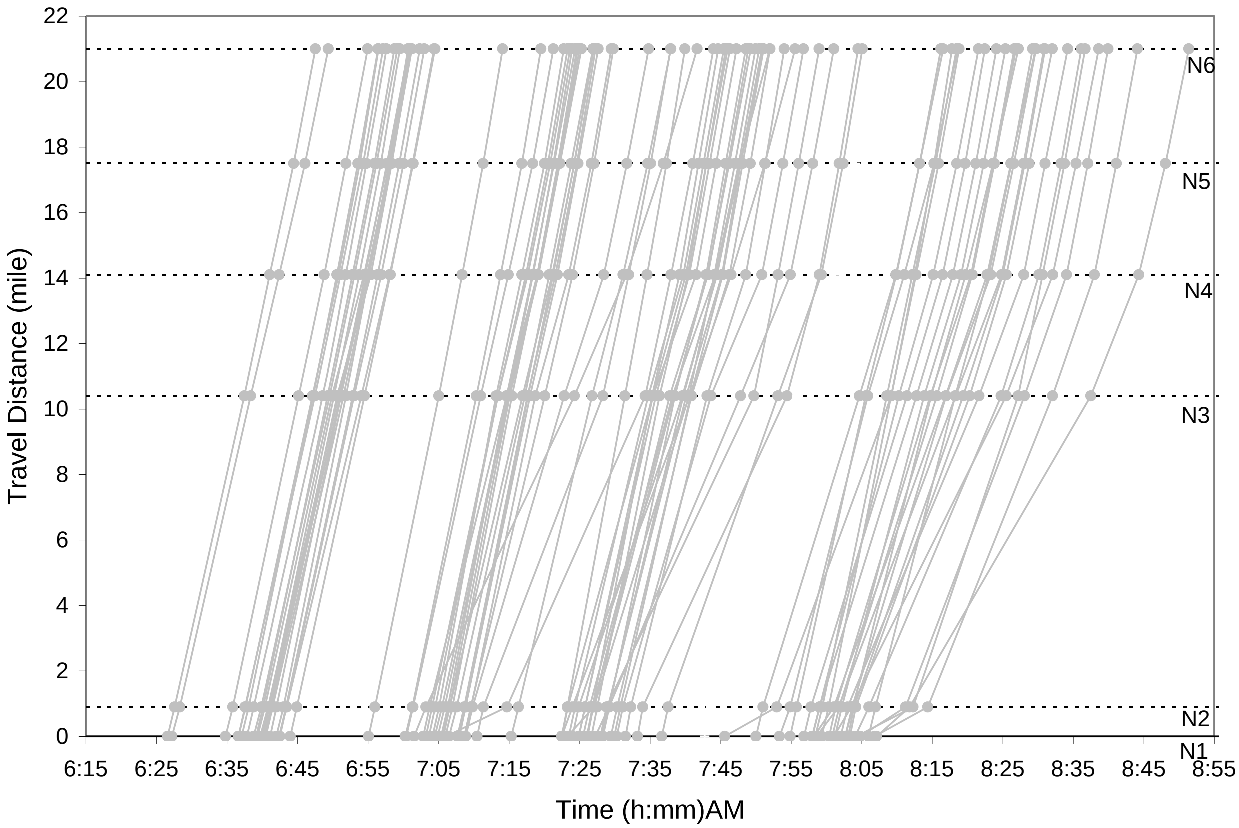

Figure B-23. Probe Vehicle Travel Profiles on I-287(A) vs. Departure Time

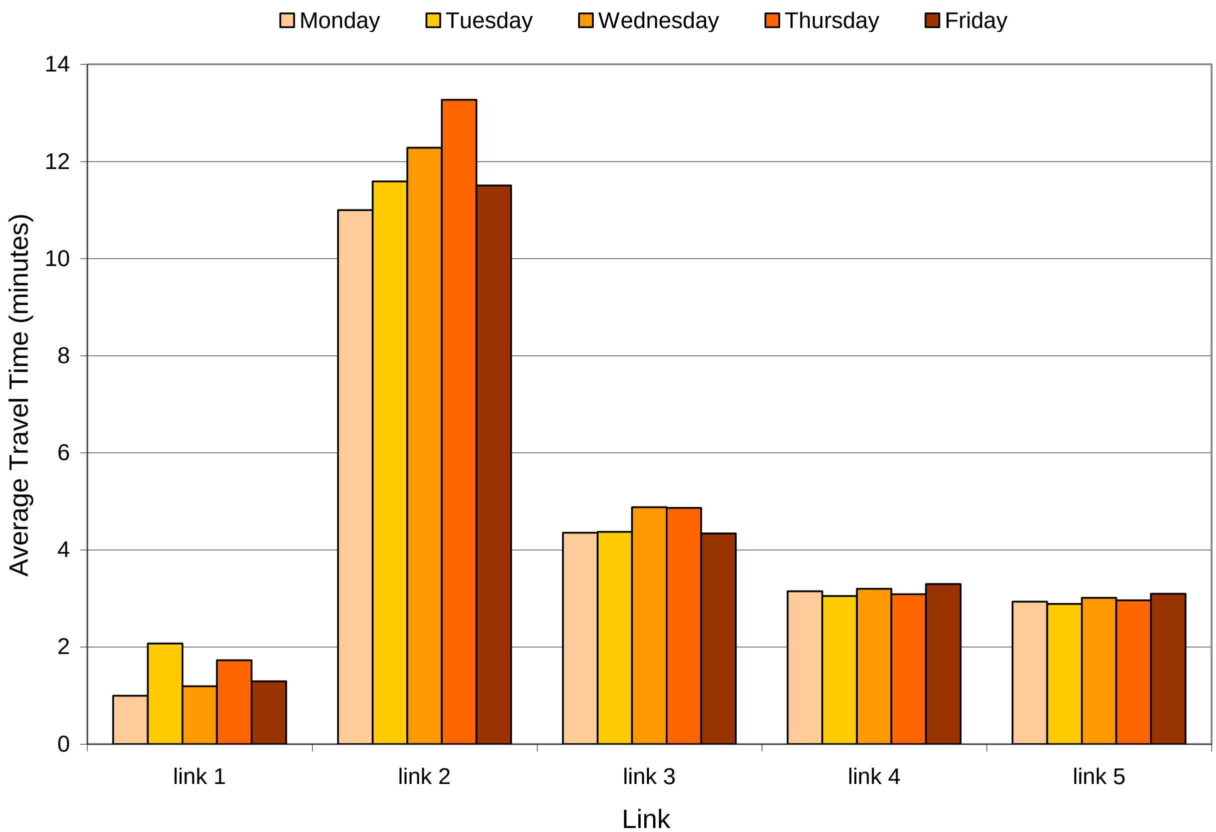

Figure B-24. I-287 (A) Mean Travel Time vs. Link and Day of the Week

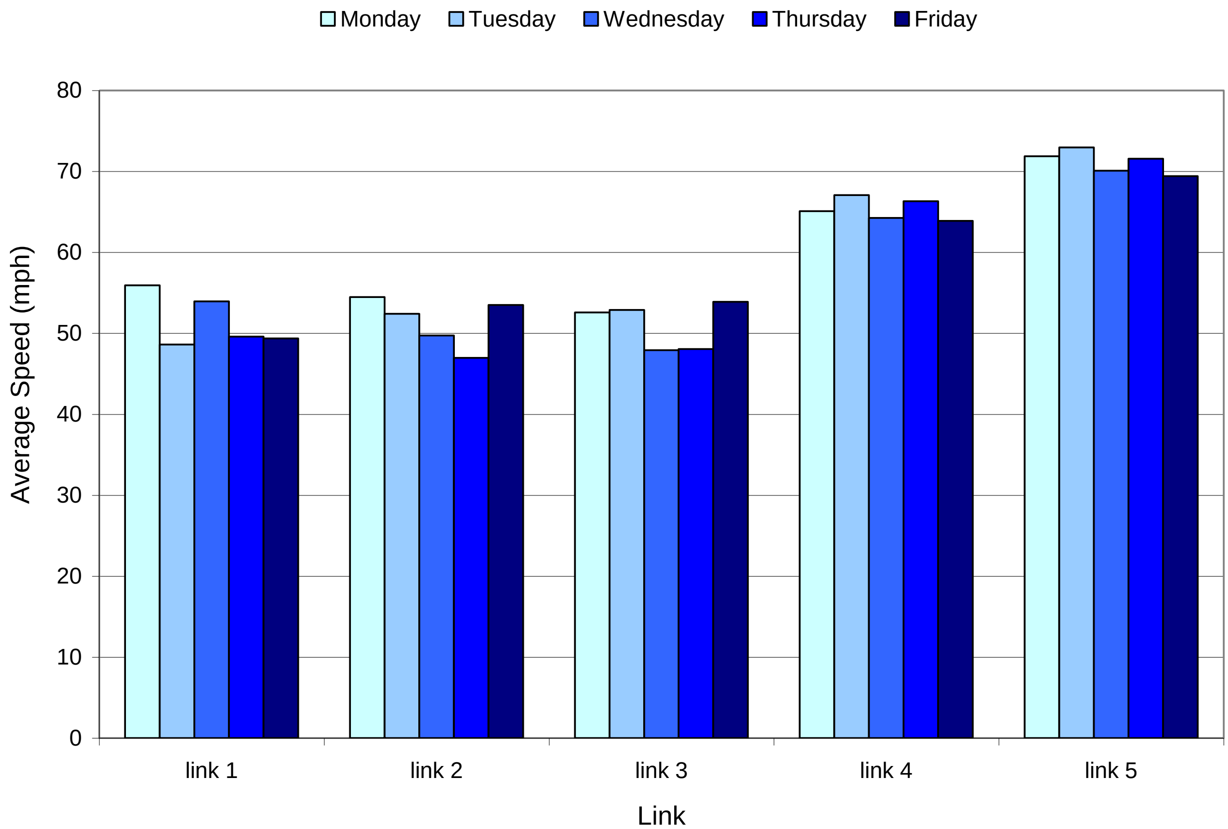

Figure B-25. I-287 (A) Mean Travel Speed vs. Link and Day of the Week

I-287 (B)

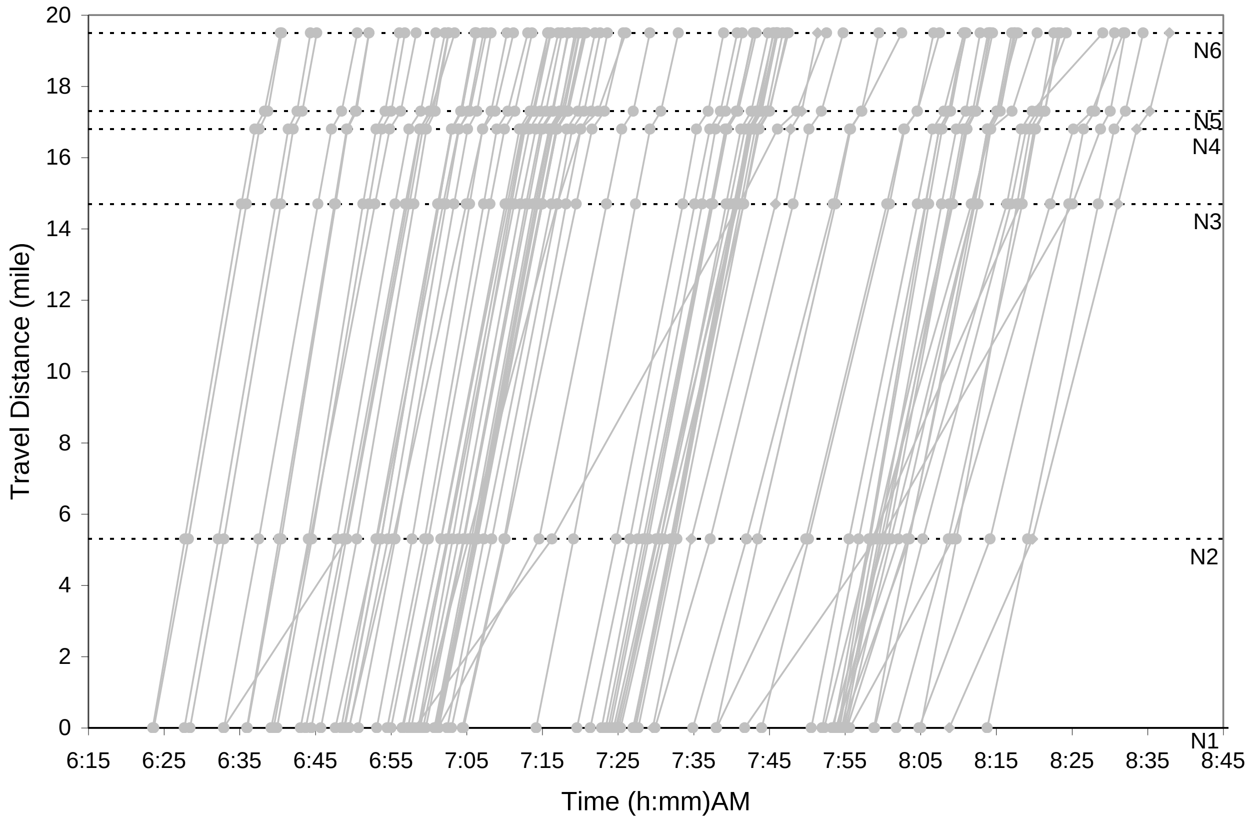

Figure B-26. Probe Vehicle Travel Profiles on I-287(B) vs. Departure Time

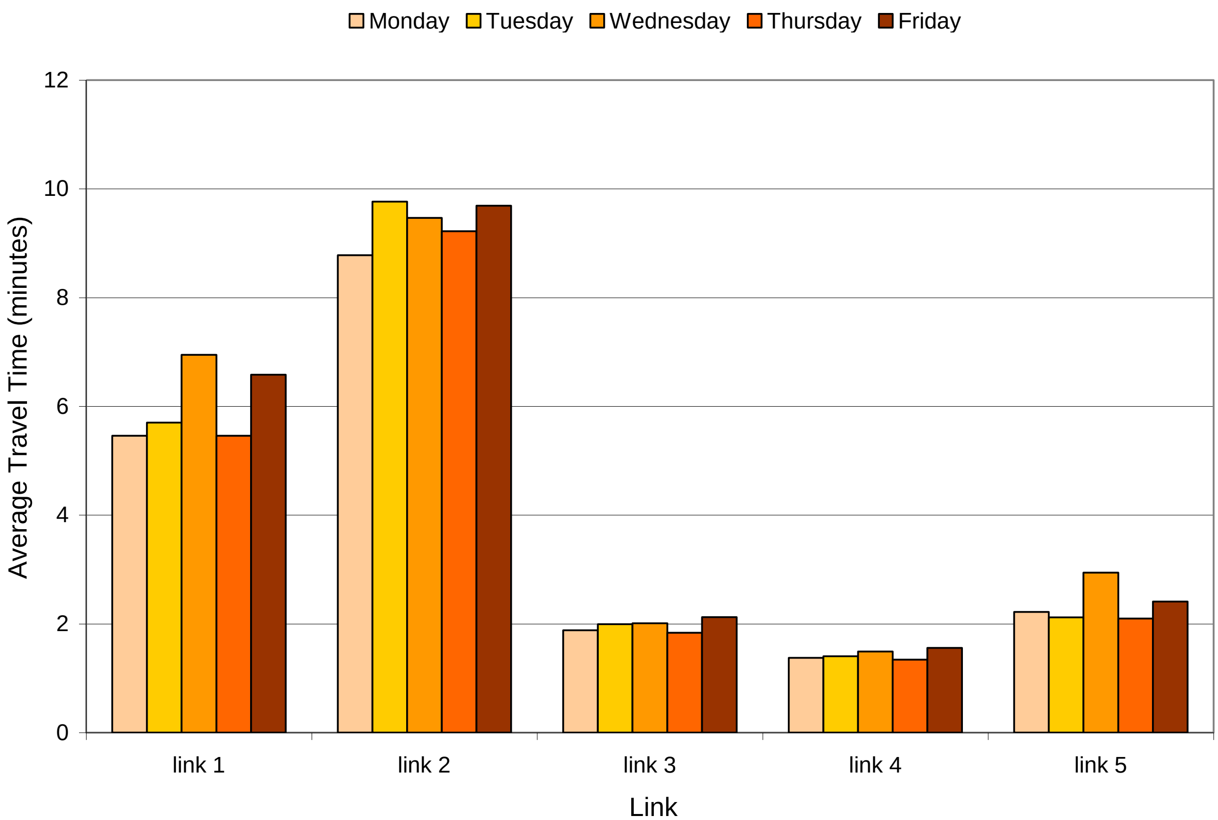

Figure B-27. I-287 (B) Mean Travel Time vs. Link and Day of the Week

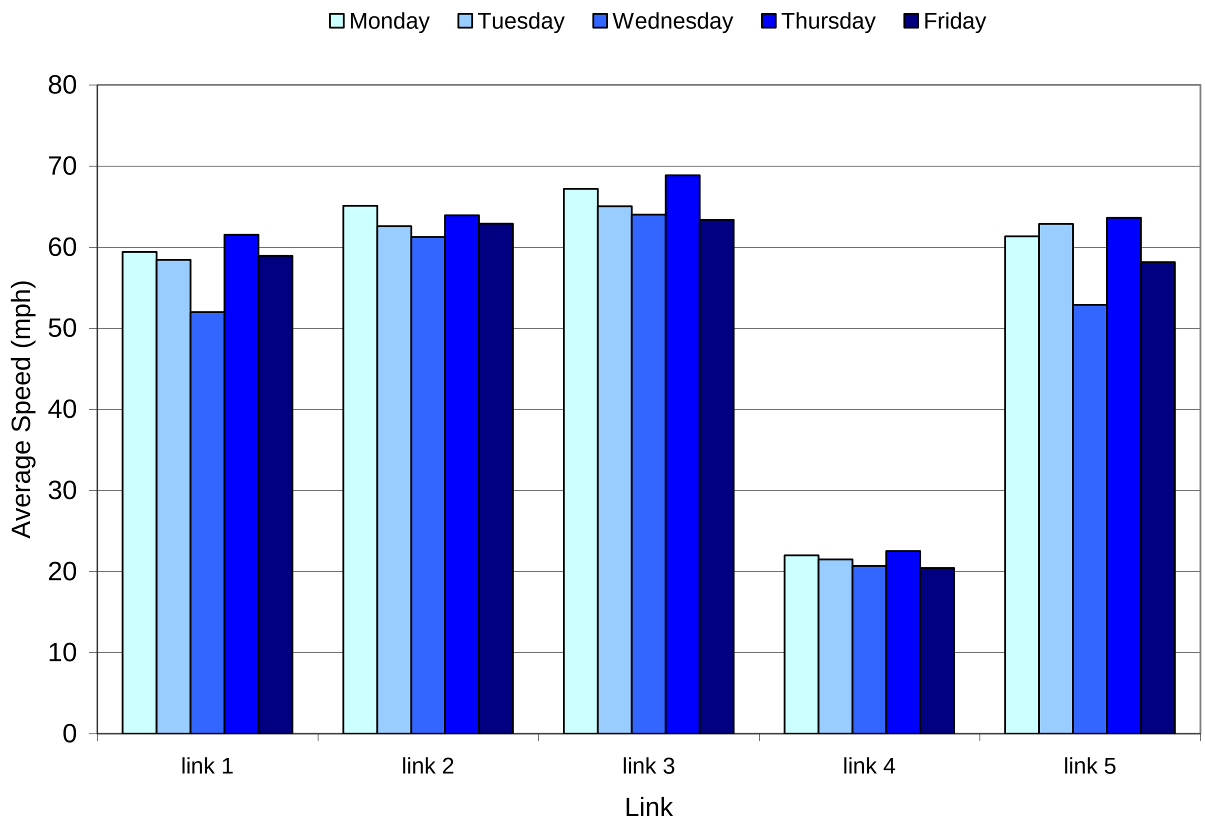

Figure B-28. I-287 (B) Mean Travel Speed vs. Link and Day of the Week

US 1 (C)

