FHWA-NJ-2008-007

Stability and Accuracy of HCM Level of Service In Darkness and Adverse Weather

Final Report

September 2008

Submitted by

Steven I. Chien, PhD., Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology

Janice R. Daniel, PhD., Associate Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology

And

Athanassios K. Bladikas, PhD., Associate Professor
Department of Industrial and Management Systems Engineering
New Jersey Institute of Technology

NJDOT Research Project Manager
Vincent F. Nichnadowicz

In cooperation with

New Jersey
Department of Transportation
Division of Research and Technology
and
U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT
STANDARD TITLE PAGE

1. Report No. NJDOT-2008-007	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Stability and Accuracy of HCM Level of Service in Darkness and Adverse Weather		5. Report Date: September 2008
		6. Performing Organization Code
7. Author(s) Steven I. Chien, PhD., Janice R. Daniel, PhD., Athanassios K. Bladikas, PhD		8. Performing Organization Report No.
9. Performing Organization Name and Address New Jersey Department of Transportation PO 600 Trenton, NJ 08625		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address New Jersey Department of Transportation PO 600 Trenton, NJ 08625	Federal Highway Adminstration U.S. Department of Transportation Washington D.C.	13. Type of Report/Period Covered Final Report
15. Supplementary Notes		

16. Abstract

The Highway Capacity Manual (HCM) uses average travel speed to assign Levels Of Service (LOS) to urban streets and arterials. However, the HCM procedure for estimating travel speeds has weaknesses, particularly in the determination of the Free-Flow Speed (FFS), by failing to account for the impact of weather conditions (e.g., rain, snow, ice, etc,) and light conditions (e.g., sunglare, darkness, etc.).

In this research, traffic data, under adverse weather, were collected and the impact of weather conditions to speed and density on selected New Jersey highways were investigated. Equations were developed to adjust the capacity estimation formula and figures suggested by HCM (2000) that can be used to accurately estimate travel times for buses and general traffic considering darkness and adverse weather.

17. Key Words Capacity, Speed, Traffic Operations, Travel Time, Level of Service, Reliability, Adverse Weather		18. Distribution Statement	
19. Security Classified (this report) Unclassified	20. Security Classified. (this page) Unclassified	21. No of Pages 77	22. Price

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the New Jersey Department of Transportation (NJDOT). This project could not have been accomplished without the assistance of numerous individuals. The data needed for conducting this study was collected by a student team at the New Jersey Institute of Technology (NJIT) listed below:

- Jongho Byun, PhD student of Department of Transportation Engineering
- Kitae Kim, PhD student of Department of Civil and Environmental Engineering
- Feng-Ming Tsai, PhD student of Department of Transportation Engineering
- Jiruttichut Leoviriyakit, PhD student of Department of Transportation Engineering
- Sung B. An, MS student of Department of Electrical Engineering
- Zing Zhang, MS student of Department of Electrical Engineering
- Meng-Chun Huang, MBA student of Department of Management

The authors thank Jerome Lutin of NJ Transit and Vincent Nichnadowicz of NJDOT who offered valuable comments and suggestions on earlier drafts of this report resulting in an improved product.

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EXECUTIVE SUMMARY

The Highway Capacity Manual (HCM) uses average travel speed to determine the Level Of Service (LOS) to urban streets and arterials. However, the HCM procedure for estimating travel speeds has weaknesses, particularly in the determination of the Free Flow Speed (FFS) which failure to account for the impact of weather conditions (e.g., rain, snow, ice, etc,) and light conditions (e.g., sunglare, darkness, etc.).

The objectives of this study were:

(1) Understand the accuracy of the current Highway Capacity Manual Levels of Service for a variety of roadways and investigate their sensitivity to the variables that determine them;
(2) Determine how adverse weather and conditions of darkness and sunglare impact the capacity and LOS of state highways and the frequency of these occurrences;
(3) Determine capacity levels at which traffic flows become unstable and measure the relationship between capacity and travel time variation that impact bus on time performance; and,
(4) Analyze the impact of adverse weather on bus travel times

There were five study locations. Eighty-two hours of data were collected under normal and adverse weather and light conditions. Approximately twenty-nine hours of data were collected under normal conditions, with at least five hours of data at each location. Twenty-eight hours of data were collected under rain and twenty-four hours under snow. Data were also collected under darkness and sunglare conditions. A total of twenty-one hours of data were collected at the five study locations under darkness. About seven hours of data were collected under normal weather and darkness, five hours under rain and darkness and eight and a half hours under snow and darkness conditions. Sunglare was not observed at all study locations, and when present it did not last for the entire period during which data were collected.

Using the collected data, the research team developed a set of adverse weather impact parameters to predict roadway speed, density, capacity, and bus travel times. The derived speed-flow-capacity equations were used to estimate operating speed and level of service under adverse weather.

Summary of the results in Tables 7 and 8:

- The goal of the study was to gather two days of data at each location under each weather condition. Overall, there were small differences between the average speeds for the two days of data.

- Under rain conditions, the reduced speeds range from 0.82 mi/hr to 37 mi/hr. The rain impact was found to not only be a function of the rain intensity, but also a function of the presence of downstream congestion.

- Under snow conditions, the reduced speeds range from 5.8 mi/hr to 33.8 mi/hr. The research showed that the snow impact is attributed to the snow intensity as well as the snow accumulation and whether the roadway has been plowed.

- Under normal weather and darkness conditions, there is little difference between the speeds for the two days under which data were collected. In general the reduced speeds range from 0.71 mi/hr to 52 mi/hr.

- Under rain and darkness conditions, the reduced speeds generally range from 7.11 mi/hr to 7.14 mi/hr.

- Similarly under snow and darkness conditions, the increased speeds range from 0.19 to 4.9 mi/hr. At one location snow and darkness caused a significant speed reduction of 19.8 mi/hr.

- Under sunglare, the reduced speeds range from 6.6 mi/hr to 20. 6 mi/hr showing that the sunglare impact can be as significant as the rain and snow impact.

- The collected data indicated the impact of adverse weather on driving behavior.