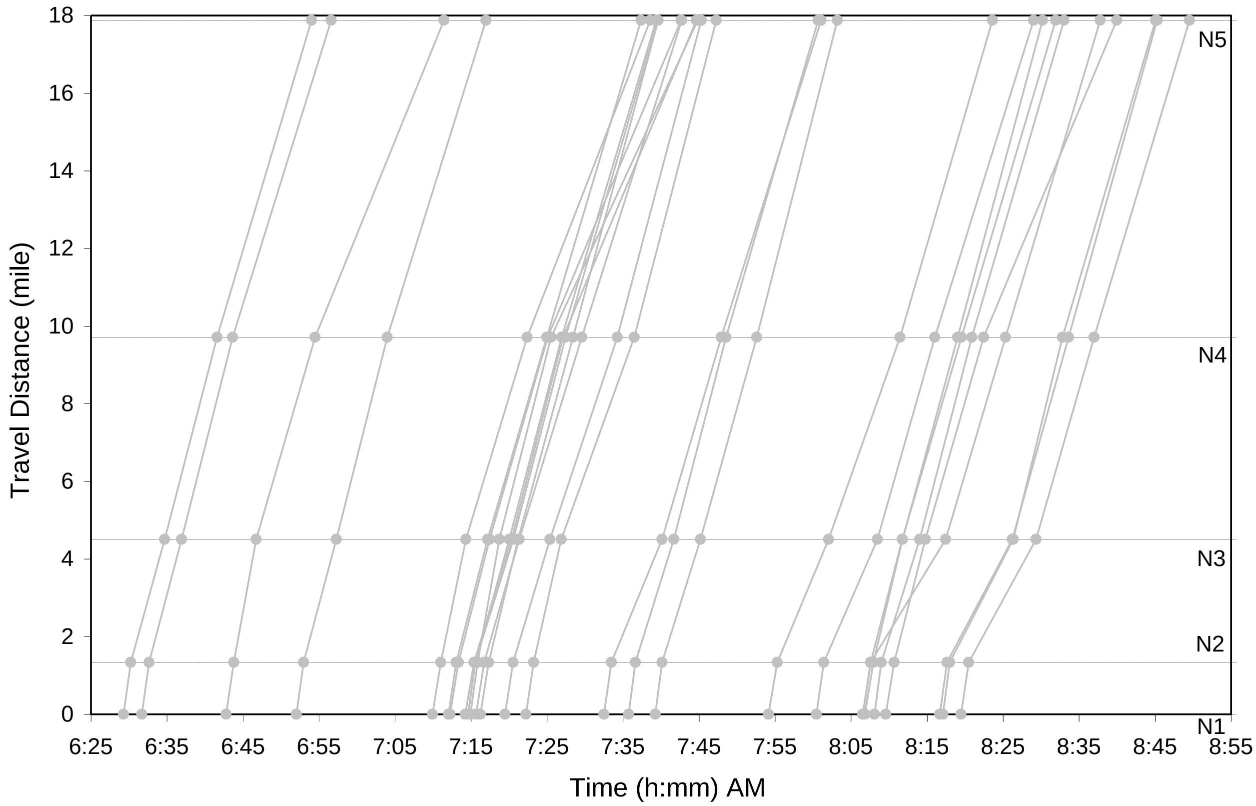

Figure B-29. Probe Vehicle Travel Profiles on US 1 (C) vs. Departure Time

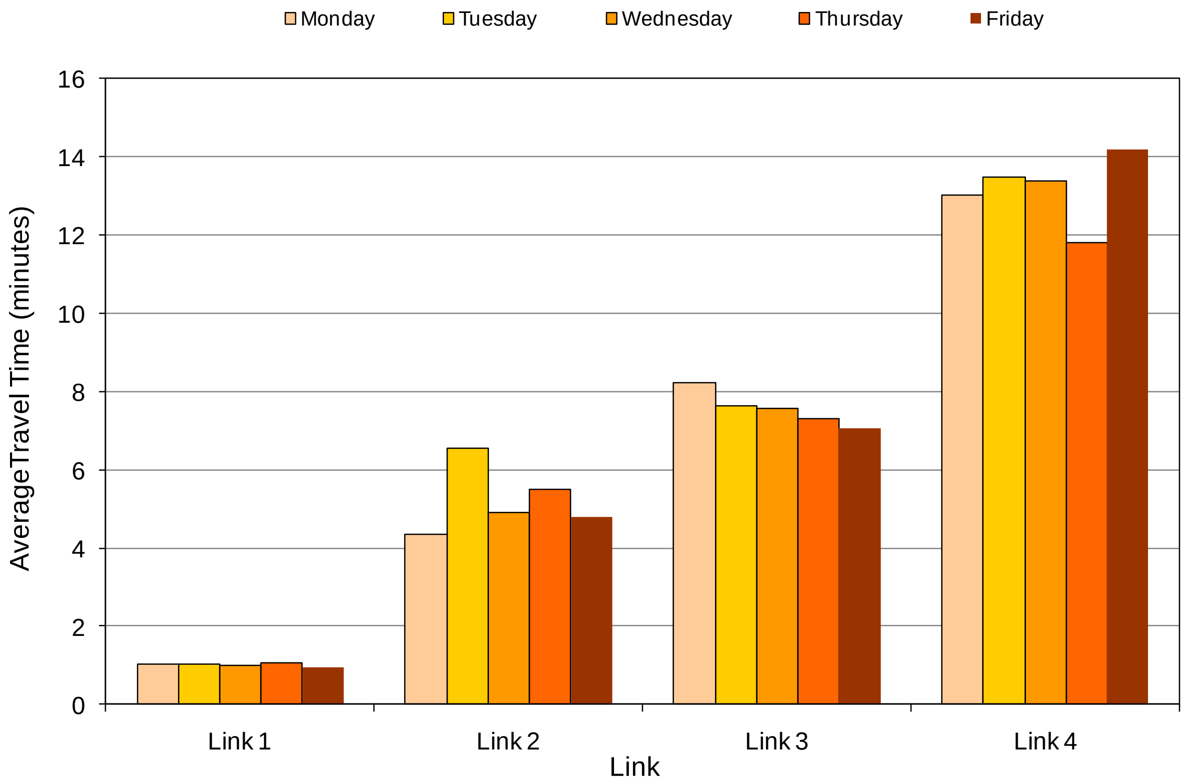

Figure B-30. US 1 (C) Mean Travel Time vs. Link and Day of the Week

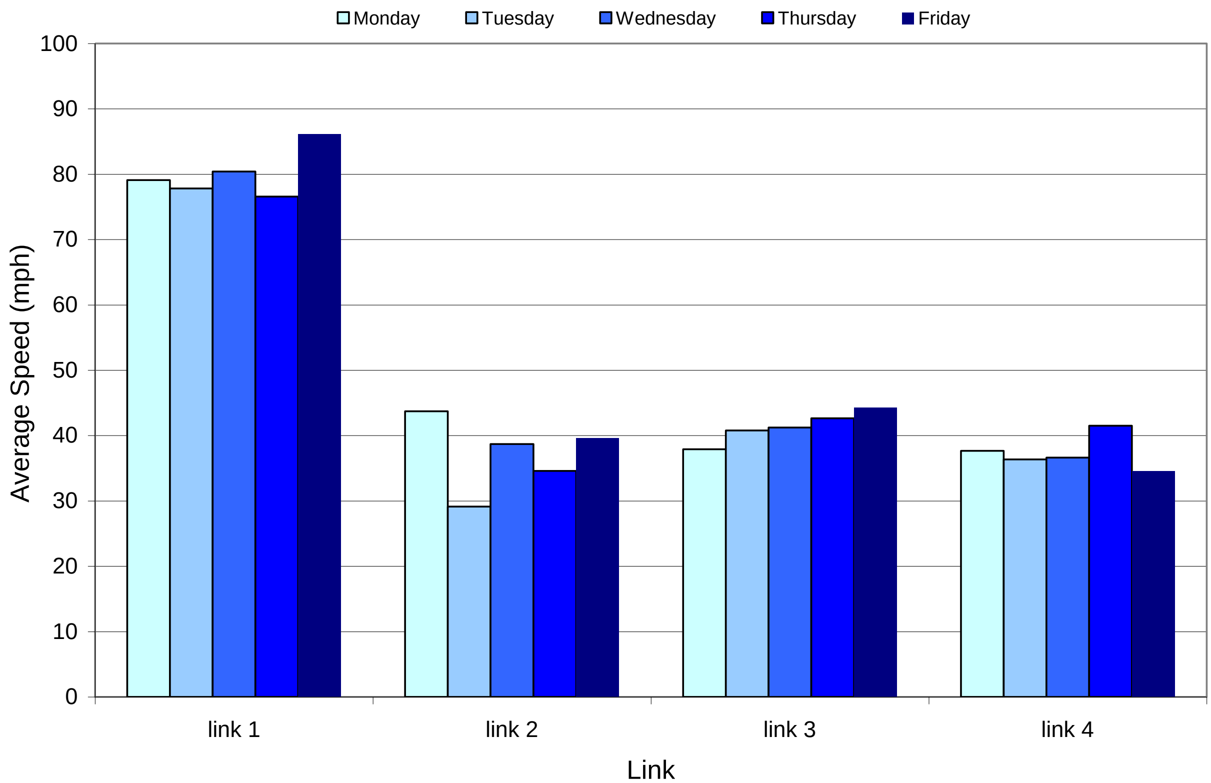

Figure B-31. US 1 (C) Mean Travel Speed vs. Link and Day of the Week

US 1(D)

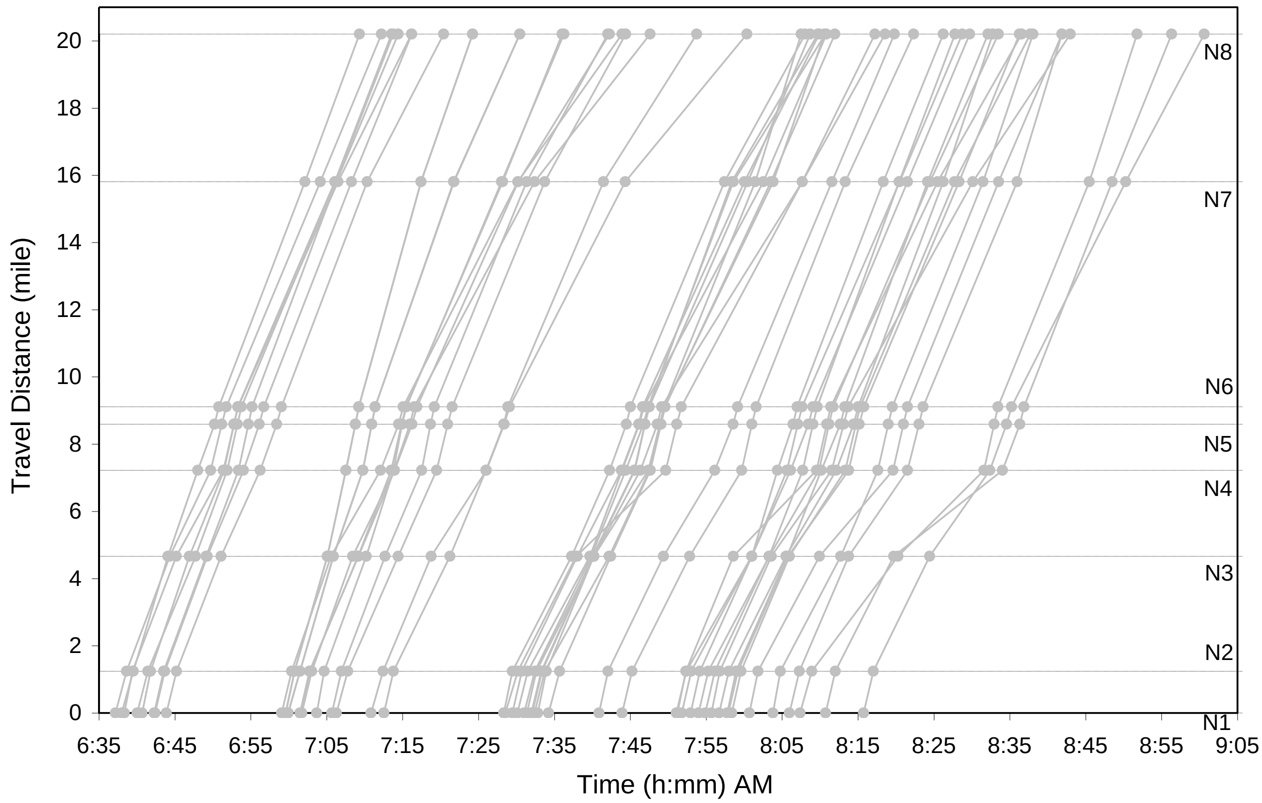

Figure B-32. Probe Vehicle Travel Profiles on US 1 (D) vs. Departure Time

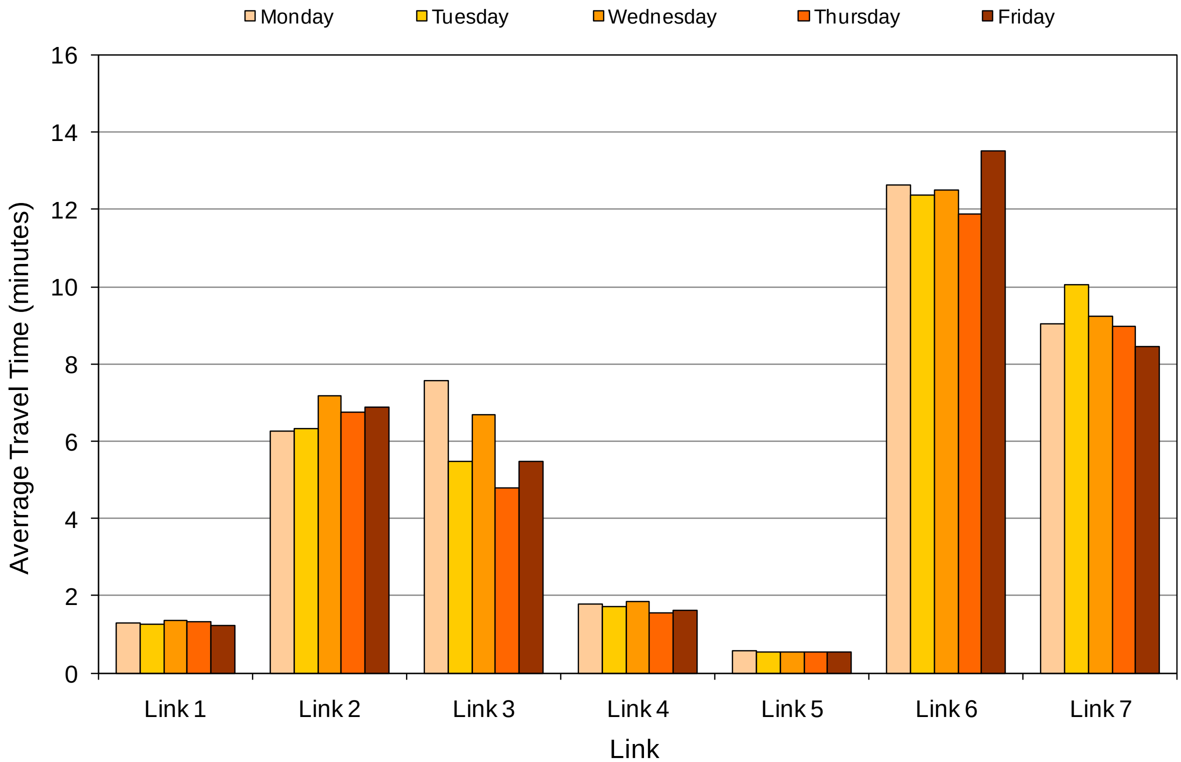

Figure B-33. US 1 (D) Mean Travel Time vs. Link and Day of the Week

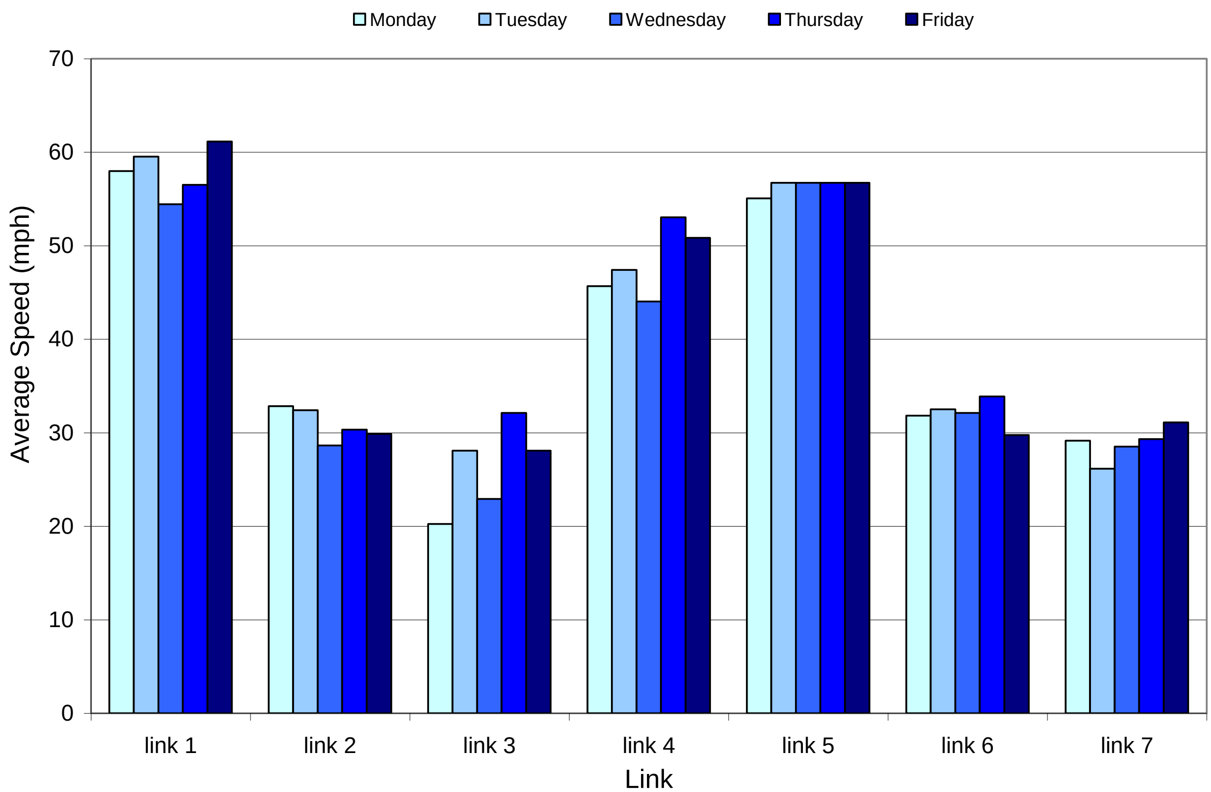

Figure B-34. US 1 (D) Mean Travel Speed vs. Link and Day of the Week

US 9

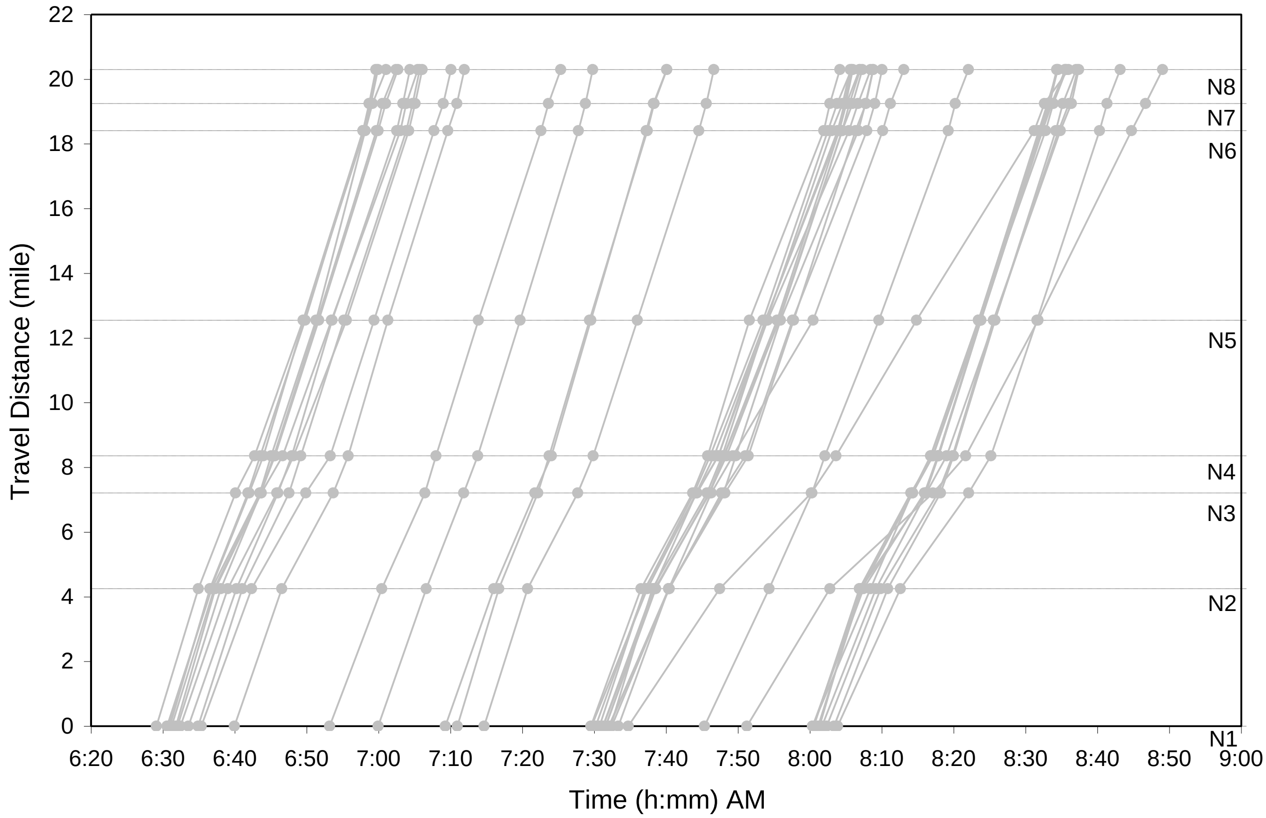

Figure B-35. Probe Vehicle Travel Profiles on US 9 vs. Departure Time

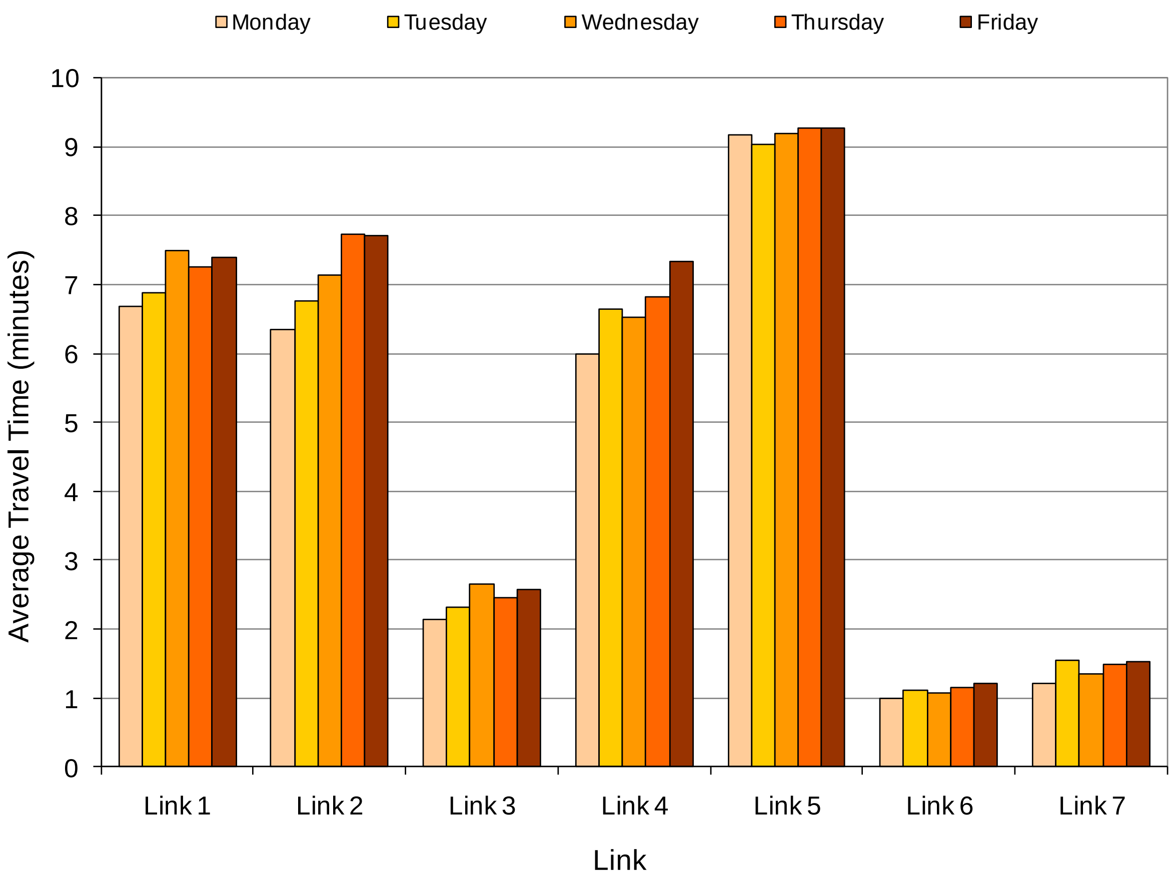

Figure B-36. US 9 Mean Travel Time vs. Link and Day of the Week

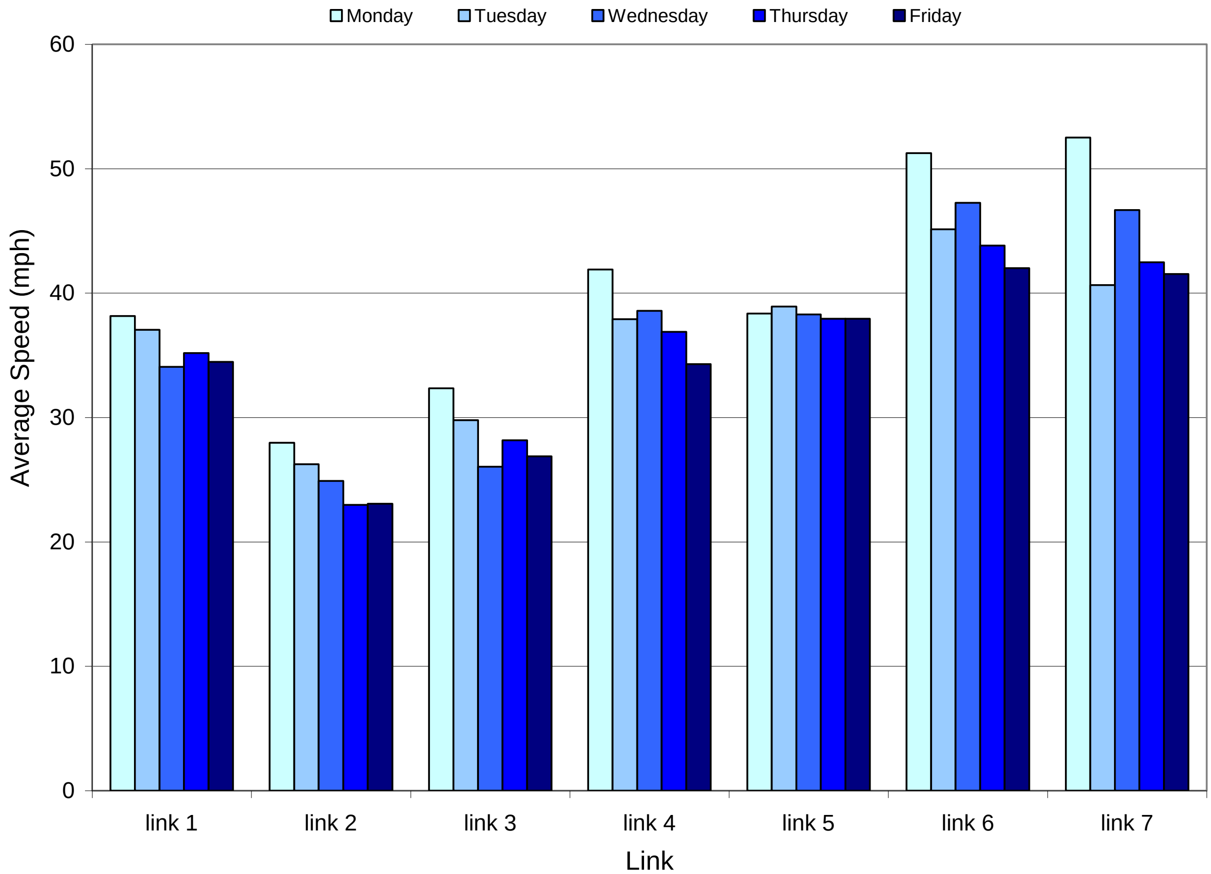

Figure B-37. US 9 Mean Travel Speed vs. Link and Day of the Week

NJ 42 & I-76

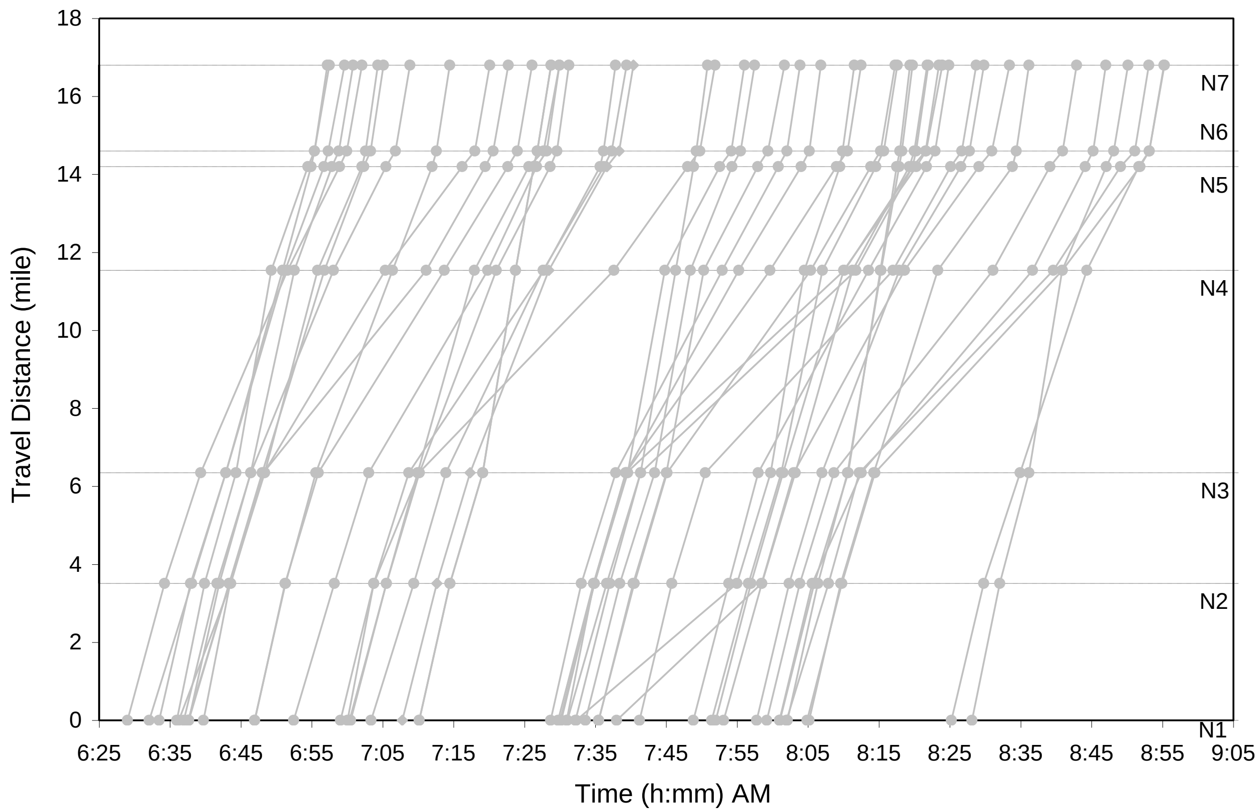

Figure B-38. Probe Vehicle Travel Profiles on NJ 42 & I-76 vs. Departure Time

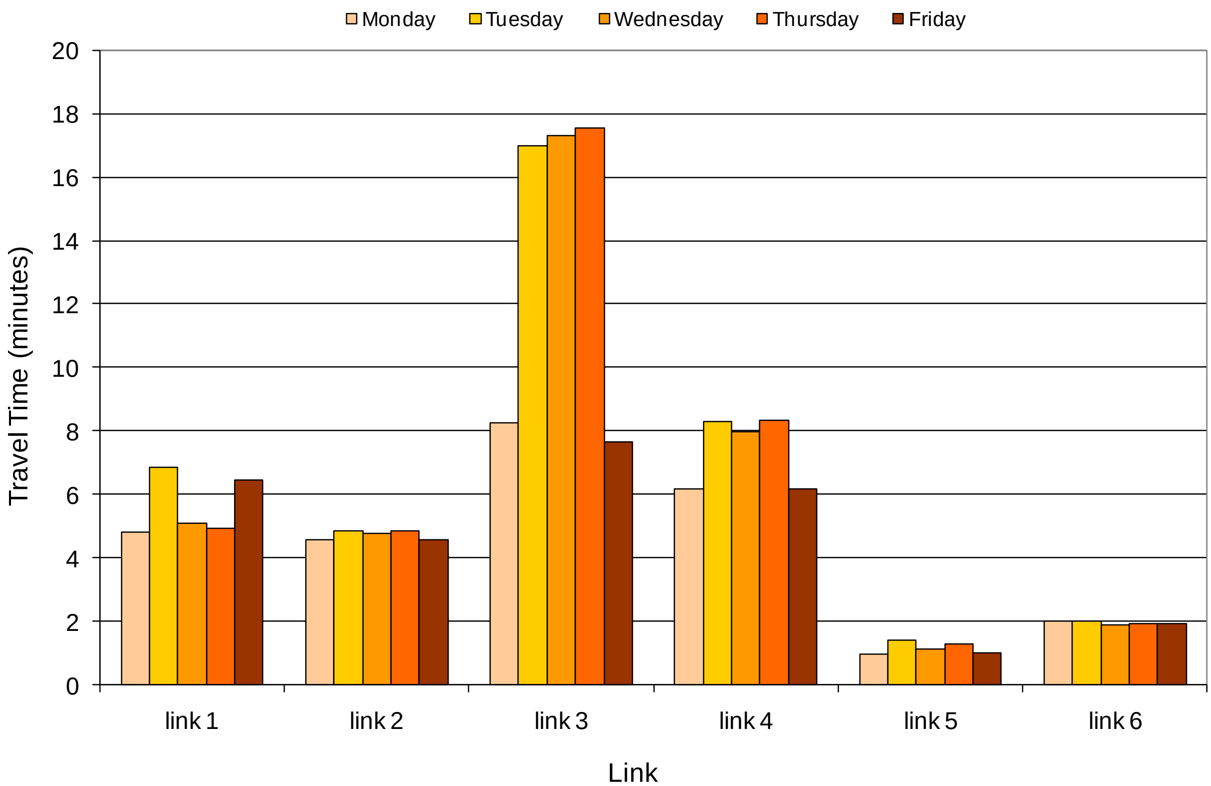

Figure B-39. NJ 42 & I-76 Mean Travel Time vs. Link and Day of the Week

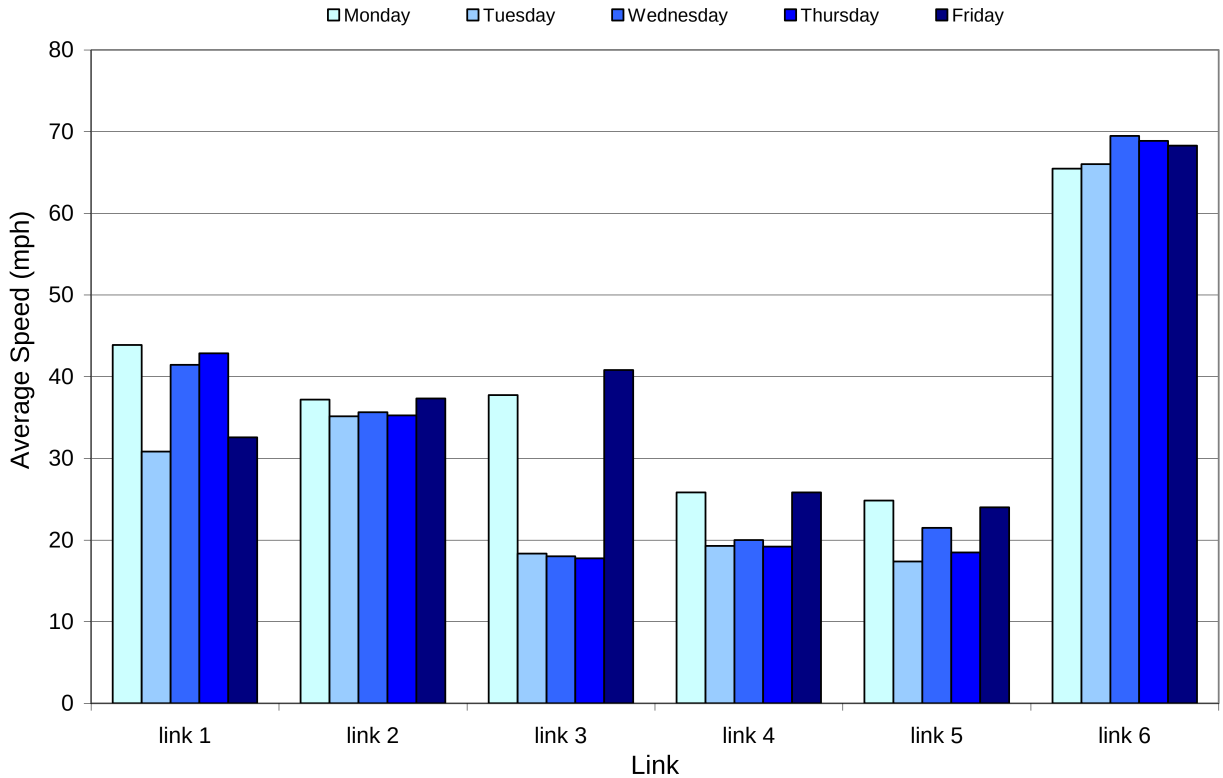