In this study, NJ Transit's Automatic Passenger Counters (APC) data was used to analyze the differences in bus actual travel times under different weather conditions. After evaluating the bus travel time from the collected APC data, it was found that buses operating with late arrival times at the beginning Time Points (TPs) can catch up at later TPs under normal weather. However, the cumulative travel time could be hard to catch up under rain. A factor that influences the significance of the results is the relatively small sample size of APC data available, and especially the lack of data under rain and snow.

The potential applications of the study results will help in exploring the weather impact on speed, density, headway, and capacity on different type of roadways and transit travel times and schedule adherence. The immediate extensions of this research include but are not limited to (1) estimating delay and travel time to assist the public in making decisions on when to travel and by what route or mode under adverse weather; (2) incorporating the estimated delay and potential congested locations due to adverse weather and developing network-wide adaptive traffic control strategies; and, (3) assessing the operational performance and identifying bottlenecks of existing transportation infrastructure under adverse weather.

INTRODUCTION

The Highway Capacity Manual (HCM) uses average travel speed to assign Levels Of Service (LOS) to urban streets and arterials. Travel speed has been well recognized as a major performance indicator to calculate travel time.

In addition to presenting a methodology for estimating travel speed, HCM has recommended directly measuring the travel speed to determine the LOS. While attempts have been made in various studies to provide vehicle travel times, most of them have been theoretical in nature and not well suited for practical applications.

Currently in HCM, FFS is used to estimate the expected capacity of roadways. To operate reliably at a speed of 55 mi/hr on a multi-lane highway, for example, the maximum flow of passenger cars is set by the HCM at 2,250 passengers per hour per lane [(20)]. This equates to a very short interval of 1.6 seconds between cars. However, drivers are taught to increase their intervals when driving in adverse weather and conditions with poor visibility. Some of the most heavily congested roadways in New Jersey run east/west, and drivers can experience significant sunglare during morning and evening peak hours. Since much commuting occurs during hours of dawn/sunset/darkness and/or under adverse weather conditions, using the current formula and figures suggested by HCM (2000) to approximate LOS might overstate the actual capacity that can be reliably achieved on New Jersey roadways.

This study focused on collecting and processing traffic and transit data and developing a sound method for estimating speed, density and headway. The traffic data were collected basically on un-interrupted roadways (e.g., freeways and arterials) under various adverse weather (e.g., rain and snow) and lighting (e.g., sunglare and darkness) conditions. The studied roadways were jointly selected by the research panel of this project and the research team.

In response to growing traffic congestion and consequent passenger demands for more reliable service, the research team developed a set of adverse weather impact parameters to estimate roadway speed, density, capacity and bus travel times based on the data collected in this study. The derived speed-flow-capacity equations were used to estimate operating speed and LOS for the studied roadways under adverse weather.

The products of this research can help in designing highway improvements, such as changing roadway alignments, determining number of lanes, and scheduling maintenance activities, by avoiding already congested roadways during specific time periods. The results derived in this study will also help to provide better estimates of traffic measures (e.g., capacities, speed, and density), LOS's, and travel times for various types of roadways and modes of transportation under adverse weather. As an example, the results of the research can be used to assist in identifying congestion on roadways and providing accurate transit and roadway information, thereby making transit a more attractive alternative. The research results were used for comparing the information recommended by the HCM (2000).

The Advanced Public Transportation Systems program (APTS), one of the major components of Intelligent Transportation Systems (ITS), was initiated by the Federal Transit Administration (FTA) to encourage the applications of emerging technologies in computers, communication and navigation for promoting the efficiency, effectiveness and safety of public transportation systems. The APTS technologies, Global Positioning Systems (GPS), Automatic Vehicle Location Systems (AVLS) and Automatic Passenger Counter Systems (APCS), have been implemented in various public transit systems to obtain real-time information, including vehicle location, speed and occupancy. This information can enhance the capability of transit passenger information systems, assist proactive transit planning and management, and improve overall service quality.

Transit agencies face increasing demands and challenges to predict whether or not buses are running on schedule. Bus travel times are prone to a high degree of variability mainly due to traffic congestion, ridership distribution, and weather conditions. There is a need to investigate how weather conditions impact the variability of bus travel times. The analysis results can be used to prepare more accurate schedules and assist transit agencies in restoring service disturbances.

Automatic Passenger Counters (APC) have been installed in NJ Transit buses. The primary benefit of APCs is the increase in both quantity and quality of information collected. APCs can link the time and location of a door open/close event. This technology has provided a good platform to obtain reliable information for predicting bus travel times between pairs of stops as well as arrival times at stops.

The APC data collected from bus Route 62 of NJ Transit was used to compare the actual bus travel time and the scheduled travel time under different weather conditions (e.g., normal, rain, and snow). The travel times between consecutive Time Points (TPs) were calculated considering the time period (e.g., peak, off-peak, whole day) and weather conditions. This report considers the impact that weather has on actual travel time and arrival time during various time periods.

RESEARCH OBJECTIVES

This research used field data (e.g., speed, volume, occupancy, headway, and travel time) collected from selected New Jersey roadways to generate speed-flow-density relationship under adverse weather, which was compared to the figures and formula suggested by HCM (2000). In addition, the Automatic Passenger Counter (APC) data provided by NJ Transit were used to evaluate the impact of adverse weather to the variability of travel times, while the weather information of the National Climatic Data Center (NCDC) were employed for mapping the weather based on the date and time of APC data. Specifically, the objectives of this study were to:

(1) Understand the accuracy of the derived current Highway Capacity Manual Levels of Service for a variety of roadways and investigate their sensitivity to the variables that determine them;

(2) Determine how adverse weather and conditions of darkness and sunglare impact the capacity and LOS of state highways and the frequency of these occurrences;

(3) Determine capacity levels at which traffic flows become unstable and measure the relationship between capacity and travel time variation that impact bus on time performance; and

(4) Analyze the impact of adverse weather on bus travel times.