Figure B-40. NJ 42 & I-76 Mean Travel Speed vs. Link and Day of the Week

NJ 70

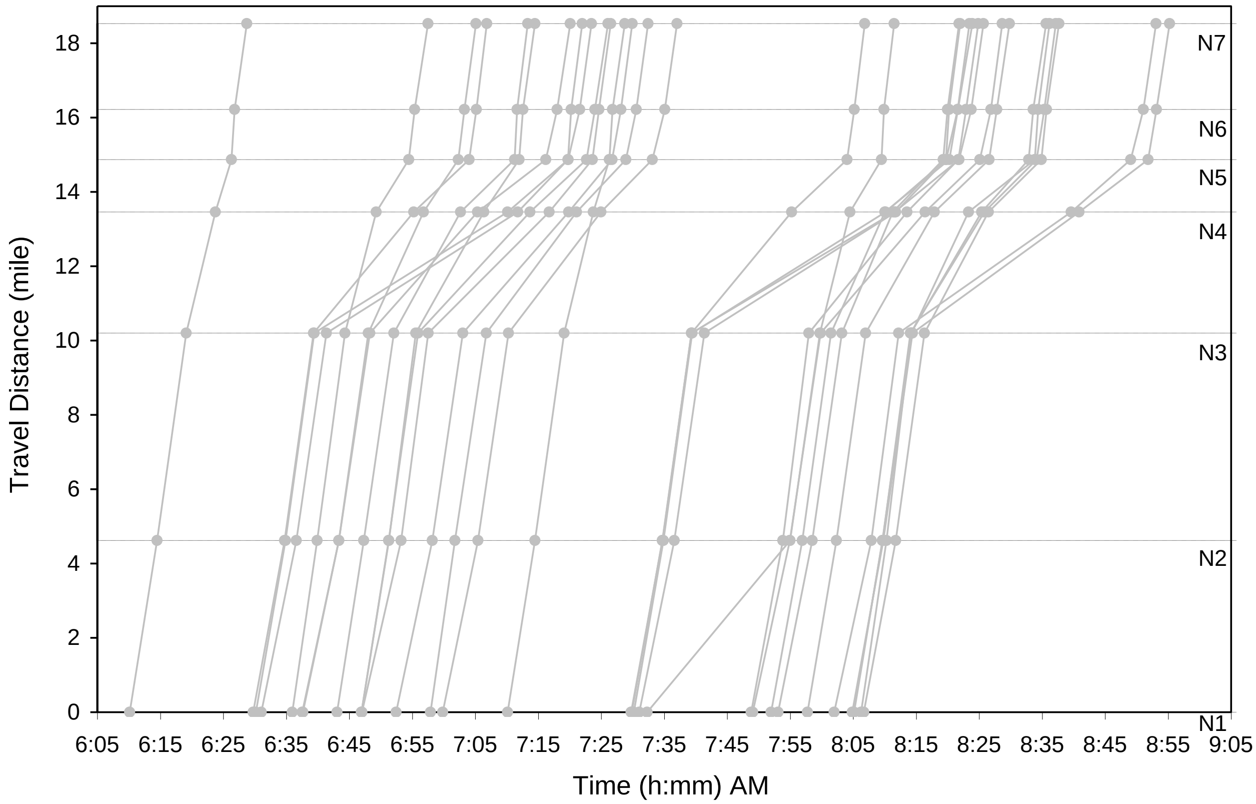

Figure B-41. Probe Vehicle Travel Profiles on NJ 70 vs. Departure Time

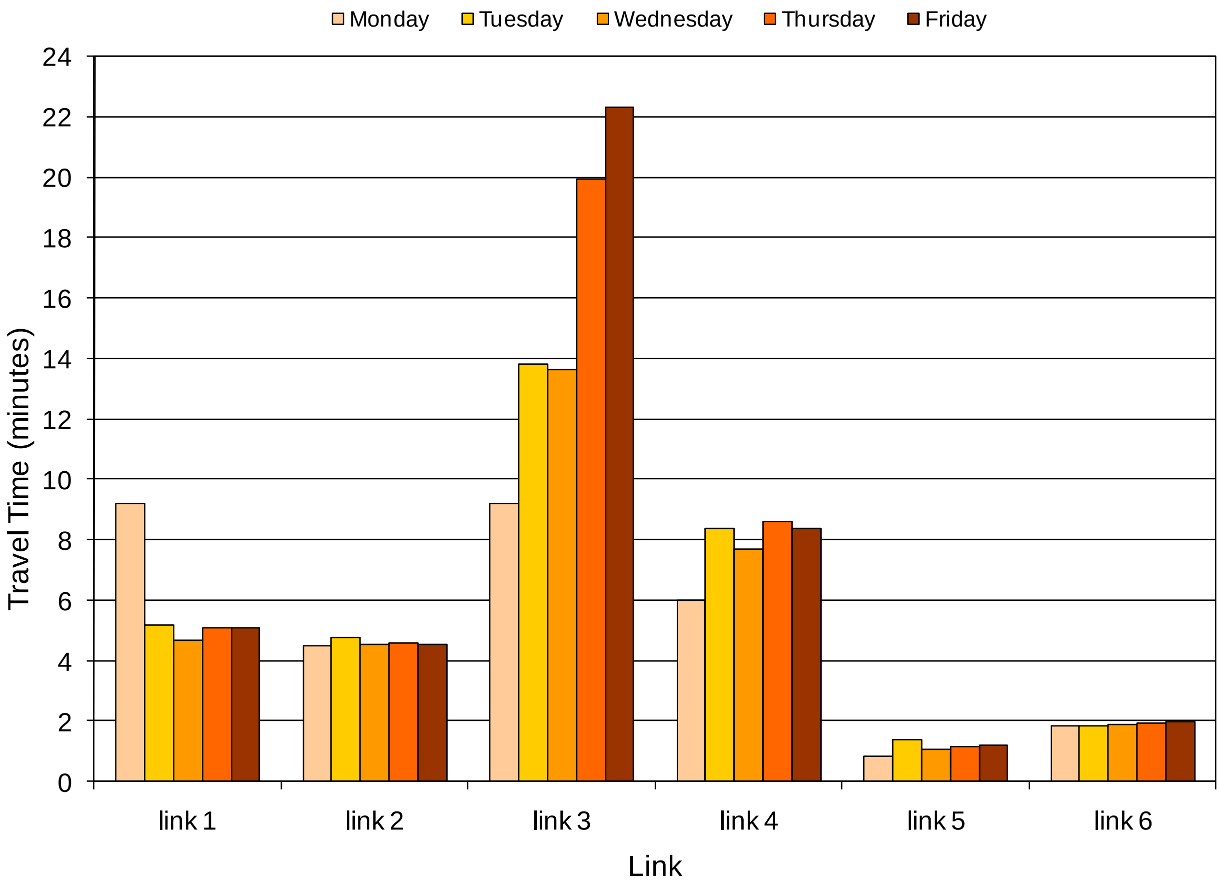

Figure B-42. NJ 70 Mean Travel Time vs. Link and Day of the Week

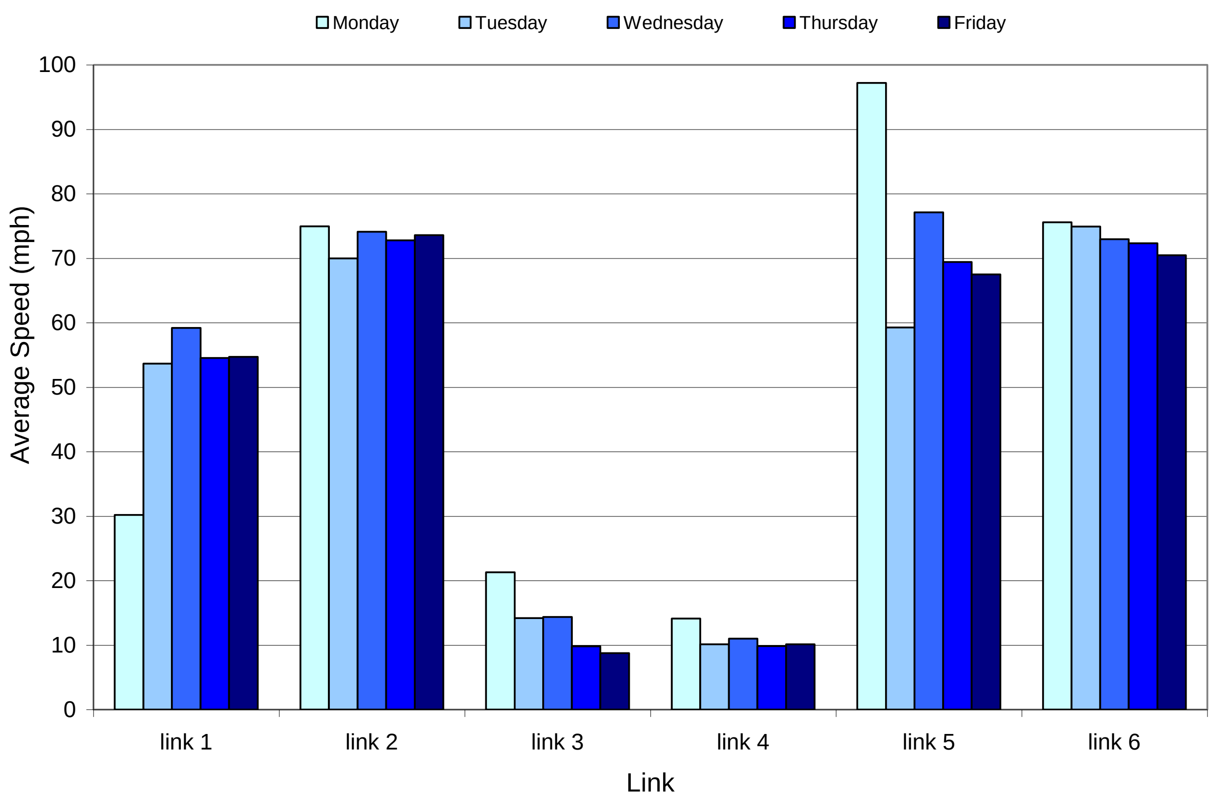

Figure B-43. NJ 70 Mean Travel Speed vs. Link and Day of the Week

NJ 73

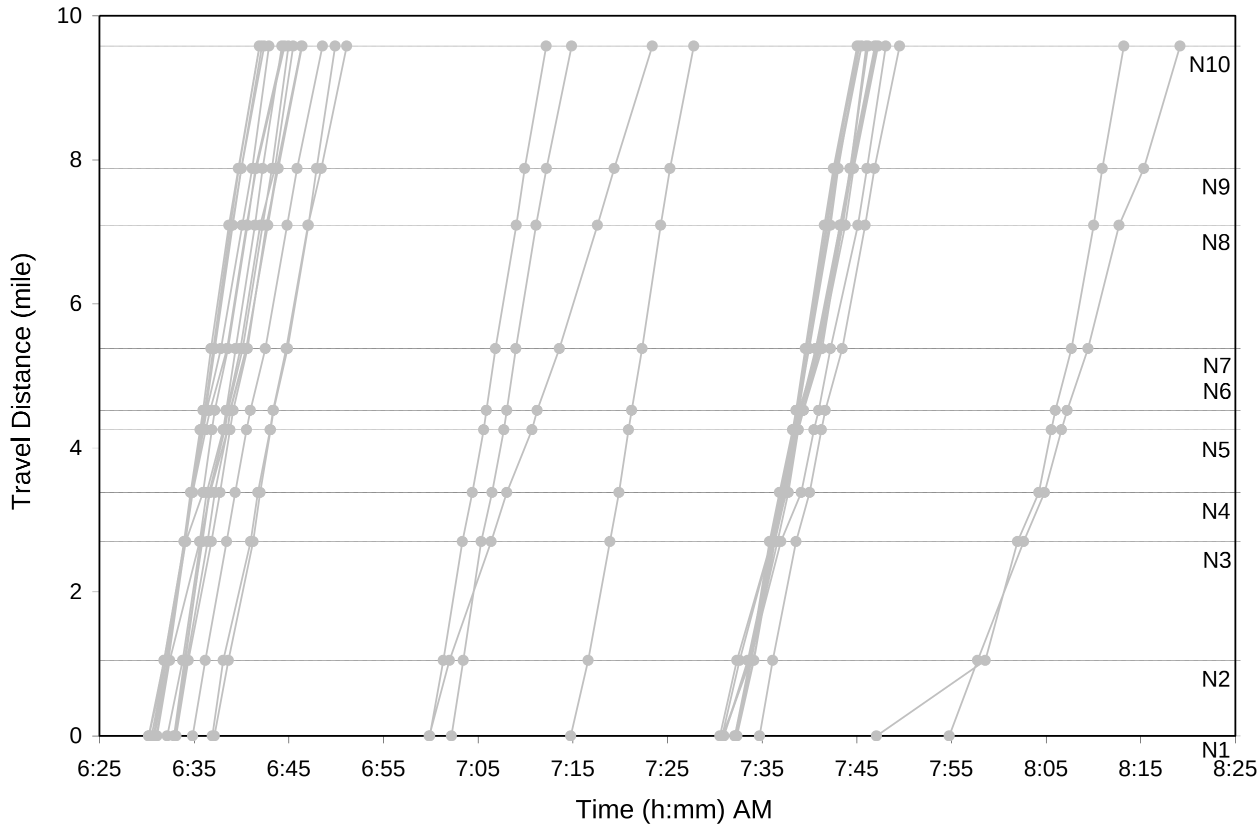

Figure B-44. Probe Vehicle Travel Profiles on NJ 73 vs. Departure Time

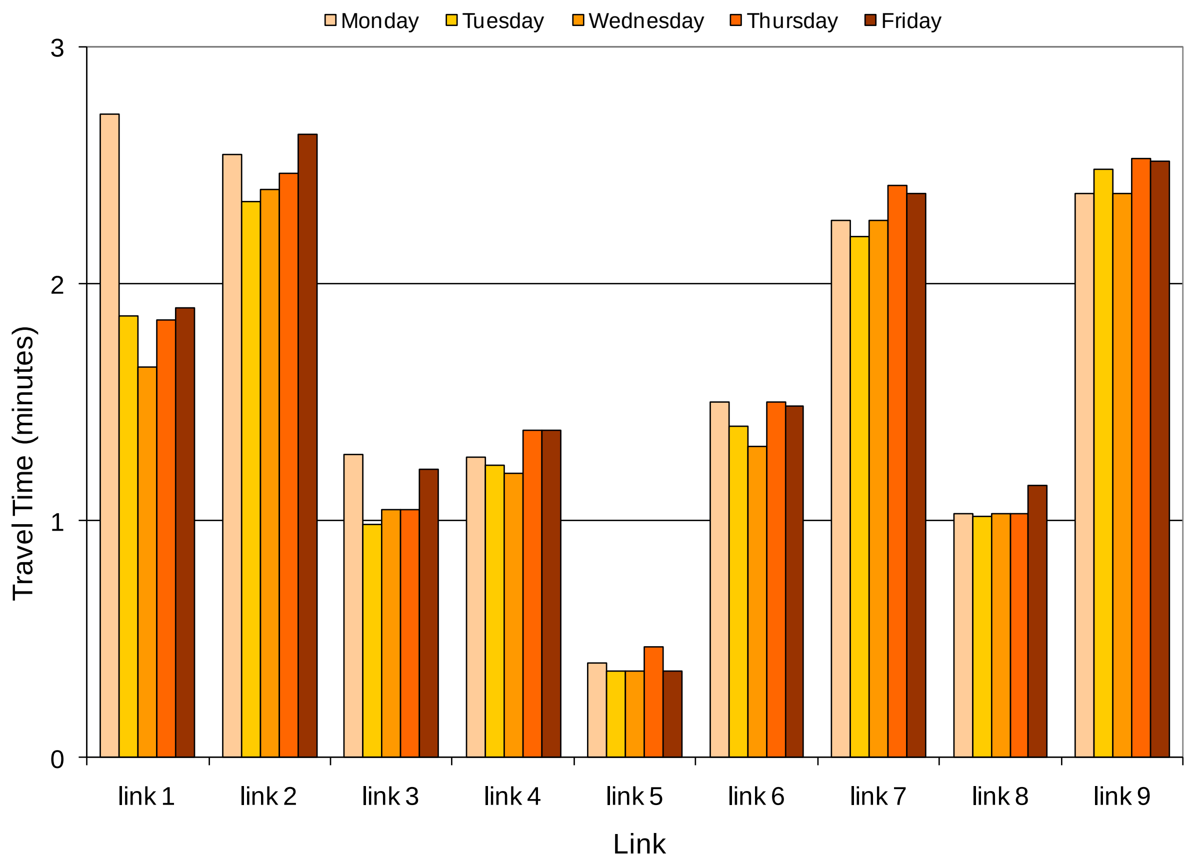

Figure B-45. NJ 73 Mean Travel Time vs. Link and Day of the Week

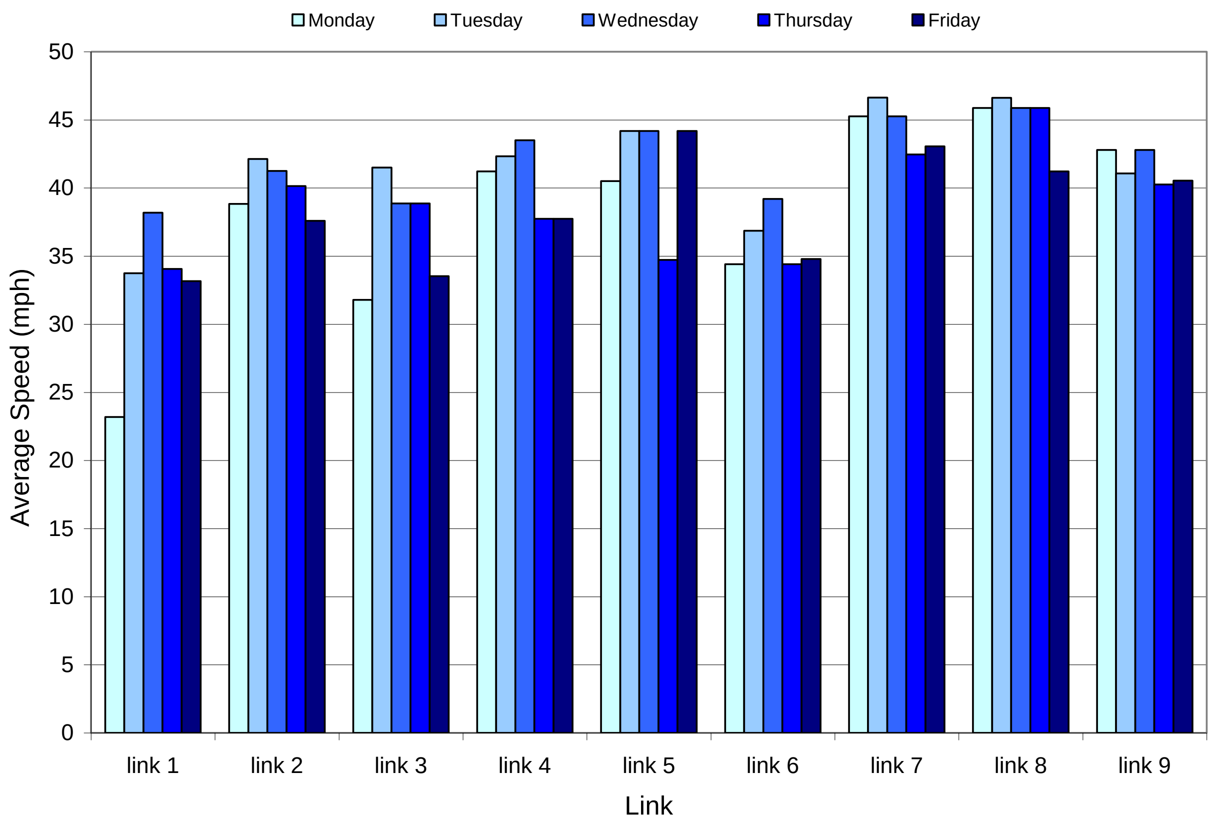

Figure B-46. NJ 73 Mean Travel Speed vs. Link and Day of the Week

NJ 29

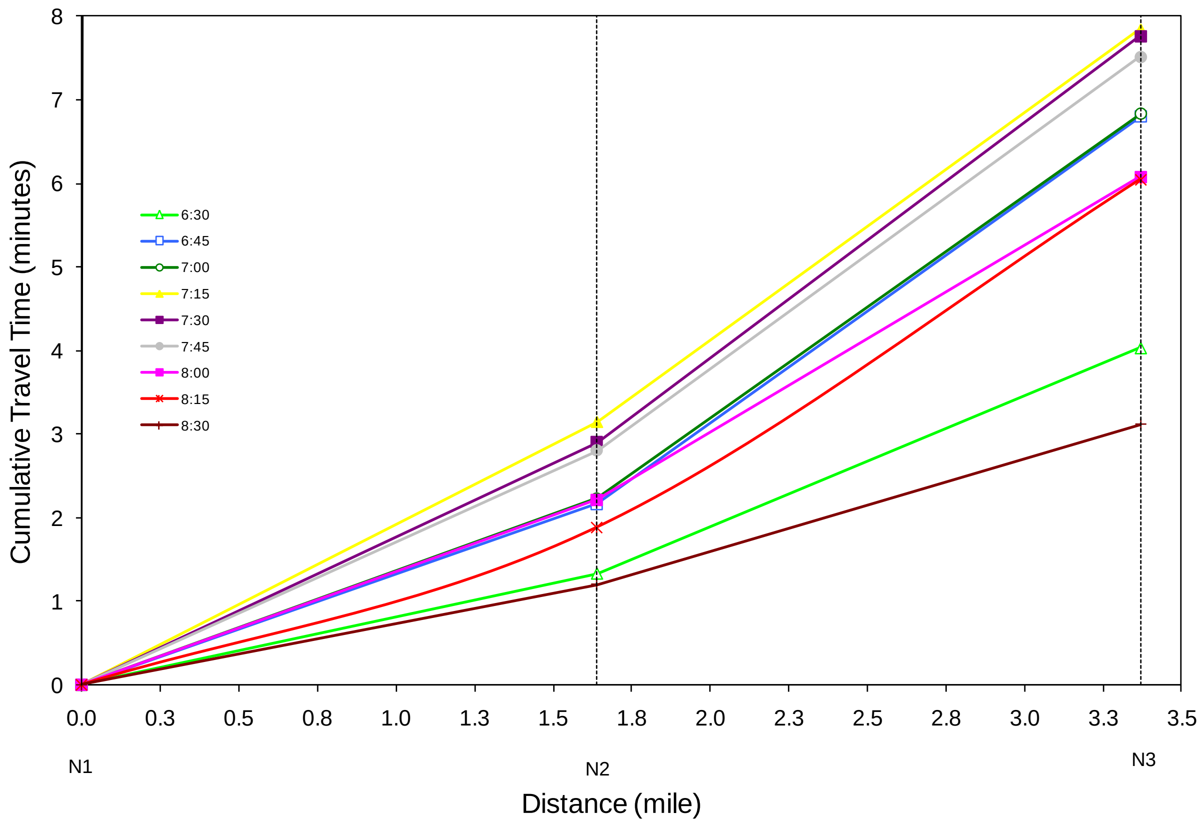

Figure B-47. Travel Times for Different Departure Time Periods (NJ 29)

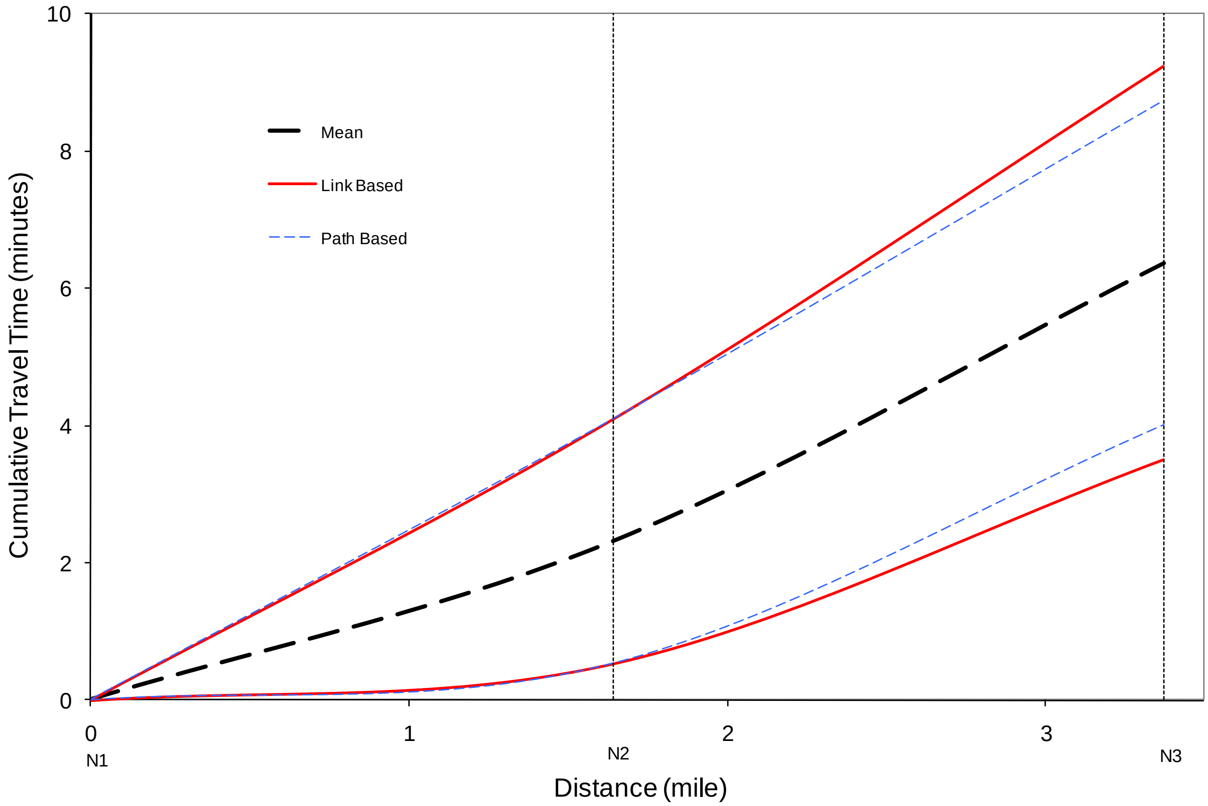

Figure B-48. Travel Time Variation with Link-Based vs. Path-Based Data (NJ 29)

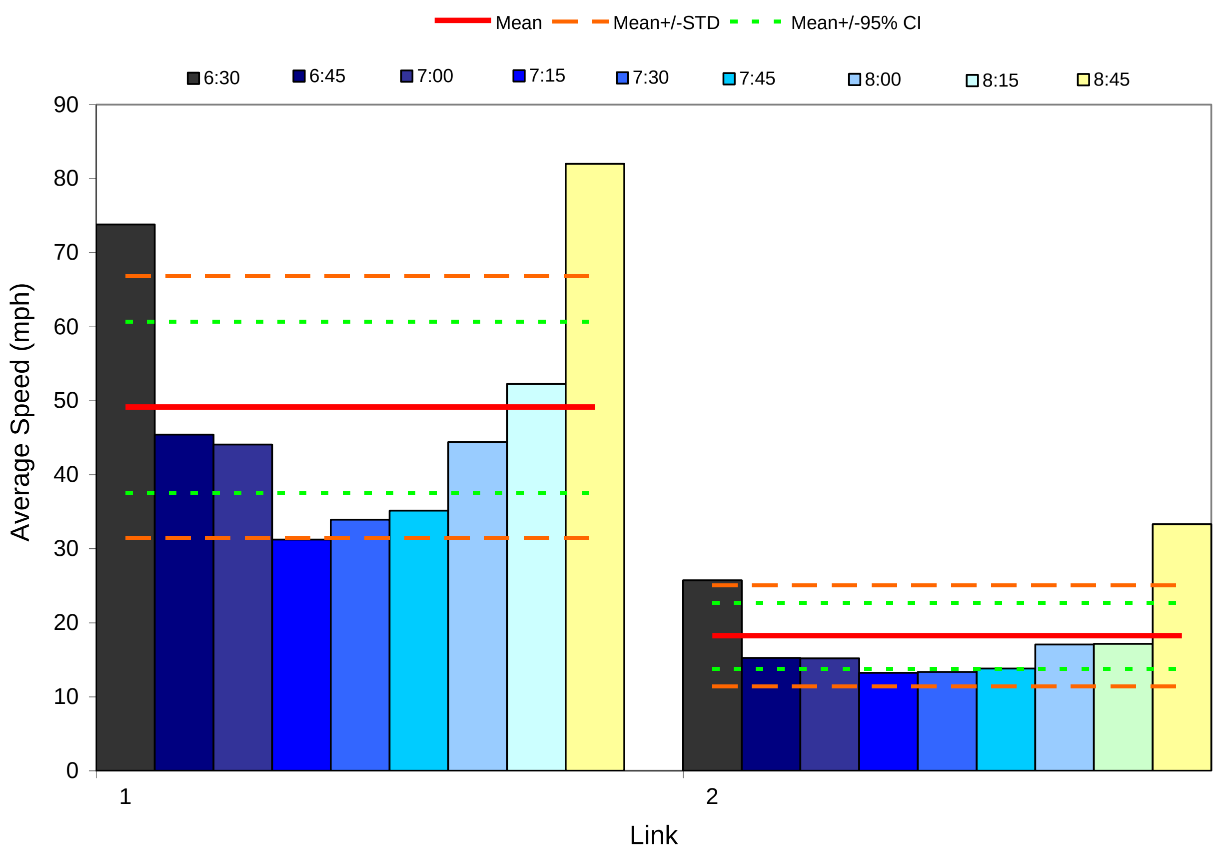

Figure B-49. Speed Variation vs. Link for Different Departure Time Periods (NJ 29)

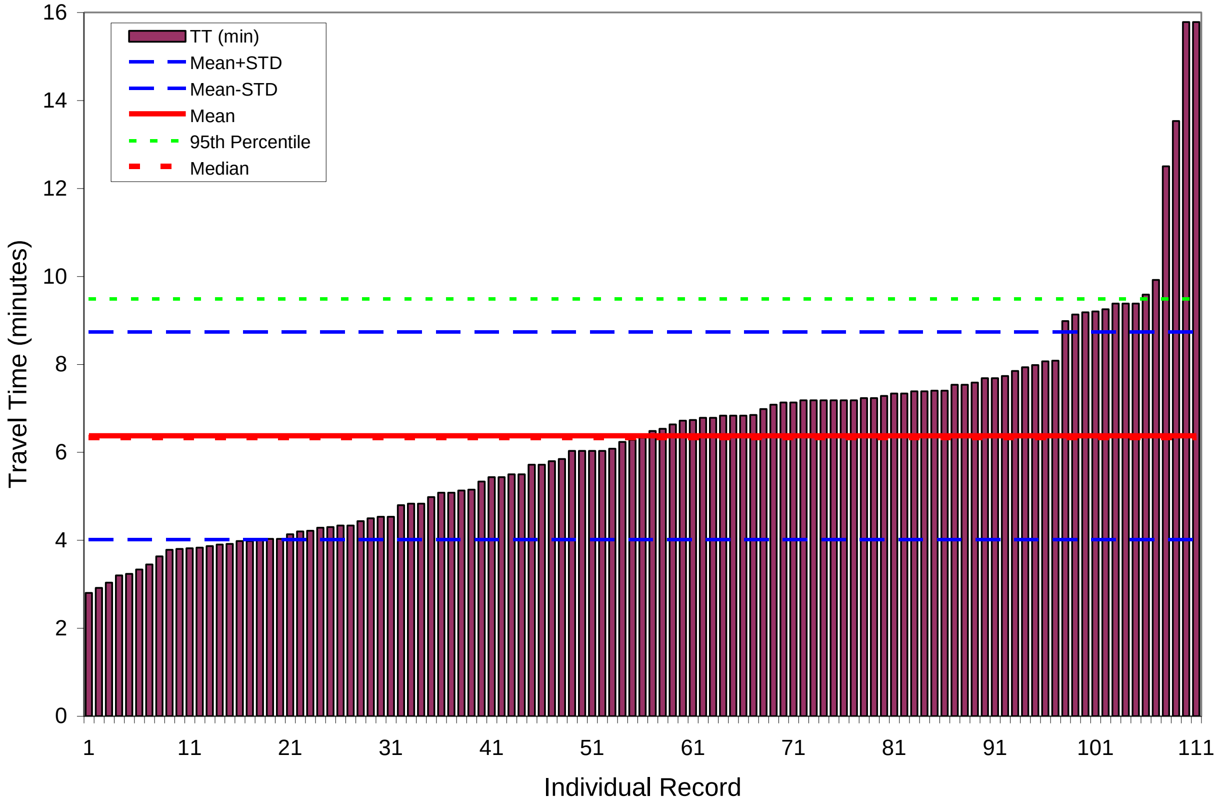

Figure B-50. Path Travel Time Distribution (NJ 29)

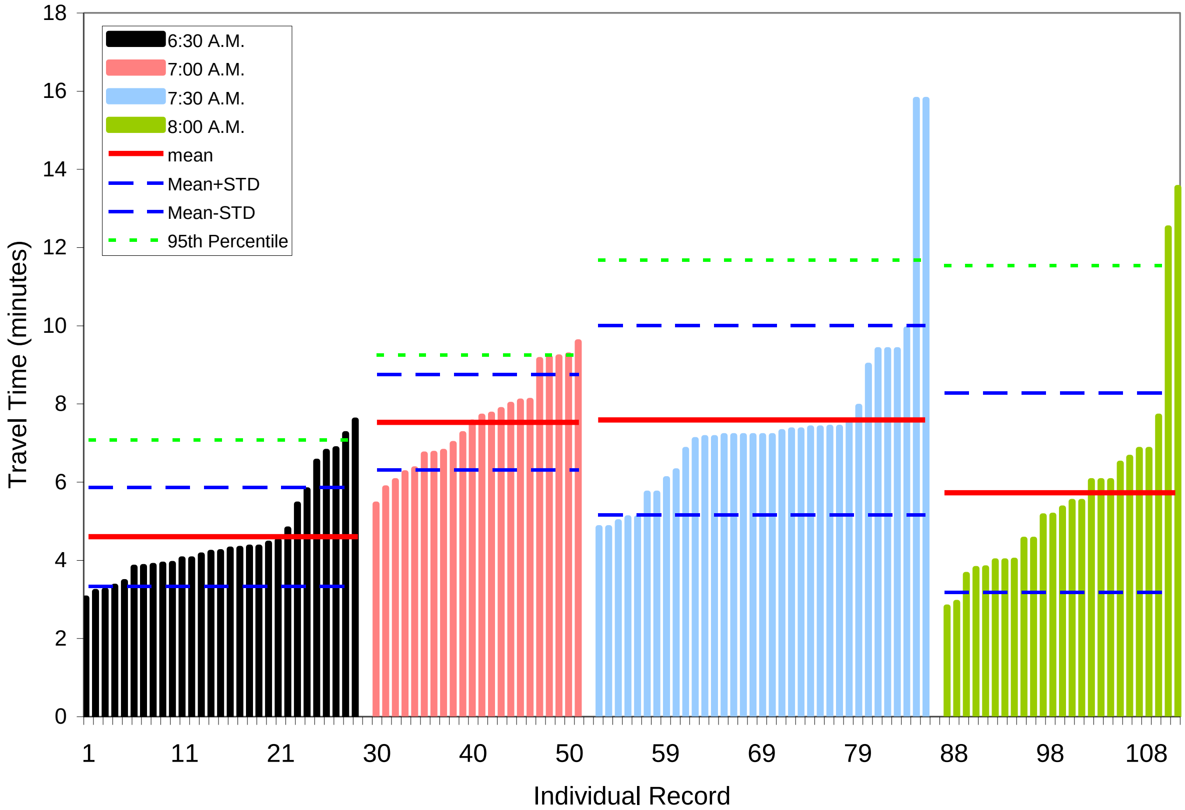

Figure B-51. Path Travel Time Distribution by Departure Time Period (NJ 29)

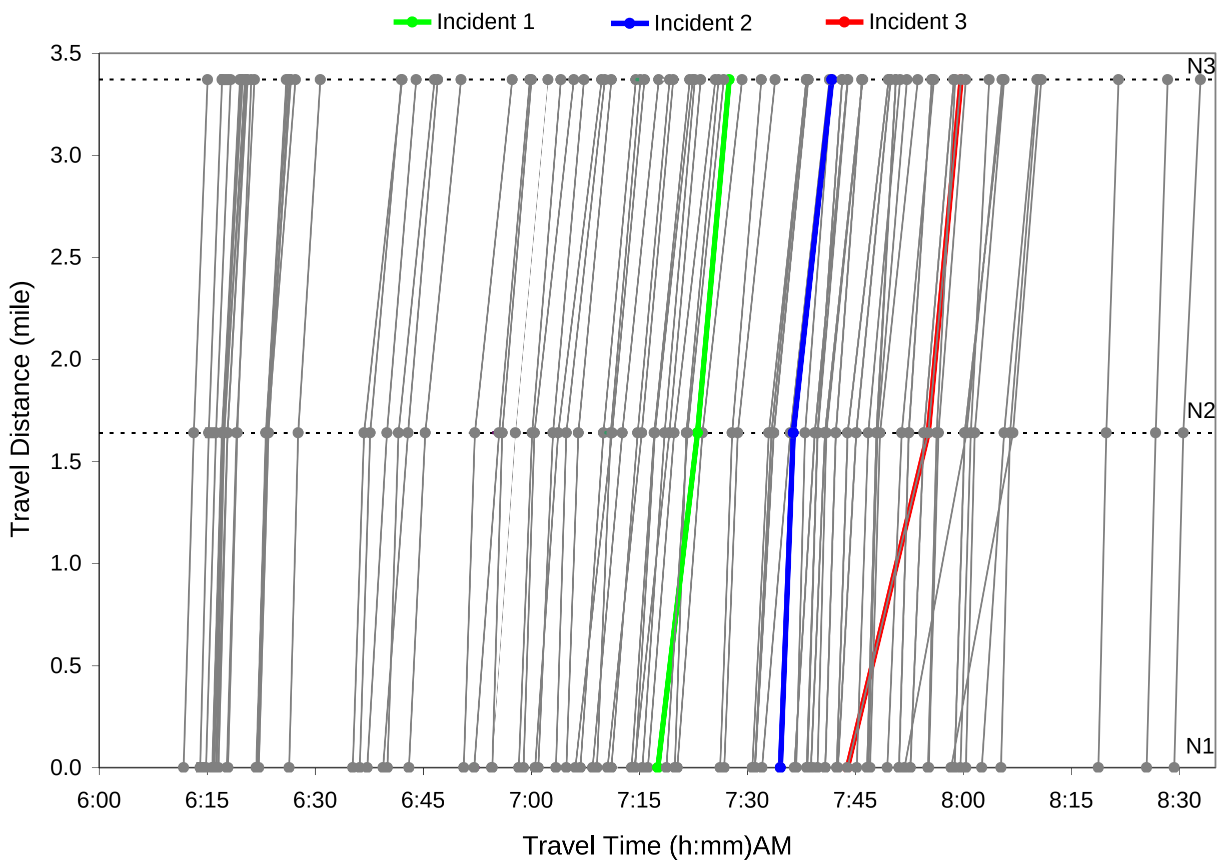

Figure B-52. Probe Vehicle Travel Profiles on NJ 29 vs. Departure Time

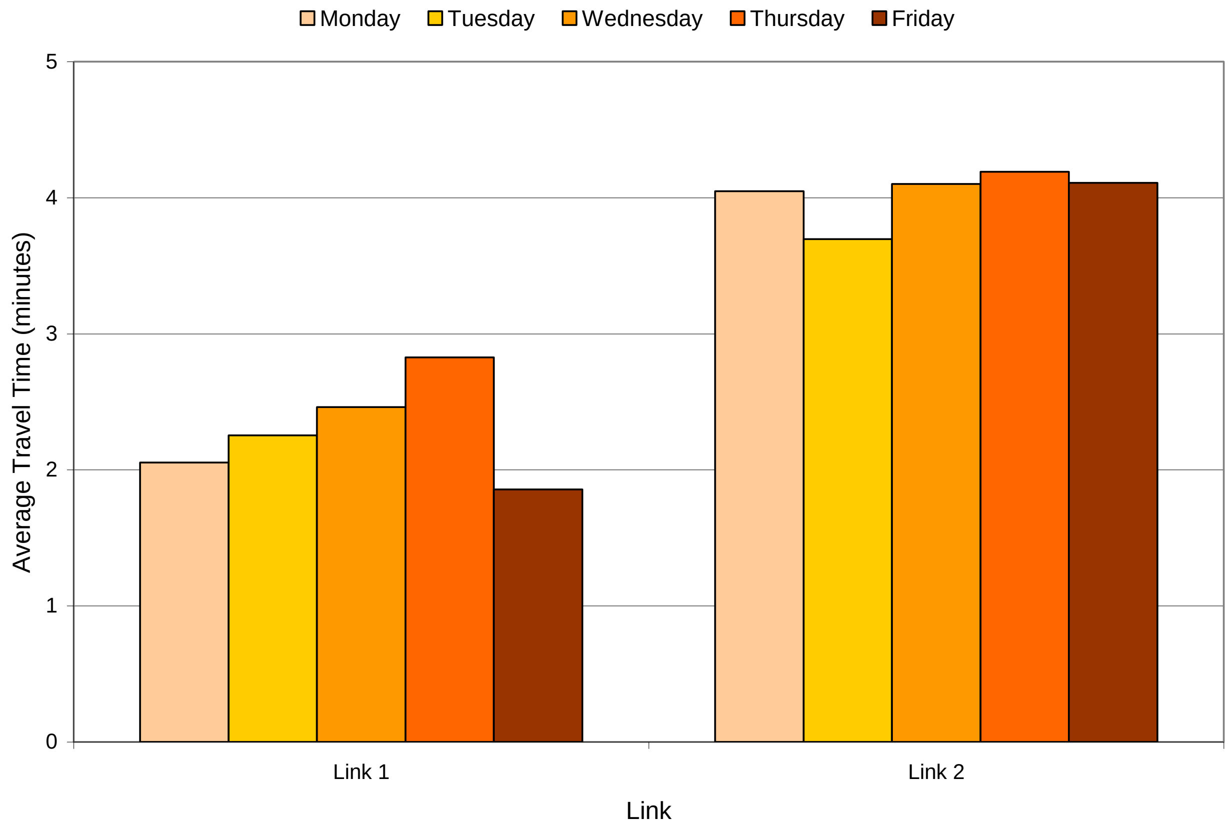

Figure B-53. NJ 29 Mean Travel Time vs. Link and Day of the Week

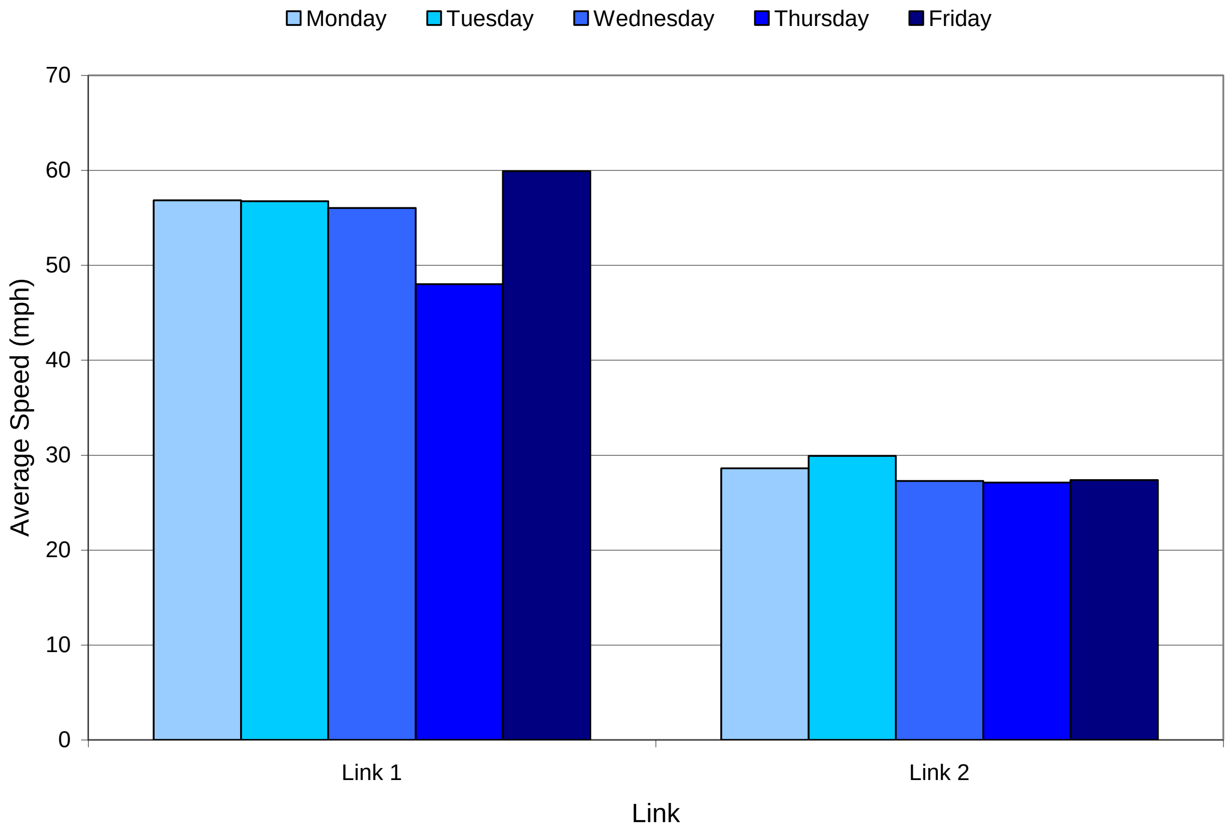

Figure B-54. NJ 29 Mean Travel Speed vs. Link and Day of the Week

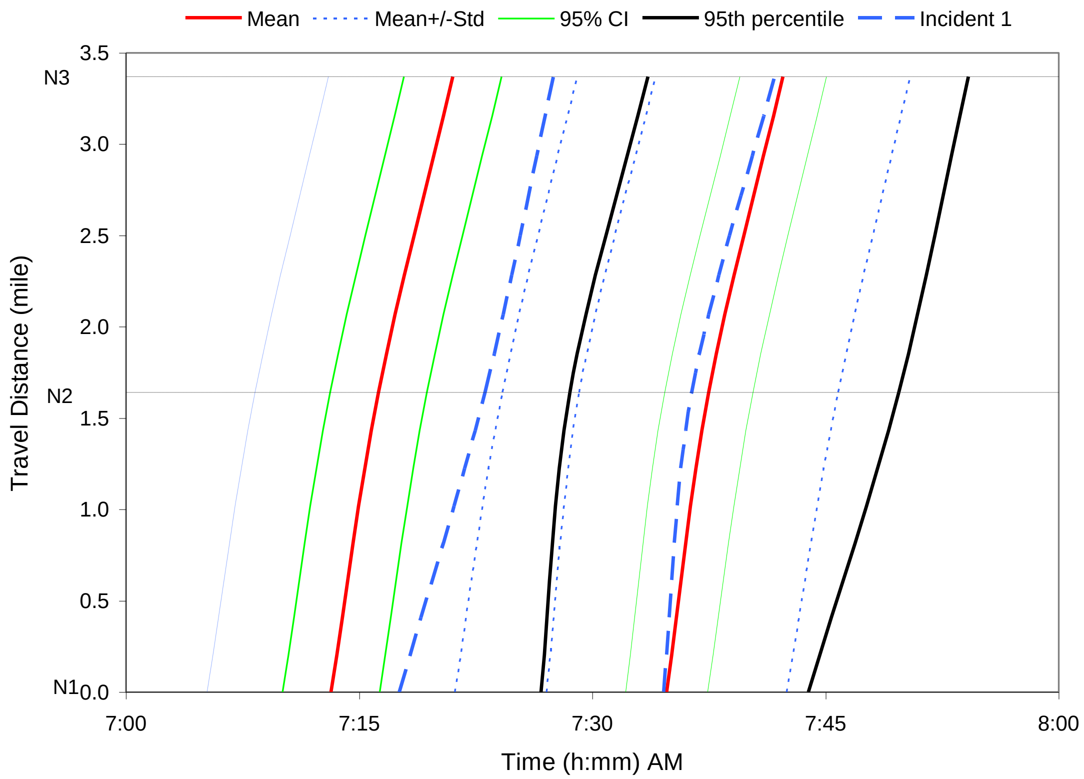

Figure B-55. Incident Impact – NJ 29

APPENDIX C: NORMALITY TEST

1) Anderson-Darling test

The Anderson-Darling test (Stephens, 1974) is used to test if a sample of data came from a population with a specific distribution. The Anderson-Darling test makes use of the specific distribution in calculating critical values. This has the advantage of allowing a more sensitive test and the disadvantage that critical values must be calculated for each distribution. The Anderson-Darling test is an alternative to the chi-square and Kolmogorov-Smirnov goodness-of-fit tests. Anderson-Darling test is defined as

H_0: The data follow a specified distribution.