RESEARCH APPROACH

An overview of the research approach for developing the working incident data base and estimating the rates of accidents and incidents is discussed in this section. Figure 1 shows the research methodology employed for conducting this project. This study started with a comprehensive literature review. With the assistance of the research panel, available studied routes and data sources were identified. A data collection plan was then developed, and related traffic and transit data were collected before a comprehensive training was given to the data collection team. The collected data were processed and results were generated. In addition to the traffic measures (e.g., speed, density, and capacity), the travelers behavior under adverse weather was investigated.

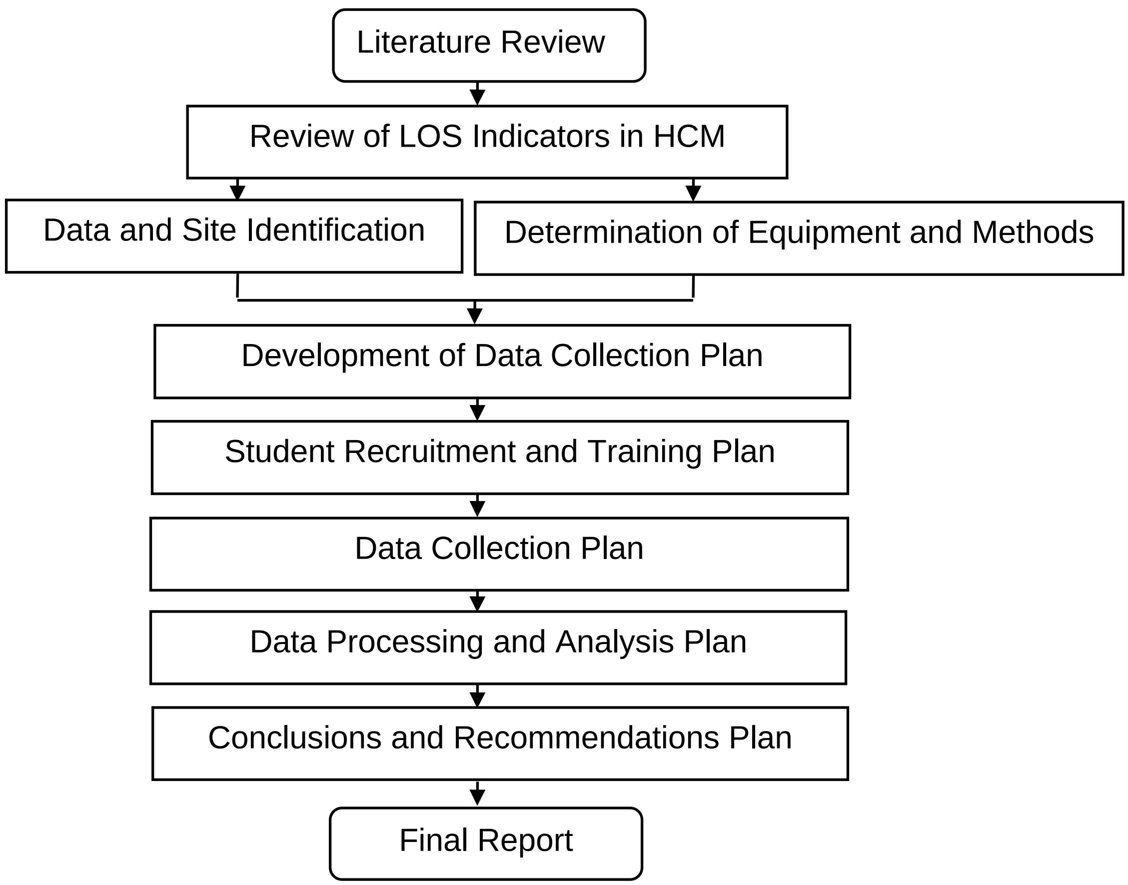


Figure 1. Configuration of Research Approach

LITERATURE REVIEW

The purpose of the literature review was to identify and review the data collection technologies employed in previous transportation studies. To conduct this project, extensive amount of traffic data under adverse weather were needed. The research team investigated automated data collection technologies, studied the application of these technologies, and evaluated their applicability to the needs of this project.

The review found that manual traffic data collection was commonly used in previous studies. However, manual data collection was labor-intensive, expensive, and might be inaccurate, and thus not considered. Therefore, automatic data collection technology with the application of state-of-the-art intrusive or non-intrusive sensors, mounting systems, portable power sources, and flexible data transmission systems was considered as another alternative. Thus, intrusive and non-intrusive technologies were reviewed, and the comparison of capabilities and characteristics of potential data collection technologies was discussed.

Data Collection Technology

Various detection equipments are used in collecting and providing real time traffic information for transportation planning decisions. They can be classified into two major traffic data collection technologies:

- Intrusive,
- Non-intrusive.

Intrusive technologies represent the most common devices used today, including inductive loops, electric sensors, and road tubes. Non-intrusive devices include passive acoustic sensors and video image detection devices (Underwood 1990) [42]. While intrusive and non-intrusive technologies are roadway-based technologies, floating cars with GPS systems are probe-based technologies that can be used to obtain traffic information.

Roadway-based detectors are embedded in the pavement, installed on the roadside or mounted on a gantry over the road. They actively or passively scan or detect traffic at their location and provide fixed-point or short-section traffic information extracted from vehicles passing the detection zone.

A probe-based system collects 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.

Two types of intrusive technologies (e.g., road tubes and inductive loop detectors) were investigated. The road tubes and inductive loop detectors (ILDs) can be used for large-scale traffic surveillance, but they are very difficult to install. A period of lane closure, which will cause traffic disruption, is needed because the devices must be either embedded in the pavement (ILDs) or secured on the surface of the roadway (road tubes).

Six non-intrusive data collection devices, shown in Table 1, are less disruptive of normal traffic operations and can be deployed more safely than intrusive detectors. In most cases, non-intrusive devices do not need to be installed in or on the pavement but can be mounted overhead (FHWA 1997) [12].