H_a: The data do not follow the specified distribution

The Anderson-Darling test statistic is defined as

$$A^2 = -N - S$$

where

$$S = \sum_{i=1}^{N} \frac{(2i-1)}{N} \left[\ln F(Y_i) + \ln\left(1 - F(Y_{N+1-i})\right) \right]$$

where F is the cumulative distribution function of the specified distribution. Note that Y_i are the ordered data. The critical values for the Anderson-Darling test are dependent on the specific distribution that is being tested. Tabulated values and formulas have been published (Stephens, 1974, 1976, 1977, 1979) for a few specific distributions (normal, lognormal, exponential, Weibull, logistic, extreme value type 1). The test is a one-sided test and the hypothesis that the distribution is of a specific form is rejected if the test statistic, A, is greater than the critical value.

2) Shapiro-Wilk Test

The Sharpiro-Wilk test, proposed in 1965, calculates a W statistic that tests whether a random sample, x_1, x_2, …,x_n, comes from a normal distribution. Small values of W are evidence of departure from normality and percentage points for the W statistic, obtained via Monte Carlo simulations, were reproduced by Pearson and Hartley (1972). This test has done very well in comparison studies with other goodness of fit tests. The W statistic is calculated as follows:

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

Where the $x_{(i)}$ are the ordered sample values and the a_i are constants generated from the means, variances and co-variance of the order statistics of a sample of size n from a normal distribution.

3) Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test is used to decide if a sample comes from a population with a specific distribution. The Kolmogorov-Smirnov (K-S) test is based on the empirical distribution function (ECDF). Given *N ordered* data points Y_1, Y_2, ..., Y_N, the ECDF is defined as

$$E_N = \frac{n(i)}{N}$$

where n(i) is the number of points less than Y_i and the Y_i are ordered from smallest to largest value. This is a step function that increases by 1/N at the value of each ordered data point.

An attractive feature of this test is that the distribution of the K-S test statistic itself does not depend on the underlying cumulative distribution function being tested. Another advantage is that it is an exact test (the chi-square goodness-of-fit test depends on an adequate sample size for the approximations to be valid). Despite these advantages, the K-S test has several important limitations:

1. It only applies to continuous distributions.
2. It tends to be more sensitive near the center of the distribution than at the tails.
3. Perhaps the most serious limitation is that the distribution must be fully specified. That is, if location, scale, and shape parameters are estimated from the data, the critical region of the K-S test is no longer valid. It typically must be determined by simulation.

Due to limitations 2 and 3 above, many analysts prefer to use the Anderson-Darling goodness-of-fit test. However, the Anderson-Darling test is only available for a few specific distributions. The Kolmogorov-Smirnov test is defined by

H_0: The data follow a specified distribution.

H_a: The data do not follow the specified distribution

The Kolmogorov-Smirnov test statistic is defined as

$$D = \max_{1 \le i \le N}\left(F(Y_i) - \frac{1-i}{N}, \frac{i}{N} - F(Y_i)\right)$$

Where F is the theoretical cumulative distribution of the distribution being tested which must be a continuous distribution (i.e., no discrete distributions such as the binomial or Poisson), and it must be fully specified.

The hypothesis regarding the distributional form is rejected if the test statistic, D, is greater than the critical value obtained from a table. There are several variations of these tables in the literature that use somewhat different scaling for the K-S test statistic and critical regions. These alternative formulations should be equivalent, but it is necessary to ensure that the test statistic is calculated in a way that is consistent with how the critical values were tabulated.

APPENDIX D: TRAVEL TIME DISTRIBUTION AND LOG-NORMALITY TEST

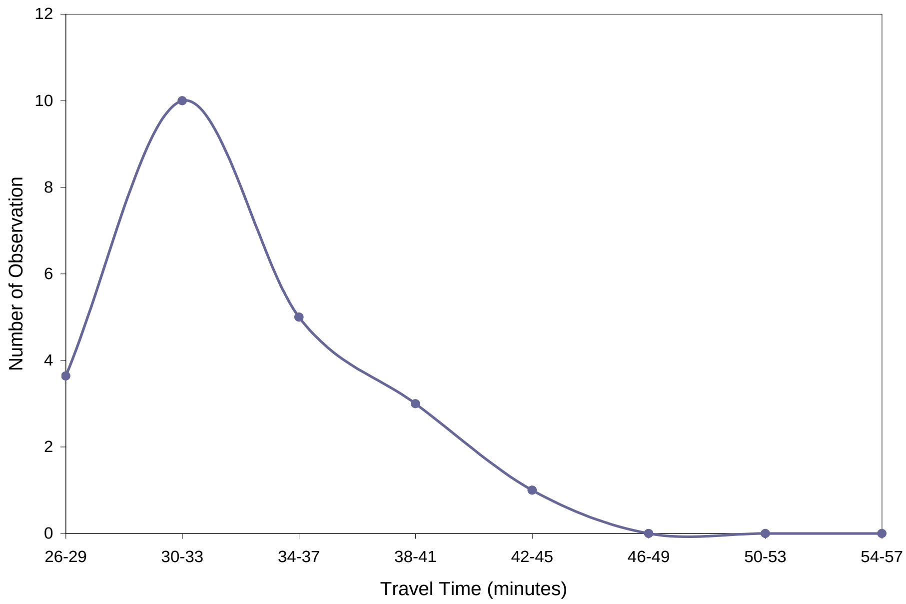

Figure D-1. Path Travel Time Distribution (NJ 4 & NJ 208)

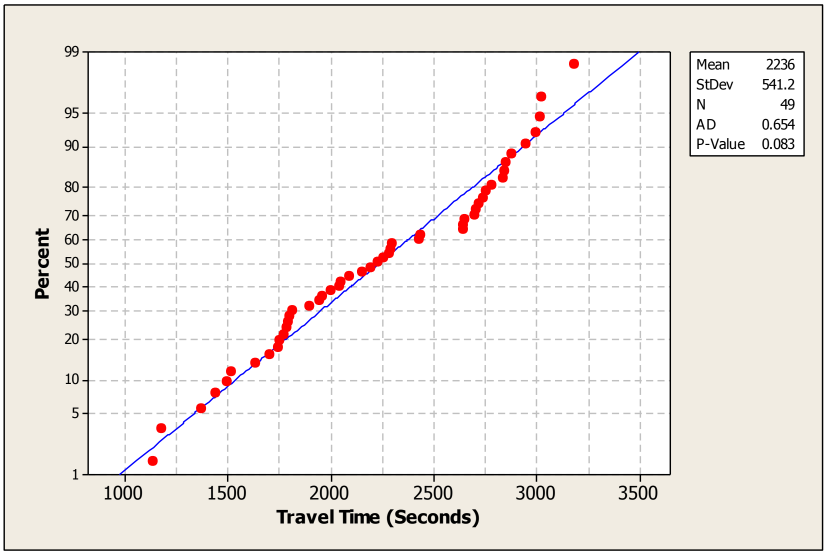

Figure D-2. Path Travel Time Distribution Log-Normality Test Results (NJ 4 & NJ 208)

*: Path travel time distribution is normal distribution

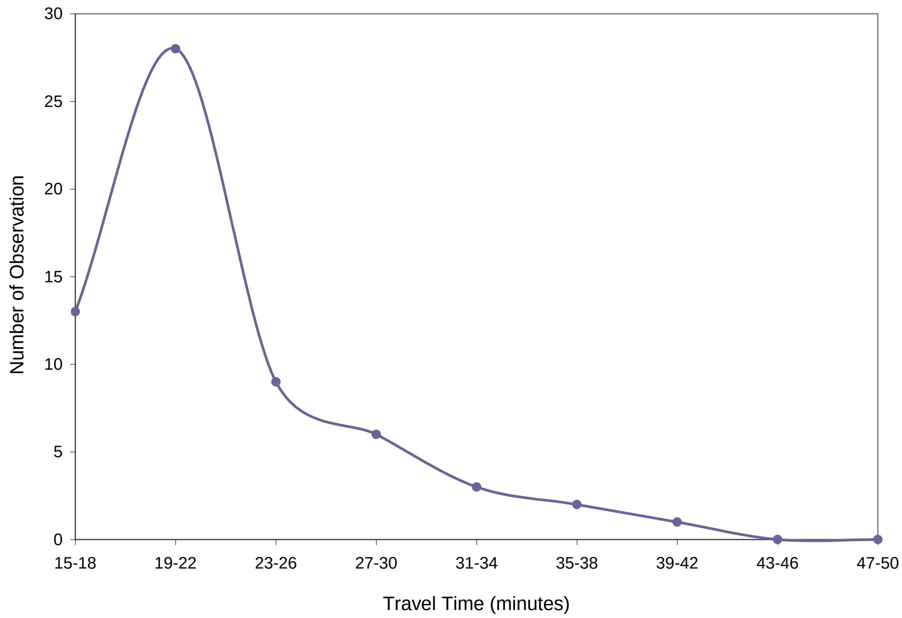

Figure D-3. Path Travel Time Distribution (I-80 & I-280)

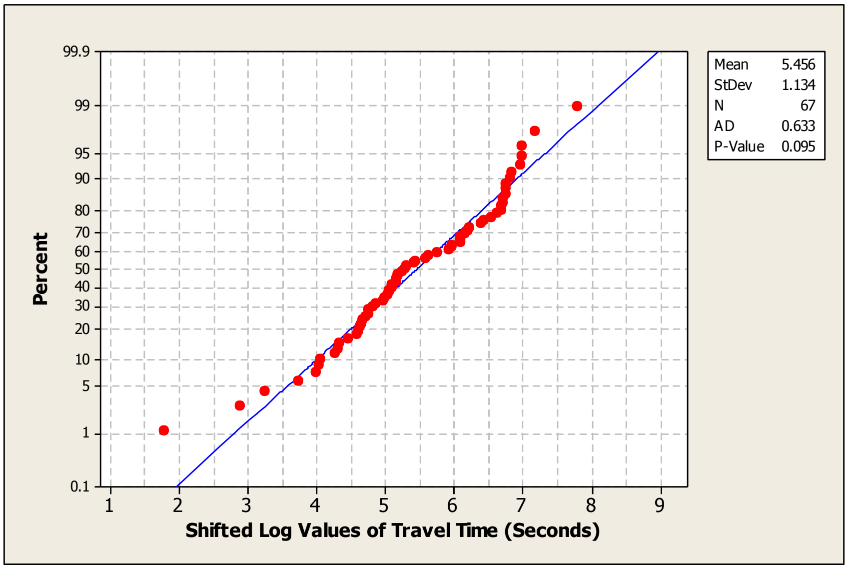

Figure D-4. Path Travel Time Distribution Log-Normality Test Results (I-80 & I-280)

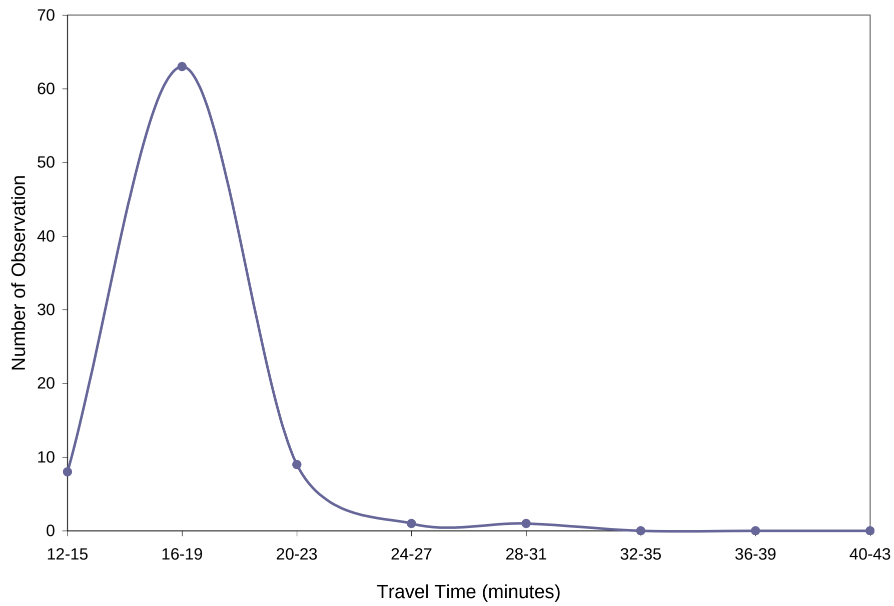

Figure D-5. Path Travel Time Distribution (NJ 24 **&** I-78)

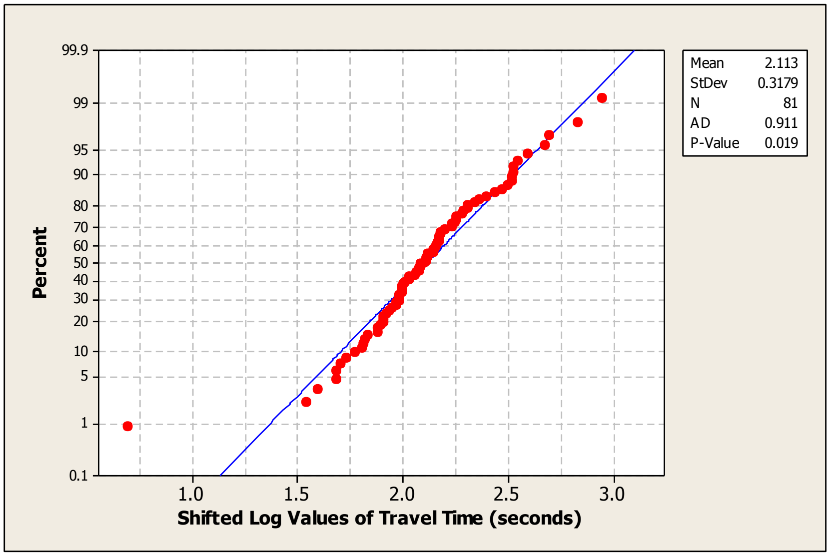

Figure D-6. Path Travel Time Distribution Log-Normality Test Results (NJ 24 **&** I-78)

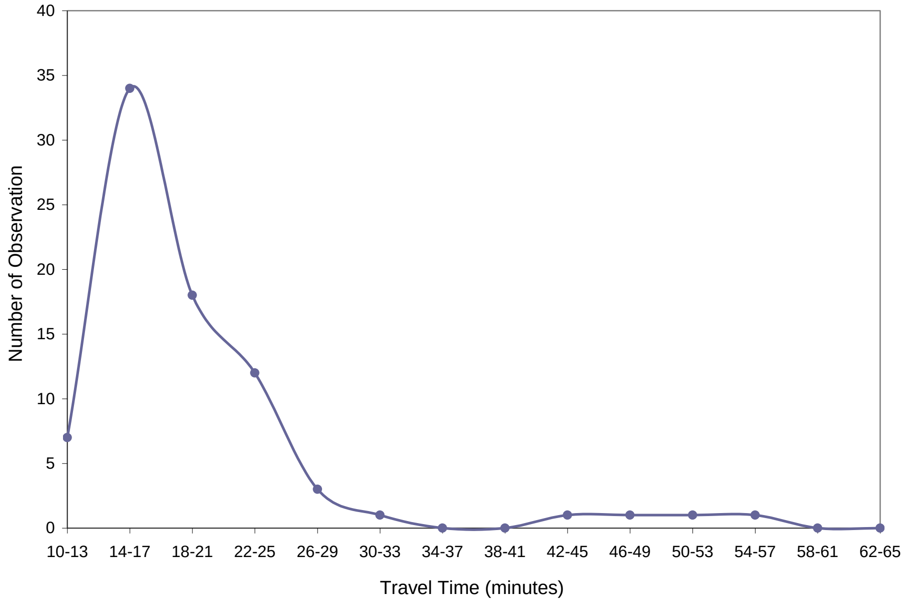

Figure D-7. Path Travel Time Distribution (US 46 & NJ 3)

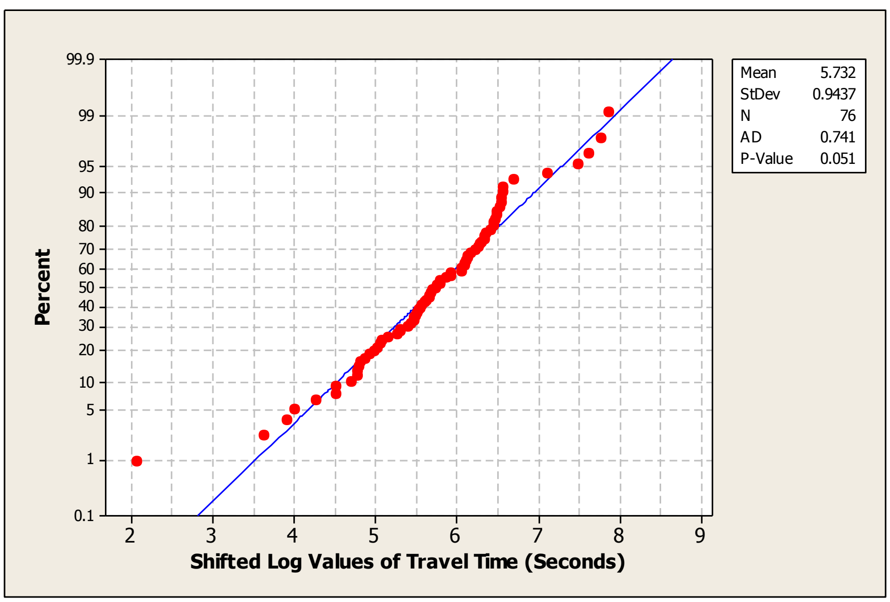

Figure D-8. Path Travel Time Distribution Log-Normality Test Results (US 46 & NJ 3)

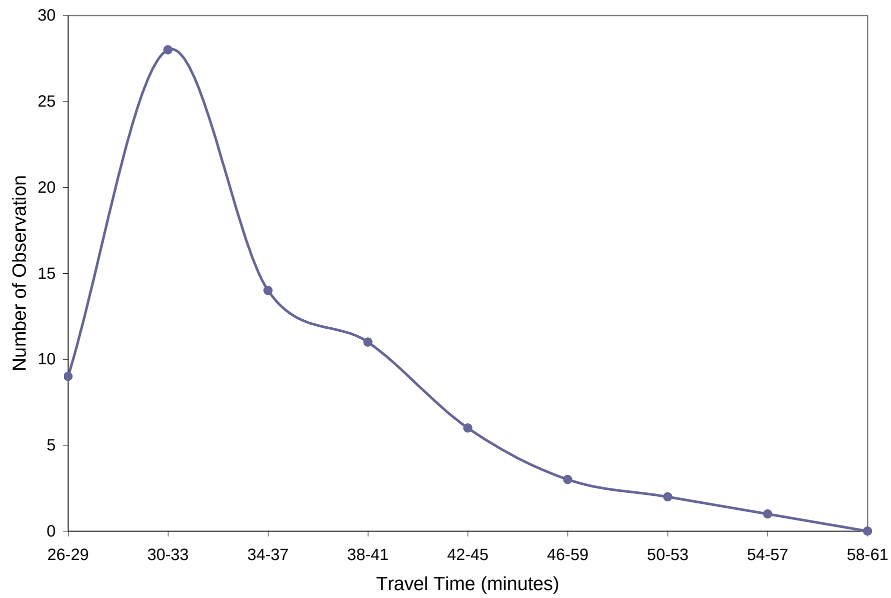

Figure D-9. Path Travel Time Distribution (US 22)

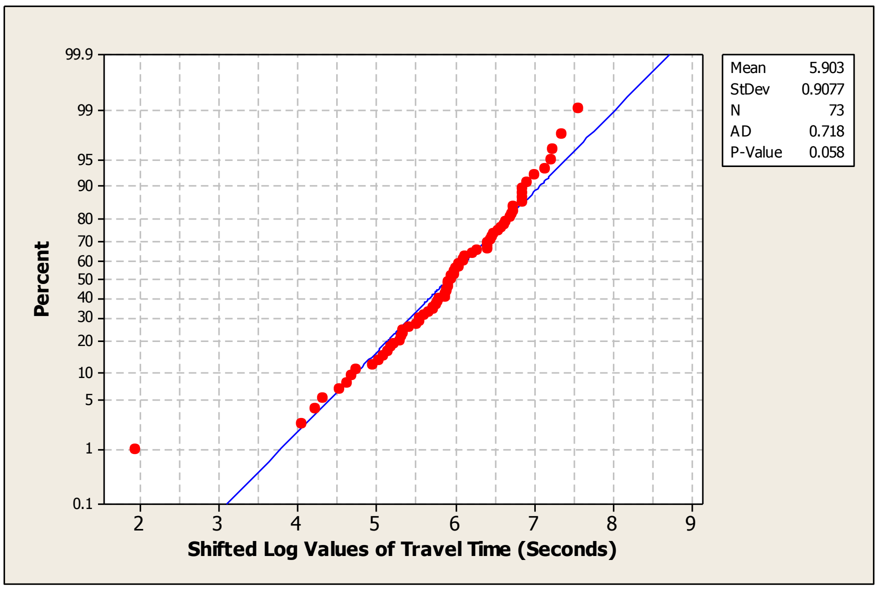

Figure D-10. Path Travel Time Distribution Log-Normality Test Results (US 22)