Table 1. Traffic Sensor Technologies

Equipment Type	Technology
Intrusive	Road Tube
	Inductive Loop
Non-intrusive	Infrared
	Magnetic
	Microwave
	Passive Acoustic
	Ultrasonic
	Video

Data collection detectors/sensors traditionally measure spot related traffic data, such as volume, occupancy, spot mean speed, vehicle presence, vehicle classification, etc. The advantages and disadvantages of sensor technologies are summarized in Table 2 [24] with respect to installation, parameter measure, and performance under adverse weather conditions.

Table 2. Advantages and Disadvantages of Sensor Technologies (Klein, 2001)

Technologies	Advantages	Disadvantages
Inductive Loop Detector	• Flexible design to satisfy large variety of applications. • Large experience base. • Provides basic traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap). • Insensitive to inclement weather such as rain, fog, and snow. • Common standard for obtaining accurate occupancy measurements. • High frequency excitation models provide classification data.	• Installation requires pavement cut. • Decreases pavement life. • Installation and maintenance require lane closure. • Wire loops subject to stresses of traffic and temperature. • Multiple detectors usually required to monitor a location. • Detection accuracy may decrease when design.
Road Tube	• Quick installation for permanent and temporary recording of data. • Low cost. • Simple to maintain.	• Inaccurate axle counting. • Temperature sensitivity of the air switch. • Cut tubes from vandalism.
Infrared	• Transmits multiple beams for accurate measurement of vehicle position, speed, and classification. • Multiple lane operation available. • Multi-zone passive sensors measure speed.	• Operation may be affected by fog when visibility is less than 20 ft (6 m) or blowing snow is present. • Installation and maintenance, including periodic lens cleaning, require lane closure. • Some models not recommended for presence detection.
Magnetic	• Can be used where loops are not feasible (e.g., bridge decks). • Some models are installed under roadway without need for pavement cuts. • Insensitive to inclement weather such as snow, rain, and fog. • Less susceptible than loops to stresses of traffic.	• Installation requires pavement cut or tunneling under roadway. • Cannot detect stopped vehicles unless special sensor layouts and signal processing software are used.
Microwave Radar	• Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications. • Direct measurement of speed. • Multiple lane operation available.	• CW Doppler sensors cannot detect stopped vehicles.

Table 2. Advantages and Disadvantages of Sensor Technologies (Klein, 2001)

Technologies	Advantages	Disadvantages
Passive Acoustic	• Passive detection. • Insensitive to precipitation. • Multiple lane operation available in some models.	• Cold temperatures may affect vehicle count accuracy. • Specific models are not recommended with slow moving vehicles in stop and-go traffic.
Ultrasonic	• Multiple lane operation available. • Capable of over-height vehicle detection. • Large Japanese experience base.	• Environmental conditions such as temperature change and extreme air turbulence can affect performance. • Temperature compensation is built into some models. • Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds.
Video Image Processor	• Monitors multiple lanes and multiple detection zones/lane. • Easy to add and modify detection zones. • Rich array of data available. • Provides wide-area detection when information gathered at one camera location can be linked to another.	• Installation and maintenance, including periodic lens cleaning, require lane closure when camera is mounted over roadway. • Performance affected by inclement weather such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-tonight transition; vehicle/road contrast; and water, salt grime, icicles, and cobwebs on camera lens. • Requires 50- to 70-ft (15- to 21-m) camera mounting height (in a side mounting configuration) for optimum presence detection and speed measurement.

Speed-Flow Relationships

Many studies have been conducted in evaluating the relationship of speed, flow and density on various types of roadways. Greenshields's research performed in 1935 was one of the most influential works on the topic of traffic stream models [16]. Greenshields estimated a linear relationship between speed and density as:

$$S = S_f \left(1 - \frac{D}{D_j}\right) \tag{1}$$

where:
- S_f = free-flow speed (mi/hr)
- D_j = jam density and (veh per lane-mile)
- S = speed at the given density (mi/hr)
- D = density (veh per lane-mile)

Therefore the parabolic relationships between flow and density and between flow and speed were derived as:

$$F = S_f \left(D - \frac{D^2}{D_j}\right) \quad OR \quad F = D_j \left(S - \frac{S^2}{S_f}\right) \tag{2}$$

Further research was extended to the relationship between speed and density and focused on the development of speed-flow models, yet adverse weather was generally not considered. Ibrahim and Hall (1994) discussed the effects of adverse weather conditions by studying the flow-occupancy and speed-flow relationships [21]. The data used in the analysis were obtained from the Queen Elizabeth Way, Mississauga freeway traffic management system, Canada. Regression analyses were performed to select proper models representing the flow-occupancy and speed-flow relationship for free-flowing traffic operations. A multivariate regression analysis was employed, which identified significant differences in traffic operations among various weather conditions. A goodness of fit test was conducted for a piecewise linear speed-flow model. It was found that rain reduced the slope of the flow-occupancy function and reduced the maximum observed flow rates, while causing a downward shift in the speed-flow function. It was also found that the free-flow speed reduced by 1.2 mi/hr (2 km/hr) for light rain, 1.9 mi/hr (3 km/hr) for light snow, 3.1 to 6.2 mi/hr (5 to 10 km/hr) for heavy rain, and 23.6 to 31.0 mi/hr (38 to 50 km/hr) for heavy snow.

Brilon and Poszlet (1996) compared speed-flow relationships based on the data collected from German autobahns to North American freeways. It was found under rain conditions, vehicle speeds in Germany were reduced by 3.1 mi/hr (5 km/hr) at night, and by 5.9 mi/hr (9.5 km/hr) at 4- lane (2-lane, 2-way) locations [7].

In a rural section of I-84 in the U.S., Kyte et al. (2000) gathered data in fog, blowing snow, high winds and other weather conditions by using existing traffic and environmental sensors [26]. The environmental variables included precipitation intensity, wind speed, visibility, and road surface condition (dry, wet, or icy/snowy). It was found that rain reduced speed by 4.5 km/hr; snow and ice reduced speed by 9.1 km/hr; and the wind speed between 16 and 32 km/hr reduced speed by 5 km/hr.