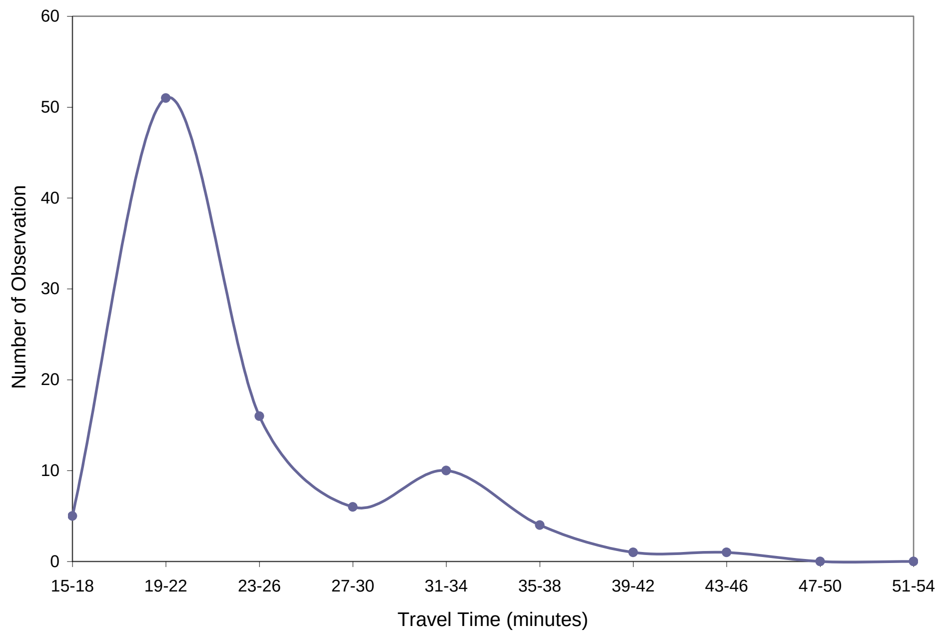

Figure D-11. Path Travel Time Distribution [I-287(A)]

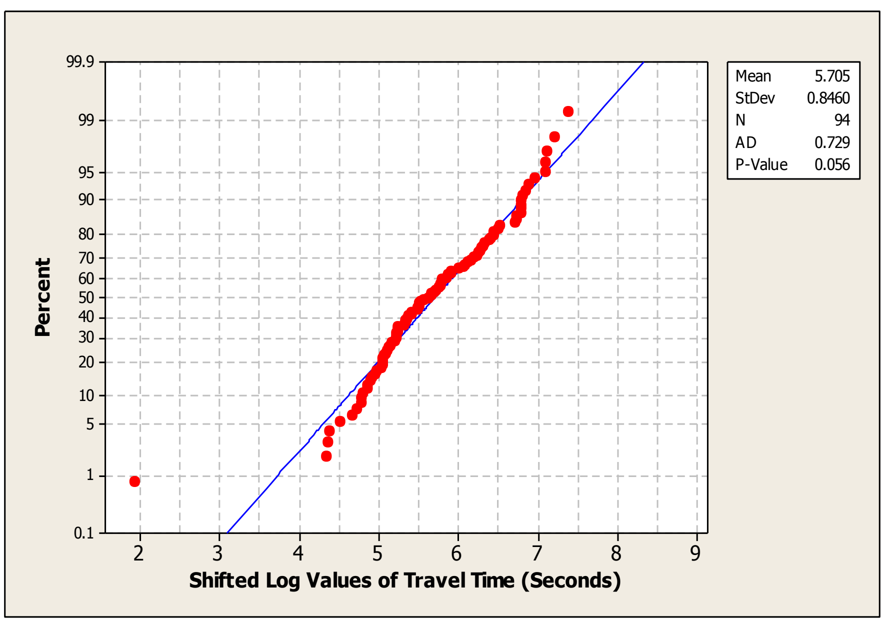

Figure D-12. Path Travel Time Distribution Log-Normality Test Results [I-287(A)]

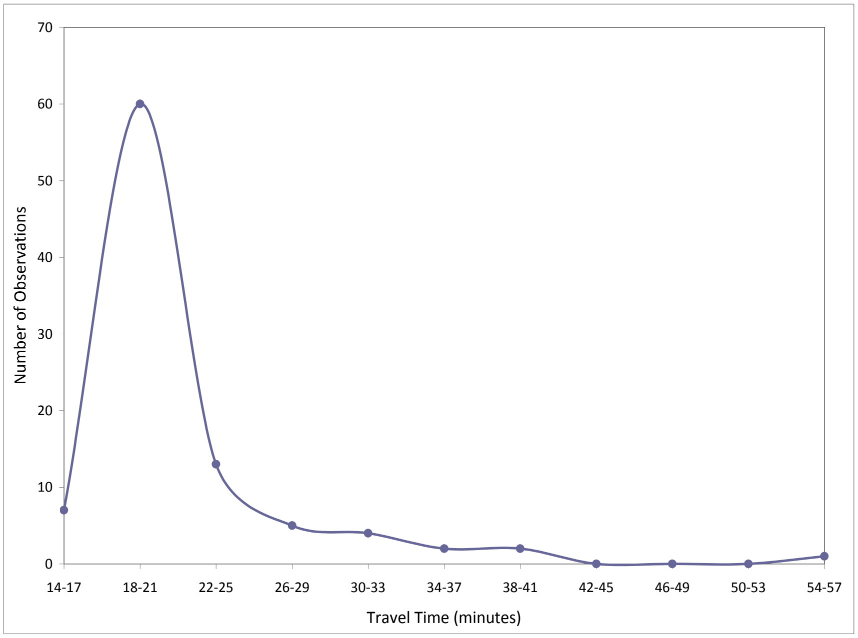

Figure D-13. Path Travel Time Distribution [I-287(B)]

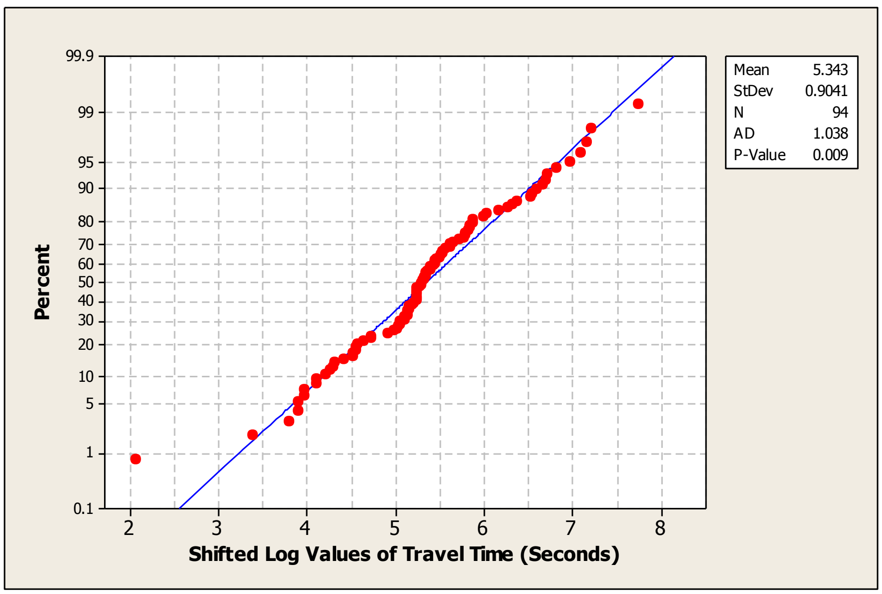

Figure D-14. Path Travel Time Distribution Log-Normality Test Results [I-287(B)]

APPENDIX E: MATLAB PROGRA.M. FOR PROCESSING CO-PILOT™ DATA

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%
for weekNo=1:5

    Id=1;
    outPut=[];
    direct=[PATH,' ',num2str(weekNo),'\']; % to-be-processed path nA.M.e
    listGps=dir([direct,'*.gps']);
    for m=1:length(listGps)

        rawData=gps2raw([direct,listGps(m).nA.M.e]);
        [sx sy]=size(rawData);
        rawDataId=zeros(sx,sy+1);
        rawDataId(:,1)=Id;
        rawDataId(:,2:5)=rawData(:,1:4);
        Id=Id+1;
        outPut=[outPut;rawDataId];

    end

    filename=[filenA.M.eXls,num2str(weekNo),'.xls'];

    xlswrite(filename,outPut,1);

end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
```

```
% This code reorganizes original data by individual trips; Does not recall any
other progrA.M.

clear;
latitude=110.94;longitude=85.2; % For calculating distance only, in KM
criterion1=0.125; % For starting point candidate selection
criterion2=0.75; % For end point candidate selection
FAR=5;

filename='rt22wk'; % Can be changed accordingly
nodeindex=xlsread('node22.xls');% Input ROUTE node info: Longi, Lati
% figure;plot(nodeindex(:,1),nodeindex(:,2),'r');grid on; % Show the NODES

[sxn,syn]=size(nodeindex); % How many points need to be calculated?

if syn>=3
    nodeindex(:,3:syn)=[];
end

for m=1:length(dir([filename,'*.xls'])) % How many weeks do you have?
```

```
% for m=5:5

data_bulk_in=xlsread([filename,num2str(m),'.xls']);[sx,sy]=size(data_bulk_in);
 % input original data

    % Data format: ID, Date, Time, Longi, Lati

%       figure;plot(data_bulk_in(:,4),data_bulk_in(:,5));grid on; % plot the
original data
%       hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the NODES


data_bulk_in(:,3)=floor(data_bulk_in(:,3)/10000)*60*60+floor((data_bulk_in(:,3
)-floor(data_bulk_in(:,3)/10000)*10000)/100)*60+data_bulk_in(:,3)-
floor(data_bulk_in(:,3)/100)*100; % transform time to seconds

    pnum=1; % Contorl possible and effective trips

    while sx>0

        ID=data_bulk_in(1,1); % The Specific ID; Ascending ID
        DATE=data_bulk_in(1,2); % The Specific DATE; Ascending Date


data_seg=data_bulk_in(1:sum((data_bulk_in(:,1)==ID).*(data_bulk_in(:,2)==DATE)
),:); % Segmented data

data_bulk_in(1:sum((data_bulk_in(:,1)==ID).*(data_bulk_in(:,2)==DATE)),:)=[];
% Remaining data
        [sx,sy]=size(data_bulk_in); % Remaining data
        [sxs,sys]=size(data_seg); % Segmented data size

        while sxs>2

            for i=1:sxs
                loc_ori(i,1:2)=nodeindex(1,1:2);
            end

            dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);

            dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % calculate the
distances btw the starting point and each point in the segmented data

            [dis,num]=sort(dis_2,1); % Look for a few candidates each of which
has the shortest distance to the starting point

            dis_2(:,2)=(data_seg(1:sxs-1,3)+data_seg(2:sxs,3))/2; % Time

            dis(1:sxs-1,2)=dis_2(num(1:sxs-1),2);
            dis(1:sxs-1,3)=num(1:sxs-1);
            dis(sum(sum(dis(:,1)<criterion1))+1:sxs-1,:)=[];
```

```
            [dis_n,num2]=sort(dis(:,3)); % Look for a few candidates each of
which have the shortest distance to the starting point

            % Make sure this is the correct direction!
            for t=length(dis_n):-1:1

                dis_A=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t),4))^2+latitude^2*(nodeindex(2,2)-data_seg(dis_n(t),5))^2);
                dis_B=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+1,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+1,5))^2);
                dis_C=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+2,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+2,5))^2);
                dis_D=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+3,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+3,5))^2);

                if ~((dis_A>dis_B)&(dis_B>dis_C)&(dis_C>dis_D))
                    dis_n(t)=[];
                end
            end

            tmp=[];

            for t=1:length(dis_n)
                for i=dis_n(t):sxs
                    if sqrt(longitude^2*(nodeindex(sxn,1)-
data_seg(i,4))^2+latitude^2*(nodeindex(sxn,2)-data_seg(i,5))^2)<criterion2
                        for j=dis_n(t)+FAR:i
                            if sqrt(longitude^2*(nodeindex(1,1)-
data_seg(j,4))^2+latitude^2*(nodeindex(1,2)-data_seg(j,5))^2)<criterion1
                                for tt=dis_n(t):j
                                    if sqrt(longitude^2*(nodeindex(1,1)-
data_seg(tt,4))^2+latitude^2*(nodeindex(1,2)-data_seg(tt,5))^2)>criterion1
                                        tmp=[tmp,t];
                                    end
                                end
                            end
                        end
                        break;
                    end
                end
            end

            dis_n(tmp)=[];clear tmp;

            % Make sure this is the correct direction!

            length_dis_n=length(dis_n);

            if length(dis_n)>0
                if dis_n(1)>1
                    num_tmp=dis_n(1)-1; % This point is a candidate!
                else
```

```
                    num_tmp=dis_n(1);
                end

            end

%               figure;plot(data_seg(:,4),data_seg(:,5));grid on; % Show each
effective trip
%               hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the
NODES
            clear loc_ori dis_all dis_2 num dis dis_n num2;

            if length_dis_n>0
                for i=1:sxs
                    loc_ori(i,1:2)=nodeindex(sxn,1:2); % End point
                end

                dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);

                dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % Calculate the
distances btw the end point and each point in the segmented data

                if (sum(sum(dis_2(:,1)<criterion2))>0)&(length_dis_n~=0)
                    data_seg(1:num_tmp,:)=[];clear num_tmp; % truncate the
segmented data
                end

                clear loc_ori dis_all dis_2; % Temporary variables
            end

            [sxs,sys]=size(data_seg);

            for i=1:sxs
                loc_ori(i,1:2)=nodeindex(1,1:2);
            end
            dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);
            dis_1(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % distance to the
starting point

            clear loc_ori dis_all; % Temporary variables

            for i=1:sxs
                loc_ori(i,1:2)=nodeindex(sxn,1:2);
            end
            dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);
            dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % distance to the end
point

            clear loc_ori dis_all; % Temporary variables
```

```
            if
(sum(sum(dis_1(:,1)<criterion1))>0)&(sum(sum(dis_2(:,1)<criterion2))>0) % both
starting point and end point have close points in raw data

                [dis,num]=sort(dis_2,1); % Look for the point closest to the
end point

                dis_2(:,2)=(data_seg(1:sxs-1,3)+data_seg(2:sxs,3))/2;
                dis(1:sxs-1,2)=dis_2(num(1:sxs-1),2);
                dis(1:sxs-1,3)=num(1:sxs-1);
                dis(sum(sum(dis(:,1)<criterion2))+1:sxs-1,:)=[];

                tmp=min(dis(:,3));

                for ttt=tmp:sxs
                    if dis_2(ttt)>dis_2(ttt+1)
                        tmp=ttt;
                    end
                    if dis_2(ttt)<dis_2(ttt+1)
                        break;
                    end
                end

                tmp=tmp+1;

                data_in=data_seg(1:tmp,:);
                data_seg(1:tmp,:)=[];
                clear tmp;% truncate the input data

%                  figure;plot(data_in(:,4),data_in(:,5));grid on; % Show each
effective trip
%                  hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the
NODES

                string2=['save ',filenA.M.e,num2str(m),'_',num2str(pnum),'
data_in -v6;'];
                eval(string2);clear data_in;

                clear loc_ori dis_1 dis_2 num dis dis_n num2;
                pnum=pnum+1;

                [sxs,sys]=size(data_seg);

            else

                clear dis_1 dis_2 num dis dis_n num2;

                sxs=0;

            end

        end %while sxs>2
```

```
    end           %while sx>0

end
```

```
% This code reorganizes original data by individual trips; Does not recall any
other progrA.M.

clear;
latitude=110.94;longitude=85.2; % For calculating distance only, in KM
criterion1=0.125; % For starting point candidate selection
criterion2=0.75; % For end point candidate selection
FAR=5;

filename='rt22wk'; % Can be changed accordingly
nodeindex=xlsread('node22.xls');% Input ROUTE node info: Longi, Lati
% figure;plot(nodeindex(:,1),nodeindex(:,2),'r');grid on; % Show the NODES

[sxn,syn]=size(nodeindex); % How many points need to be calculated?

if syn>=3
    nodeindex(:,3:syn)=[];
end

for m=1:length(dir([filename,'*.xls'])) % How many weeks do you have?
% for m=5:5


data_bulk_in=xlsread([filenA.M.e,num2str(m),'.xls']);[sx,sy]=size(data_bulk_in
); % input original data

    % Data format: ID, Date, Time, Longi, Lati

%       figure;plot(data_bulk_in(:,4),data_bulk_in(:,5));grid on; % plot the
original data
%       hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the NODES


data_bulk_in(:,3)=floor(data_bulk_in(:,3)/10000)*60*60+floor((data_bulk_in(:,3
)-floor(data_bulk_in(:,3)/10000)*10000)/100)*60+data_bulk_in(:,3)-
floor(data_bulk_in(:,3)/100)*100; % transform time to seconds

    pnum=1; % Contorl possible and effective trips

    while sx>0

        ID=data_bulk_in(1,1); % The Specific ID; Ascending ID
        DATE=data_bulk_in(1,2); % The Specific DATE; Ascending Date


data_seg=data_bulk_in(1:sum((data_bulk_in(:,1)==ID).*(data_bulk_in(:,2)==DATE)
),:); % Segmented data
```

```
data_bulk_in(1:sum((data_bulk_in(:,1)==ID).*(data_bulk_in(:,2)==DATE)),:)=[];
% Remaining data
        [sx,sy]=size(data_bulk_in); % Remaining data
        [sxs,sys]=size(data_seg); % Segmented data size

        while sxs>2

            for i=1:sxs
                loc_ori(i,1:2)=nodeindex(1,1:2);
            end

            dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);

            dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % calculate the
distances btw the starting point and each point in the segmented data

            [dis,num]=sort(dis_2,1); % Look for a few candidates each of which
has the shortest distance to the starting point

            dis_2(:,2)=(data_seg(1:sxs-1,3)+data_seg(2:sxs,3))/2; % Time

            dis(1:sxs-1,2)=dis_2(num(1:sxs-1),2);
            dis(1:sxs-1,3)=num(1:sxs-1);
            dis(sum(sum(dis(:,1)<criterion1))+1:sxs-1,:)=[];
            [dis_n,num2]=sort(dis(:,3)); % Look for a few candidates each of
which have the shortest distance to the starting point

            % Make sure this is the correct direction!
            for t=length(dis_n):-1:1

                dis_A=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t),4))^2+latitude^2*(nodeindex(2,2)-data_seg(dis_n(t),5))^2);
                dis_B=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+1,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+1,5))^2);
                dis_C=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+2,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+2,5))^2);
                dis_D=sqrt(longitude^2*(nodeindex(2,1)-
data_seg(dis_n(t)+3,4))^2+latitude^2*(nodeindex(2,2)-
data_seg(dis_n(t)+3,5))^2);

                if ~((dis_A>dis_B)&(dis_B>dis_C)&(dis_C>dis_D))
                    dis_n(t)=[];
                end
            end

            tmp=[];

            for t=1:length(dis_n)
                for i=dis_n(t):sxs
```

```
                    if sqrt(longitude^2*(nodeindex(sxn,1)-
data_seg(i,4))^2+latitude^2*(nodeindex(sxn,2)-data_seg(i,5))^2)<criterion2
                        for j=dis_n(t)+FAR:i
                            if sqrt(longitude^2*(nodeindex(1,1)-
data_seg(j,4))^2+latitude^2*(nodeindex(1,2)-data_seg(j,5))^2)<criterion1
                                for tt=dis_n(t):j
                                    if sqrt(longitude^2*(nodeindex(1,1)-
data_seg(tt,4))^2+latitude^2*(nodeindex(1,2)-data_seg(tt,5))^2)>criterion1
                                        tmp=[tmp,t];
                                    end
                                end
                            end
                        end
                        break;
                    end
                end
            end

            dis_n(tmp)=[];clear tmp;

            % Make sure this is the correct direction!

            length_dis_n=length(dis_n);

            if length(dis_n)>0
                if dis_n(1)>1
                    num_tmp=dis_n(1)-1; % This point is a candidate!
                else
                    num_tmp=dis_n(1);
                end

            end

%              figure;plot(data_seg(:,4),data_seg(:,5));grid on; % Show each
effective trip
%              hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the
NODES
            clear loc_ori dis_all dis_2 num dis dis_n num2;

            if length_dis_n>0
                for i=1:sxs
                    loc_ori(i,1:2)=nodeindex(sxn,1:2); % End point
                end

                dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);

                dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % Calculate the
distances btw the end point and each point in the segmented data

                if (sum(sum(dis_2(:,1)<criterion2))>0)&(length_dis_n~=0)
                    data_seg(1:num_tmp,:)=[];clear num_tmp; % truncate the
segmented data
                end
```

```
            clear loc_ori dis_all dis_2; % Temporary variables
        end

        [sxs,sys]=size(data_seg);

        for i=1:sxs
            loc_ori(i,1:2)=nodeindex(1,1:2);
        end
        dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);
        dis_1(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % distance to the
starting point

        clear loc_ori dis_all; % Temporary variables

        for i=1:sxs
            loc_ori(i,1:2)=nodeindex(sxn,1:2);
        end
        dis_all=(longitude*longitude*(loc_ori(:,1)-
data_seg(:,4)).*(loc_ori(:,1)-data_seg(:,4))+latitude*latitude*(loc_ori(:,2)-
data_seg(:,5)).*(loc_ori(:,2)-data_seg(:,5))).^(1/2);
        dis_2(:,1)=dis_all(1:sxs-1)+dis_all(2:sxs); % distance to the end
point

        clear loc_ori dis_all; % Temporary variables

        if
(sum(sum(dis_1(:,1)<criterion1))>0)&(sum(sum(dis_2(:,1)<criterion2))>0) % both
starting point and end point have close points in raw data

            [dis,num]=sort(dis_2,1); % Look for the point closest to the
end point

            dis_2(:,2)=(data_seg(1:sxs-1,3)+data_seg(2:sxs,3))/2;
            dis(1:sxs-1,2)=dis_2(num(1:sxs-1),2);
            dis(1:sxs-1,3)=num(1:sxs-1);
            dis(sum(sum(dis(:,1)<criterion2))+1:sxs-1,:)=[];

            tmp=min(dis(:,3));

            for ttt=tmp:sxs
                if dis_2(ttt)>dis_2(ttt+1)
                    tmp=ttt;
                end
                if dis_2(ttt)<dis_2(ttt+1)
                    break;
                end
            end

            tmp=tmp+1;

            data_in=data_seg(1:tmp,:);
```

```
                data_seg(1:tmp,:)=[];
                clear tmp;% truncate the input data