Jones et al. (1970) found that the capacity of a segment of I-45 in Houston, Texas was reduced by 14 to 19 % under rain [23]. A similar study of I-35W in Minneapolis was conducted by Ries (1981) [39], and the difference between roadway capacities for rain and snow was investigated. It was found that the even light precipitation might reduce the capacity by 8 %. It was also found that each additional 0.01 in/hr of rain decreased the capacity by 0.6 %, and the impact of snow was more significant than that under rain. Every 0.01 in/hr increment of snow decreased capacity by 2.8 %. Hall and Barrow (1988) investigated the impacts of adverse weather on the flow-occupancy relationship for Queen Elizabeth Way near Hamilton, Ontario. Roadway capacity was found significantly reduced due to rain events.

Botha and Kruse (1992) conducted a study to show how adverse weather reduces saturation flow rates at signalized intersections [5]. The study investigated the effects of residual ice and snow on saturation flow rates and delay times at signalized intersections in Fairbanks, Alaska. In comparison to the HCM, the winter data collection and subsequent analysis showed that winter saturation flow measurements were much less than those suggested in the HCM. It was found that when snow and ice were prevalent, saturation flow rates were 19 % lower than the recommended HCM rates.

While addressing freeway capacity reduction due to adverse weather in Chapter 22 of the Highway Capacity Manual 2000 [20], the following statements were recommended:

- No significant reductions in capacities due to light rains until visibility is affected;
- Light snow causes 5% to 10% reduction in capacities;
- Heavy rain causes 14% to 15% reduction in capacities; and
- Heavy snow causes 25% to 30% reduction in capacities.

The percentages suggested by HCM (2000) were consistent with the findings observed and summarized in previous studies.

A study was performed by Kwon, Mauch and Varaiya (2006) to determine the impact of incidents, special events, lane closures and adverse weather on delay [(25)]. They found that incidents and special events together account for 17.8 % of total delays. The study concluded that 33 % of all delays could be eliminated by operational improvements such as using ramp metering. Excess demand caused 47 % of total delay and rain caused 1.6 % of delays.

Han, Chin, and Hwang (2003) laid a framework for determining the impact of adverse weather conditions on delay [(25)]. Using GIS and weather databases, travel delays were estimated. The estimation procedure employed NCDC's Storm Data and FHWA's HPMS and NHPN databases. The estimation procedure involved estimating the impacts of weather for data obtained in 1999. An adverse weather condition was found to cause approximately one to six minutes of delay. There is an increase of 7 to 36 % travel time under adverse weather, compared to that under normal condition. The study also found that American drivers had a very low probability (0.6%) of experiencing a moderate travel delay due to adverse weather conditions on their typical trips during any day of 1999. The majority of delays occurred during winter and early spring.

Highway Capacity Manual 2000

The Highway Capacity Manual's methodology for estimating LOS at basic freeway segments is based on the free-flow speed of the study roadways. The free-flow speed was estimated through an algorithm which accounts for the effects of various parameters, including lane width, shoulder width, number of freeway lanes and interchange density (HCM 2000) [(20)]. The capacity of a basic freeway segment was a function of free flow speed and ranged between 2,250 passenger cars per hour per lane (pcphpl) (free-flow speed = 55 mi/hr and density = 43.6 pc/mi/ln) to 2,400 pcphpl (free-flow speed = 75 mi/hr and density = 46.0 pc/mi/ln). A speed-flow diagram was generated for free-flow speeds under 75 miles per hour (mi/hr).

Previous Research for Bus Operations

A literature review related to automatic vehicle location (AVL) and automatic passenger counter (APC) systems has shown an increase in the use of these systems in transit agencies across the United States. This emergence has also led to an improvement of the quality of technology available for accurate information. Another major step forward for the AVL systems is the increased and more accurate use of GPS data to determine bus locations. The majority of the literature review listed several perceived benefits as common reasons for installing this technology on buses. The most common benefits of AVL systems include increased passenger safety, increased passenger satisfaction due to improved information dissemination, and improved efficiency for the transit operator. Conversely, a number of technological problems involving hardware, software and implementation were also discussed.

Studies have been conducted to investigate different factors that may have significant influence on bus operations. For example, Guenthner and Sinha (1983) investigated the relationship between passenger boarding and alighting counts and bus delay [(14)]. Guenthner and Hamat (1988) examined the characteristics of bus arrival time under influences of other factors (e.g., travel distance, location of the peak load point, and headway) [(15)]. Levine and Wachs (1996) conducted statistical analyses to identify the factors (e.g., time of day, day of week, traffic volume, road type, etc.) affecting vehicle occupancy in California [(27)]. Rajbhandari et al. (2004) developed a regression model to estimate bus dwell time based on AVL/APC data, in which explanatory variables affecting bus dwell time were identified and their impacts were analyzed [(38)]. Chen and Liu (2005) developed neural network models to analyze the impacts of passenger activities on bus operational characteristics such as dwell time [(8)]. These studies generate useful information toward identifying critical factors that have a significant impact on various aspects of bus operations.

SPEED-FLOW-DENSITY RELATIONSHIP UNDER ADVERSE WEATHER

The relationship among speed, flow and density was investigated and discussed in this section. The discussion started by introducing the methodology adopted for data collection and processing. The results and findings are discussed at the end of this section.

Methodology

The weather and traffic data were collected to investigate speed-flow-density relationships. The results can be used to improve the speed-flow-density relationships provided in the Highway Capacity Manual (HCM 2000). The results from this research will be useful by transportation system practitioners in evaluating roadway systems under adverse weather conditions.

Data Collection Plan

To investigate the impact of adverse weather on New Jersey roadways, five New Jersey roadway segments were studied. These five locations were identified by the New Jersey Department of Transportation (NJDOT) and New Jersey Transit (NJ Transit) as roadways impacted by adverse weather conditions and also having high traffic flows during the morning and evening peak periods. The AM and PM peak periods were from 6:00 to 9:00 AM and 4:00 to 7:00 PM, respectively. The selected locations and their related geographical information are listed in Table 3. Other sites were excluded due to difficulty in obtaining useable video images at the sites.

Table 3. Study Locations

Sites	Overpass	Time	No. of Lanes	Location
US 46	North Rd	AM (6:00-9:00)	3	Essex County
NJ 3	Peterson Plank Rd	AM (6:00-9:00)	4	Bergen County
I – 80	Queen Anne Rd	AM (6:00-9:00)	3	Bergen County
I – 78	Hillcrest Rd	PM (4:00-7:00)	3	Essex County
NJ 22	South St	PM (4:00-7:00)	2	Essex County

To determine the effects of adverse weather conditions, it was essential for the study to collect and analyze an ample amount of traffic data under various weather conditions. As the study locations were not equipped with traffic detectors, data collection equipment was needed to be used. The data for the study roadways were obtained using a video image recording device and the video imaging processing system Autoscope 2004. The following provides a brief discussion of the Autoscope system.

Autoscope

In recent years, a number of aboveground technologies have emerged to complement or replace in-ground inductive loops. These new technologies include video detection, radar, ultrasonic, infrared and laser. Video detection has been the most successful, providing unsurpassed richness of data as well as video images, wider coverage areas and greater versatility of the applications (e.g., wide area detection, accuracy in measuring vehicle counts and speed, detecting of stopped vehicles, and reconfiguring the detector to reflect changes in road geometry).

Michalopoulos (1991) discussed that vehicle detection by video cameras is one of the most promising new technologies for wireless large-scale data collection and implementation of advanced traffic control and management schemes such as vehicle guidance/navigation [(25)]. Autoscope can work with any camera, and under congested flow and other artifact conditions while still being able to use the camera for surveillance. Although more work is underway to establish reliability as well as performance on a long-term continuous operation, the elusive goal of wide-area video detection research and development is now extremely close to fulfillment. The ability exists to detect cost-effectively vehicles via video cameras with satisfactory accuracy for traffic surveillance and control. Autoscope should be considered as a wide-area detection system. The Autoscope® 2004 System is a full traffic surveillance management system that uses machine-vision technology to produce highly accurate traffic measurements. Each component of the system is essential to the overall process of detecting, calculating, and collecting these types of traffic data:

- Vehicle presence and passage
- Speed
- Average speed
- Density
- Time occupancy
- Incident detection
- Vehicle length
- Space occupancy
- Flow rate
- Volume
- Time headway
- Level of service

Descriptions of Study Locations

The following provides a description of each of the study locations.

Route 46 – Notch Road, Clifton

Route 46 is an Urban Principal Arterial roadway located in Essex County. The roadway consists of six lanes with three lanes is each direction and with no parking on either side of the roadway. Route 46 intersects with Valley Road and Route 3 East as shown Figure 2.

Figure 2. US 46 Geographic Location (http://maps.google.com)

Route 3 - Paterson Plank Road, Carlstadt

Route 3 is an Urban Freeway/Expressway located in Bergen County. The roadway consists of eight lanes with four lanes is each direction and with no parking on either side of the roadway. Route 3 intersects with Route 1 as shown in Figure 3.

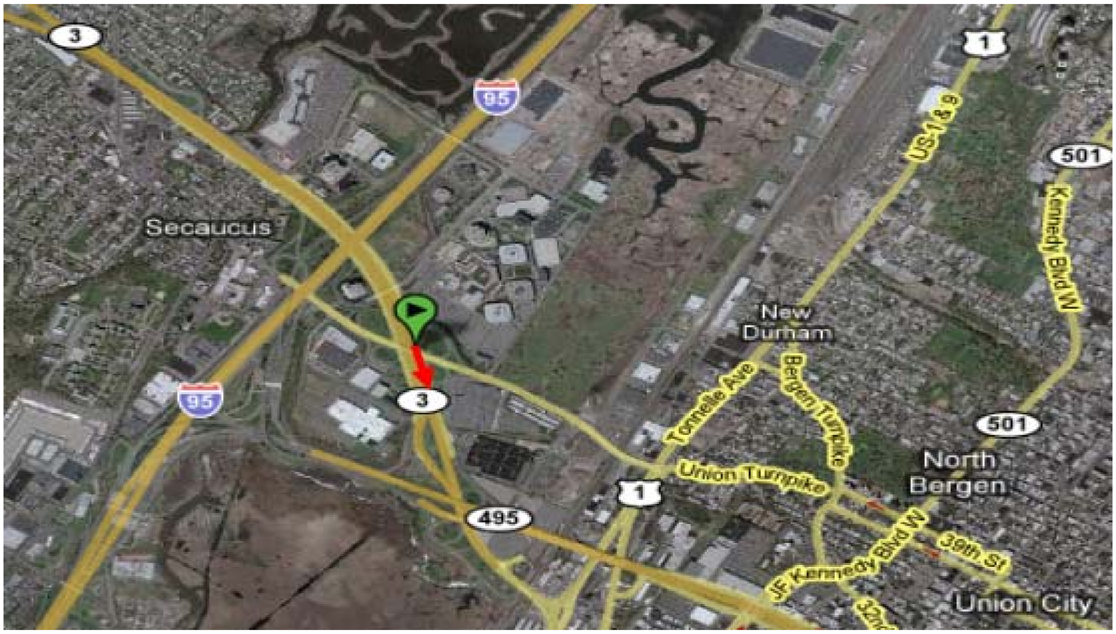


Figure 3. NJ 3 Geographic Location (Source: http://maps.google.com)

I-80 – Queen Ann Road, Bogota

I-80 is an Urban Interstate located in Bergen County. The roadway consists of ten lanes with five lanes is each direction and with no parking on either side of the roadway. Figure 4 shows how I-80 accesses I-95.