%                  figure;plot(data_in(:,4),data_in(:,5));grid on; % Show each
effective trip
%                  hold on;plot(nodeindex(:,1),nodeindex(:,2),'r'); % Show the
NODES

                string2=['save ',filenA.M.e,num2str(m),'_',num2str(pnum),'
data_in -v6;'];
                eval(string2);clear data_in;

                clear loc_ori dis_1 dis_2 num dis dis_n num2;
                pnum=pnum+1;

                [sxs,sys]=size(data_seg);

            else

                clear dis_1 dis_2 num dis dis_n num2;

                sxs=0;

            end

        end %while sxs>2

    end           %while sx>0

end
```

APPENDIX F: TRAVEL TIME DATA (ALK)

Table F-1 - Travel Time Data from ALK

New Jersey Area Co-Pilot™ Segment Travel Speed Summary Data (6A.M. ~ 9 A.M., Weekday)															
	Monument i				Monument j										
Route	Node ID	GPS Coordinate		Mile Post	Node ID	GPS Coordinate		Mile Post	No. of Data	Link Dist.	Avg. Speed	STD of Spd	Median Spd	Min Spd	Max Spd
#	#	(degree decimal)		(miles)	#	(degree decimal)		(miles)	#	(miles)	(mph)	(mph)	(mph)	(mph)	(mph)
US 1 (from I-295 to US-130)	001-1	40.287239	-74.691436	6.76	001-2	40.297745	-74.678777	8.10	1	1.39	51	0	51	51	51
	001- 2	40.297745	-74.678777	8.10	001-3	40.331414	-74.638087	11.27	9	2.973	51.6	5	49.6	46.5	62.1
	001- 3	40.331414	-74.638087	11.27	001-4	40.386518	-74.571109	16.47	2	5.184	53.9	2.9	56.8	51	56.8
	001- 4	40.386518	-74.571109	16.47	001-5	40.461786	-74.458659	24.64	19	8.026	45.6	7.9	46.3	31.9	59
US 1 (from I-130 to US-295)	001-5	40.464064	-74.450336	24.64	001-4	40.386518	-74.571109	16.47	39	8.026	46.5	9	47.3	27.6	60.8
	001-4	40.386518	-74.571109	16.47	001-3	40.331414	-74.638087	11.27	6	5.191	52.2	5.6	56.4	42.7	58.1
	001-3	40.331414	-74.638087	11.27	001-2	40.297745	-74.678777	8.10	10	3.131	58.1	5.1	60.4	47.1	64.3
	001-2	40.297745	-74.678777	8.10	001-1	40.286801	-74.692142	6.76	2	1.306	57.8	0.5	58.4	57.3	58.4
US 1 (from NJ-18 to US-22)	001-6	40.485635	-74.416201	27.30	001-7	40.499829	-74.406966	28.54	8	1.05	53.2	13.9	64.5	29.8	69.5
	001-7	40.499829	-74.406966	28.54	001-8	40.528326	-74.354389	31.96	3	4.238	25.8	4.8	28.7	19	29.8
	001-8	40.528326	-74.354389	31.96	001-9	40.552445	-74.317674	34.52	3	2.508	32.8	11.3	38.8	17	42.7
	001-9	40.552445	-74.317674	34.52	001-10	40.564900	-74.297726	35.89	2	1.361	31.3	1.1	32.4	30.2	32.4
	001-10	40.564900	-74.297726	35.89	001-11	40.571407	-74.292986	36.41	2	0.269	41.4	1.2	42.7	40.2	42.7
	001-11	40.571407	-74.292986	36.41	001-12	40.650516	-74.221227	43.11	1	6.826	32.8	0	32.8	32.8	32.8
	001-12	40.650516	-74.221227	43.11	001-13	40.704232	-74.183572	47.50	1	4.506	16.7	0	16.7	16.7	16.7
US 1 (from US-22	001-13	40.704232	-74.183572	47.50	001-12	40.650516	-74.221227	43.11	5	4.359	33.1	3.9	32.2	28.1	38.9
	001-12	40.650516	-74.221227	43.11	001-11	40.571407	-74.292986	36.41	3	6.828	35.6	4	37.7	30	39.2
	001-11	40.571407	-74.292986	36.41	001-10	40.564900	-74.297726	35.89	9	0.268	45.9	6.2	46.3	35.5	53.8

to NJ-18)	001-10	40.564900	-74.297726	35.89	001-9	40.552445	-74.317674	34.52	7	1.353	32.3	8.2	29.1	23.7	46.3
	001-9	40.552445	-74.317674	34.52	001-8	40.528326	-74.354389	31.96	2	2.508	33.3	2.6	35.9	30.7	35.9
	001-8	40.528326	-74.354389	31.96	001-7	40.499829	-74.406966	28.54	3	3.678	35.1	7.1	35.1	26.4	43.9
	001-7	40.499829	-74.406966	28.54	001-6	40.485635	-74.416201	27.30	10	1.05	56.8	7.2	54.9	47.5	73.1
US 9	009-1	39.993448	-74.211416	94.50	009-2	40.046801	-74.221896	98.75	1	3.675	45.5	0	45.5	45.5	45.5
	009-2	40.046801	-74.221896	98.75	009-3	40.090067	-74.216342	101.71	1	3.13	34.7	0	34.7	34.7	34.7
	009-3	40.090067	-74.216342	101.71	009-4	40.106220	-74.219440	102.86	1	1.126	28.1	0	28.1	28.1	28.1
	009-4	40.106220	-74.219440	102.86	009-5	40.165099	-74.235756	107.05	1	4.209	47.3	0	47.3	47.3	47.3
	009-5	40.165099	-74.235756	107.05	009-6	40.241697	-74.278293	112.91	2	5.831	44.7	2.9	47.6	41.8	47.6
	009-6	40.241697	-74.278293	112.91	009-7	40.251814	-74.286862	113.75	3	0.842	44.4	5	47.8	37.3	48.3
	009-7	40.251814	-74.286862	113.75	009-8	40.265689	-74.293812	114.80	4	1.043	45.8	10.3	52.5	28.2	53.7
NJ 18	018-1	40.373213	-74.311590	30.80	018-2	40.405863	-74.357231	34.11	5	3.305	51.5	4.6	51.1	46.7	59.8
	018-2	40.405863	-74.357231	34.11	018-3	40.439636	-74.393427	37.14	5	3.269	47	4.5	45.9	40.9	53.2
	018-3	40.439636	-74.393427	37.14	018-4	40.472696	-74.409248	39.58	6	2.438	39.2	7.8	38.9	30.1	54.4
	018-4	40.472696	-74.409248	39.58	018-5	40.483452	-74.418302	40.61	4	1.03	40.7	3.4	42.8	34.8	43.5
	018-5	40.483452	-74.418302	40.61	018-6	40.495310	-74.439490	42.29	9	1.536	35.1	7.2	35.4	24.4	47.3
NJ-42 & I-76	042-1	39.689332	-74.992979	0.00	042-2	39.729524	-75.032914	3.51	14	3.489	43.2	7.5	48.1	28.5	54.2
	042-2	39.729524	-75.032914	3.51	042-3	39.767348	-75.048611	6.35	13	2.504	35.3	2.1	34.9	31.4	38.7
	042-3	39.767348	-75.048611	6.35	042-4	39.830855	-75.088637	11.54	6	5.497	37.8	10.2	35.2	24.4	58.2
	042-4	39.830855	-75.088637	11.54	042-5	39.867846	-75.101385	14.20	7	2.655	42.1	15.1	39.9	21.4	63.5
	042-5	39.867846	-75.101385	14.20	076-1	39.873950	-75.102210	0.00	9	0.423	48.9	15.2	51.3	25	77.2
	076-1	39.873950	-75.102210	0.00	076-2	39.898603	-75.109348	2.20	11	1.755	54.7	7.3	55.8	44.7	72.9
I-70	070-1	39.887334	-74.742823	18.53	070-2	39.904692	-74.824659	13.91		4.542					
	070-2	39.904692	-74.824659	13.91	070-3	39.893833	-74.927352	8.33		5.546					
	070-3	39.893833	-74.927352	8.33	070-4	39.909097	-74.984579	5.07		3.248					
	070-4	39.909097	-74.984579	5.07	070-5	39.913799	-75.010359	3.66	1	1.407	22.9	0	22.9	22.9	22.9
	070-5	39.913799	-75.010359	3.66	070-6	39.919503	-75.034459	2.31	3	1.345	36	2.3	37.4	32.7	37.9

	070-6	39.919503	-75.034459	2.31	070-7	39.934111	-75.068514	0.00	4	2.064	42	4.8	42.8	37	49.6
NJ-73	073-1	39.895093	-74.928632	24.3	073-2	39.923440	-74.948760	26.47	1	2.235	55	0	55	55	55
	073-2	39.923440	-74.948760	26.47	073-3	39.934730	-74.965640	27.68		1.303					
	073-3	39.934730	-74.965640	27.68	073-4	39.943194	-74.978402	28.55	17	0.777	46.4	15.7	54.4	5.9	60.5
	073-4	39.943194	-74.978402	28.55	073-5	39.945681	-74.982202	28.82	22	0.265	51.3	11.9	54.4	26.5	69.1
	073-5	39.945681	-74.982202	28.82	073-6	39.956646	-74.987611	29.68	45	0.966	51.9	7.8	53.5	37.2	66.4
	073-6	39.956646	-74.987611	29.68	073-7	39.983633	-75.017615	32.18	29	2.385	52.9	7.1	54	30.4	60.9
	073-7	39.983633	-75.017615	32.18	073-8	39.995090	-75.030973	33.24	16	1.063	48.6	13.8	53.9	10.2	64.9
US 46 & NJ 3	046-1	40.894883	-74.240614	56.7	046-2	40.892670	-74.224136	57.58	32	0.878	52.5	7.6	52.6	31.3	65
	046-2	40.892670	-74.224136	57.58	003-1	40.871118	-74.189700	0.00	23	2.37	49.1	10	50.2	15.2	59.5
	003-1	40.871118	-74.189700	0.00	003-2	40.852595	-74.175650	1.53	24	1.527	54.8	4.8	54.8	46.2	65.5
	003-2	40.852595	-74.175650	1.53	003-3	40.823579	-74.125150	4.89	27	3.357	48.3	16	52.1	3.9	67.6
	003-3	40.823579	-74.125150	4.89	003-4	40.811121	-74.101762	6.39	26	1.499	50.7	12.7	47.1	24.9	74.4
	003-4	40.811121	-74.101762	6.39	003-5	40.802352	-74.072627	8.14	23	1.788	53.6	12.6	54.2	5.4	77.7
	003-5	40.802352	-74.072627	8.14	003-6	40.787892	-74.049948	9.72	29	1.578	51.6	11.8	55.1	17.5	78.4
NJ 208 & NJ 4	208-1	41.017236	-74.216496	9.3	208-2	41.007138	-74.192458	7.87	18	1.234	55.7	4.7	56.8	46.2	62.3
	208-2	41.007138	-74.192458	7.87	208-3	40.949944	-74.136937	2.88	17	4.631	53.7	7.8	55.5	27.4	63
	208-3	40.949944	-74.136937	2.88	004-1	40.926497	-74.093758	0.00	18	3.182	51.2	6.7	52.4	26.7	59.2
	004-1	40.926497	-74.093758	0.00	004-2	40.922679	-74.079881	2.9	11	0.583	52	4.4	52.5	41.4	56.4
	004-2	40.922679	-74.079881	2.9	004-3	40.920632	-74.071906	3.34	9	0.541	54.4	4.8	55.4	45.6	60.7
	004-3	40.920632	-74.071906	3.34	004-4	40.905750	-74.033210	5.67	16	2.61	53.5	4.7	53.3	44.3	66.1
	004-4	40.905750	-74.033210	5.67	004-5	40.878904	-73.981007	9.04	14	3.321	39	12.3	41.5	15.6	60.1
	004-5	40.878904	-73.981007	9.04	004-6	40.864962	-73.974483	10.22	7	0.868	26.4	21.3	17.6	4.2	53
NJ 17	017-1	41.000399	-74.100959	18.33	017-2	40.980345	-74.084549	16.56	24	1.716	53.8	3.2	54.4	45.6	58.9
	017-2	40.980345	-74.084549	16.56	017-3	40.939776	-74.071371	13.66	26	2.605	55.1	2.9	56	49.5	59
	017-3	40.939776	-74.071371	13.66	017-4	40.920650	-74.072440	12.33	22	1.521	53.7	5	54	38.9	60.4
	017-4	40.920650	-74.072440	12.33	017-5	40.886541	-74.068483	9.90	23	2.753	38.9	8.4	40.7	16.8	49.3

	017-5	40.886541	-74.068483	9.90	017-6	40.876260	-74.063980	9.13	20	0.748	46.1	4.5	47.2	35.6	52.8
	017-6	40.876260	-74.063980	9.13	017-7	40.867419	-74.064262	8.44	20	0.644	41.9	4.4	42.8	29.9	48.4
	017-7	40.867419	-74.064262	8.44	017-8	40.832712	-74.088817	5.76	21	2.793	40.1	5.1	40.6	22.7	50.6
	017-8	40.832712	-74.088817	5.76	017-9	40.814459	-74.102751	4.00	25	1.324	31.5	5.2	31.4	25	48.1
US 22	022-1	40.575047	-74.563264	36.82	022-2	40.579142	-74.526003	39.01	2	1.935	50.2	3.9	54.1	46.3	54.1
	022-2	40.579142	-74.526003	39.01	022-3	40.603525	-74.475739	42.16	1	3.107	42.2	0	42.2	42.2	42.2
	022-3	40.603525	-74.475739	42.16	022-4	40.626730	-74.438100	44.87	2	2.549	46.4	9.1	55.5	37.3	55.5
	022-4	40.626730	-74.438100	44.87	022-5	40.654455	-74.402768	47.41	2	2.702	44.3	15.4	59.7	28.9	59.7
	022-5	40.654455	-74.402768	47.41	022-6	40.684941	-74.328161	52.04	3	4.621	41.6	6.4	39.8	34.7	50.3
	022-6	40.684941	-74.328161	52.04	022-7	40.691901	-74.267916	55.26	4	3.208	52.7	11.1	48.2	43.3	71.8
	022-7	40.691901	-74.267916	55.26	022-8	40.708054	-74.187325	60.22	4	4.615	39.9	3	41.7	34.9	42.9
NJ 24 & I-78	024-1	40.804913	-74.444417	0.60	024-2	40.790116	-74.425178	2.09	22	1.481	57.5	10.5	58.7	20.9	77.7
	024-2	40.790116	-74.425178	2.09	024-3	40.738062	-74.367030	7.07	17	4.924	61.2	6.1	59.8	52.9	81.5
	024-3	40.738062	-74.367030	7.07	024-4	40.717989	-74.331779	9.45	8	2.339	59.6	6.2	62.4	49.6	69.9
	024-4	40.717989	-74.331779	9.45	024-5	40.711779	-74.321400	10.18	6	0.713	55.3	8.1	54.1	44.5	70.2
	024-5	40.711779	-74.321400	10.18	078-1	40.713997	-74.297783	50.58	6	1.267	57.3	4.5	60.4	51	62.3
	078-1	40.713997	-74.297783	50.58	078-2	40.705230	-74.245101	53.42	39	2.873	66.3	4.9	66.5	53.6	74.1
	078-2	40.705230	-74.245101	53.42	078-3	40.709275	-74.184728	57.20	41	3.576	58.4	5.6	57.6	47.7	70.1
I-80 & I-280	080-1	40.862855	-74.410017	43.62	080-2	40.858756	-74.369098	46.36	41	2.176	62.6	4.8	62.3	45	73.7
	080-2	40.858756	-74.369098	46.36	280-1	40.813142	-74.309389	4.95	4	5.449	57.1	3.8	60.2	51.9	61.5
	280-1	40.813142	-74.309389	4.95	280-2	40.797041	-74.251397	8.26	18	3.352	54.2	7.8	54.4	41.2	71.7
	280-2	40.797041	-74.251397	8.26	280-3	40.775191	-74.241485	9.91	19	1.679	55.6	9.7	55.2	41.5	78
	280-3	40.775191	-74.241485	9.91	280-4	40.759245	-74.208640	12.12	17	2.106	53.5	6.4	50.7	47	71.7
	280-4	40.759245	-74.208640	12.12	280-5	40.747995	-74.167612	14.42	11	2.33	43.7	13.9	46.4	11.6	61
	280-5	40.747995	-74.167612	14.42	280-6	40.750210	-74.128366	16.65	13	2.391	41.6	11.6	43.7	5.8	53.7
I-287 (from I-	287-1	40.528682	-74.337098	0.00	287-2	40.528320	-74.354263	0.93	28	0.908	57	7.7	57.4	39.2	70.3
	287-2	40.528320	-74.354263	0.93	287-3	40.539186	-74.516936	10.48	34	9.538	52.5	10.7	53.9	13	66.7

95 to I-78)	287-3	40.539186	-74.516936	10.48	287-4	40.574790	-74.567593	14.24	37	3.343	61.7	5	61.6	51.4	74.3
	287-4	40.574790	-74.567593	14.24	287-5	40.595095	-74.623300	17.66	33	3.627	60.6	4.9	60.4	51.8	72.4
	287-5	40.595095	-74.623300	17.66	287-6	40.642668	-74.645679	21.17	18	3.717	64.7	4.9	64.4	57.4	76.5
I-287 (from I-78 to I-80)	287-6	40.642668	-74.645679	21.17	287-7	40.688970	-74.577602	26.48	111	5.297	55.7	5	55.4	27.8	70
	287-7	40.688970	-74.577602	26.48	287-8	40.788571	-74.469169	35.89	99	9.4	58.9	7.5	60.3	27.1	73
	287-8	40.788571	-74.469169	35.89	287-9	40.795550	-74.468390	38.00	92	0.485	62.3	5.4	62.2	49.6	82.4
	287-9	40.795550	-74.468390	38.00	287-10	40.832549	-74.438251	39.55	42	3.172	59.1	4.4	60.2	51.5	70
	287-10	40.832549	-74.438251	39.55	287-11	40.860957	-74.418390	42.02	51	2.218	63.1	5.2	63.9	53.7	78.1
I-287 (from I-80 to I-78)	287-11	40.860957	-74.418390	42.02	287-10	40.832549	-74.438251	39.55	61	2.221	62.4	5.8	62.4	51.1	90.9
	287-10	40.832549	-74.438251	39.55	287-9	40.795550	-74.468390	38.00	43	3.172	57.9	4.3	58.3	50.6	67.3
	287-9	40.795550	-74.468390	38.00	287-8	40.788571	-74.469169	35.89	78	0.485	62.2	5.5	61.9	53	79.9
	287-8	40.788571	-74.469169	35.89	287-7	40.688970	-74.577602	26.48	85	9.4	60.1	6.3	60.2	20.4	74.3
	287-7	40.688970	-74.577602	26.48	287-6	40.642668	-74.645679	21.17	38	5.338	59.5	4.3	59.3	51.6	71.3
I-287 (from I-78 to I-95)	287-6	40.642668	-74.645679	21.17	287-5	40.595095	-74.623300	17.66	29	3.723	61.1	10.9	63.3	26.9	74.9
	287-5	40.595095	-74.623300	17.66	287-4	40.574790	-74.567593	14.24	47	3.598	60.1	4.5	59.7	50.4	71
	287-4	40.574790	-74.567593	14.24	287-3	40.539186	-74.516936	10.48	46	3.343	60.1	4.9	60.4	48.8	73.2
	287-3	40.539186	-74.516936	10.48	287-2	40.528320	-74.354263	0.93	23	9.538	55.2	4.2	54	48.7	69.4
	287-2	40.528320	-74.354263	0.93	287-1	40.528682	-74.337098	0.00	26	0.908	57.6	7.7	56.3	47.5	76.6
NJ 29	029-1	40.184419	-74.729352	0.00	029-2	40.192191	-74.751909	1.64	5	1.391	62.5	3	60.3	59.9	66.9
	029-2	40.192191	-74.751909	1.64	029-3	40.209727	-74.766013	3.37	5	1.59	38.2	9.1	43.1	20	43.2
NJ 27	027-1	40.491804	-74.454326	15.70	027-2	40.655648	-74.231038	32.90		17.157					
US 30	030-1	39.777219	-74.908899	18.40	030-2	39.947932	-75.118038	0.90		21.201					
NJ 33 & NJ 130	033-1	40.218017	-74.757410	0.00	033-2	40.216275	-74.620987	7.80		8.261					
	033-2	40.216275	-74.620987	7.80	130-1	40.215930	-74.620397	62.60	1	0.08	6.3	0	6.3	6.3	6.3
	130-1	40.215930	-74.620397	62.60	130-2	40.347807	-74.497694	74.30		11.899					
NJ 47	047-1	39.574994	-75.046601	53.00	047-2	39.782500	-75.102037	68.30		15.217					
NJ 41	041-1	39.783434	-75.101740	0.00	041-2	39.914040	-75.010244	10.80		11.161					

NJ 35	035-1	40.116329	-74.072953	16.00	035-2	40.353626	-74.075516	34.20		17.954					
NJ 88 (EB)	088-1	40.089944	-74.216277	0.00	088-2	40.080249	-74.048135	10.00		10.098					
NJ 88 (WB)	088-2	40.080249	-74.048135	10.00	088-1	40.089944	-74.216277	0.00		10.862					
NJ 168	168-1	39.767598	-75.049053	0.00	168-2	39.91738	-75.101655	10.70		11.784					
US 46 & NJ 10	046-3	40.890215	-74.666157	32.20	046-4	40.879358	-74.65114	33.30		2.962					
	046-4	40.879358	-74.65114	33.30	010-1	40.878593	-74.650823	0.00		2.531					
	010-1	40.878593	-74.650823	0.00	010-2	40.832421	-74.437984	13.00		31.525					