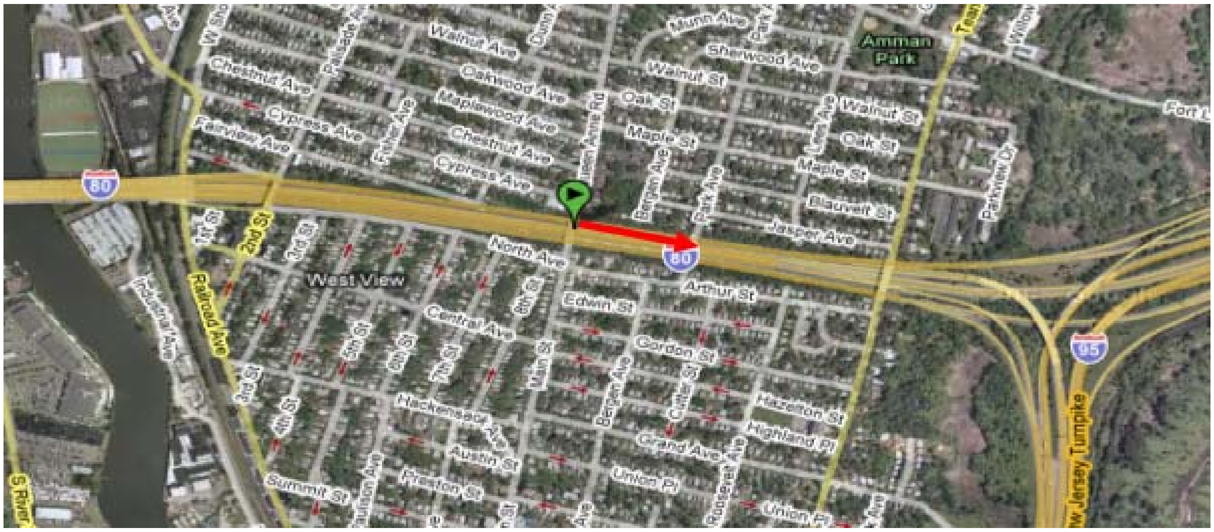


Figure 4. I-80 Geographic Location (Source: http://maps.google.com)

I-78 – Hillcrest Road, Watchung

I-78 is an Urban Interstate located in Somerset County. The roadway consists of six lanes with three lanes is each direction and with no parking on either side of the roadway as shown in Figure 5.

Figure 5. I-78 Geographic Location (Source: http://maps.google.com)

NJ 22 – South Street, Hillside

Route 22 is an Urban Principal Arterial located in Union County. The roadway consists of four lanes with two lanes is each direction and with no parking on either side of the roadway as shown in Figure 6.

Figure 6. NJ 22 Geographic Location (Source:http://maps.goole.com)

<u>Data Collected</u>

One of the objectives of this study is to estimate speed-flow relationships under adverse weather conditions. To address this objective, speed, flow and density data were collected at each of the study locations under no adverse weather, rain, snow, darkness and sunglare conditions. To establish the impacts of these weather and light conditions, comparisons were made between speed, flow and density under no adverse weather conditions, referred to as "normal" conditions, and each weather and light condition. The comparison between normal and adverse weather conditions was limited to either the AM or PM peak period of the day. The data sets for each peak period included a varied range of speed and flow conditions. During the study, it was important to include days with different types of weather conditions with varied intensities. For this reason, data were collected for at least two days under normal and rain conditions at each roadway location. The research team was not able to collect two days of data under snow due to a limited number of snow days during the data collection period.

Table 4 shows the hours of data collected under each weather and light condition for each roadway. In total at the five study locations, 82 hours of data were collected under normal conditions and under adverse weather and light conditions. Approximately 29 hours of data were collected under normal conditions, with at least five hours collected at each location. Twenty-eight hours of data were collected under rain and twenty-four hours under snow. Tables 5 and 6 show the rain and snow intensity, respectively, for each of the study roadways. The rain intensity ranged from 0.01 to 0.24 in/hr within five hours where there was a trace of rain. A trace of rain is defined as rain intensity less than 0.01 in/hr. Snow intensity ranged from 0.01 to 0.09 in/hr within 6 hours where there was a trace of snow. At NJ 3 and US 22, three hours of data were collected under snow. At I-80, US46 and I-78, six hours of data were collected under snow.

Data were also collected under darkness and sunglare conditions. A total of 21 hours of data were collected at the five study locations under darkness. About 7 hours of data were collected under normal weather and darkness (normal-darkness), 5 hours under rain and darkness (rain-darkness) and 8.5 hours under snow-darkness conditions. Sunglare was not present at all study locations and not for the entire peak period during which data were collected. For this reason only one hour of data was collected under sunglare.

Table 4. Hours of Data Collected

Locations	Normal		Rain		Snow		Sunglare
	Light	Darkness	Light	Darkness	Light	Darkness	
US 46	6.0	1.6	6.0	0.3	6.0	0.3	-
NJ 3	6.0	0.5	6.0	0.5	3.0	0.5	-
I-80	5.75	0.5	6.0	1.0	6.0	3.0	0.25
I-78	6.0	1.75	5.0	2.0	6.0	3.0	0.22
NJ 22	5.42	3.0	5.5	1.5	3.0	1.75	0.57
Total	**29.17**	**7.35**	**28.5**	**5.3**	**24**	**8.55**	**1.04**

Weather Information

Weather data were obtained from the National Climatic Data Center website. The data were obtained on days with adverse weather conditions. Details for each rain and snow event were identified using archived weather databases from the National Climatic Data Center (NCDC) [29]. The Center has long served the nation as a national resource of climate information. Rain and snow-related weather events were identified using the National Weather Service's "Hourly Precipitation Data (HPD)" databases. The databases provide hourly precipitation amounts recorded by three gauge locations: the National Weather Service; Federal Aviation Administration; and, cooperative observer stations. HPD includes maximum precipitation for nine daily periods, ranging in length from 15 minutes to 24 hours, for selected stations. The hourly precipitation table is provided from the National Environmental Satellite, Data and Information Service. It provides the amount of precipitation for each time period.

Table 5. Rain Intensity at Study Locations

Locations	Dates M/D/Y	Rain Intensity (In/hr)		
		6 – 7 AM	**7 – 8 AM**	**8 – 9 AM**
US 46	01/08/07	0.12	0.11	0.05
	10/25/07	0.07	Trace[a]	Trace[a]
NJ 3	10/25/07	0.07	Trace[a]	Trace[a]
	2/13/08	0.23	0.22	NA
I-80	04/16/07	0.16	0.24	0.24
	10/25/07	0.05	Trace[a]	NA
I-78		**4 – 5 PM**	**5 – 6 PM**	**6 – 7 PM**
	02/01/08	0.01	0.16	0.06
	02/13/08	0.02	0.01	Trace
NJ 22	02/26/08	0.02	0.03	0.06
	03/19/08	0.09	0.06	0.08

[a]: Trace refers to precipitation amount is less than 0.01 in/hr

Table 6. Snow Intensity at Study Locations

Locations	Dates M/D/Y	Snow Intensity (in/hr)		
		6 – 7 AM	**7 – 8 AM**	**8 – 9 AM**
US 46	02/26/07	Trace[a]	Trace[a]	Trace[a]
	02/22/08	0.06	0.04	0.05
NJ 3	02/22/08	0.06	0.04	0.05
I-80	02/14/07	0.04	0.02	0.07
	02/22/08	0.06	0.04	0.05
I-78		**4 – 5 PM**	**5 – 6 PM**	**6 – 7 PM**
	12/13/07	0.09	0.05	Trace
	02/12/08	0.02	Trace[a]	0.01
NJ 22	12/13/07	0.09	0.05	Trace

[a]: Trace refers to precipitation amount is less than 0.01 in/hr

Summary of Data under Lighted Conditions

Using the data collected, speed, flow and density were determined under each weather and light condition. Table 5 shows a summary of the speed, density and flow data collected for each of the study locations under each weather conditions and during light conditions. The following states the impact of weather at each roadway.

Overall

Under normal conditions, the average speed ranges from 40 mi/hr on Route 22 to 75 mi/hr on I-78. The average speed is reported for each of the two days of data collected in Table 7. In general, there are small differences between the average speeds for two days of data. This difference ranges from 0.78 mi/hr at NJ 3 to 6.47 mi/hr at NJ 22. Under rain conditions, speeds decrease between 0.82 mi/hr at I-78 with a rain intensity of 0.01 in/hr to 37 mi/hr at US 46 with a rain intensity of 0.09 in/hr. At one location, NJ 22, speeds under rain increased by 16 mi/hr at a rainfall intensity of 0.02 in/hr. This increase only occurred for one of the two days of speed data collected under rain. For the second day of speed data, collected at NJ 22, speeds decreased by 16.9 mi/hr when compared to average speeds under normal conditions. Under snow conditions, speeds decrease between 5.8 mi/hr at NJ 22 and 33 mi/hr at I-80.

I-80

At I-80, the average speed under normal conditions varies from 64.9 mi/hr to 71.3 mi/hr for an average speed over the two days of 68.1 mi/hr. At this location speed data were gathered both under low rain intensity (0.02 in/hr) and heavy rain intensity (0.21 in/hr). Under low rain intensity, the average speed is 58.8 mi/hr and under heavy rain the average speed is 53.7 mi/hr. Compared to the average speed under lighted conditions, there is a 9.3 mi/hr reduction in speed under low rain intensity and a 14.4 mi/hr reduction in speed under heavy rain. This speed reduction is referred to in Table 5 as the “rain impact.”

Speed data were also gathered under snow at low snow intensity of 0.04 in/hr and 0.5 in/hr. Although the intensity is similar for the two days when data were gathered, there is a significant difference between the average speeds with an average speed of 34.3 mi/hr for Day 1 and 48.5 mi/hr for Day 2. The difference between the average speeds under similar snow intensity may be due to differences in snow accumulation or roadway conditions. Compared to the average speed under normal conditions there is a reduction in speed under snow, or a “snow impact,” of between 19.6 mi/hr for a 0.04 in/hr snow intensity and 33.8 mi/hr for a 0.05 in/hr snow intensity.

NJ 3

At NJ 3, the average speed under normal conditions over the two days is 62.3 mi/hr. At this location speed data were gathered under low rain intensity (0.02 in/hr) and moderate to heavy rain intensity (0.15 in/hr). Under low rain intensity, the average speed is 50.2 mi/hr and under moderate/heavy rain the average speed is 40.8 mi/hr. The rain impact under low rain intensity is 12.1 mi/hr and 21.5 mi/hr under moderate/heavy rain intensity. Speed data were also gathered under low snow intensity of 0.05 in/hr. Under the 0.05 in/hr snow intensity, the average speed is 39.4 mi/hr with a snow impact of 22.9 mi/hr.

Table 7. Summary of Traffic Stream Parameters under Lighted Conditions

Weather Condition	I-80			NJ 3			US 46			I-78			NJ 22		
	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]
Normal (Day 1)	64.9	23.11	2060	62.71	23.39	2240	58.66	22.11	2000	73.56	15.32	1720	36.61	47.08	2370
Normal (Day 2)	71.34	18.99	2040	61.93	24.04	2000	63.48	15.60	1600	75.86	15.88	1680	43.08	36.30	1980
Normal (Day 3)	65.86	21.12	2220		-	-		-	-		-	-		-	-
Average	**67.37**	**21.07**	**2170**	**62.32**	**23.71**	**2120**	**61.07**	**18.85**	**1800**	**74.71**	**15.60**	**1700**	**39.85**	**41.69**	**2175**
Rain (Day 1)	58.81	24.71	2040	50.27	33.79	2280	23.74	60.69	1740	73.88	13.68	1365	56.09	24.72	1830
Intensity (in/hr)		0.02			0.02			0.09			0.01			0.02	
Rain Impact	**-9.31**	**3.64**	**-67**	**-12.05**	**10.07**	**160**	**-37.33**	**41.84**	**-60**	**-0.82**	**-1.92**	**-335**	**16.24**	**-16.97**	**-345**
Rain (Day 2)	53.73	25.23	1760	40.87	37.81	1920	48.69	34.99	2180	69.28	13.43	1290	22.94	47.98	1560
Intensity (in/hr)		0.21			0.15			0.02			0.02			0.07	
Rain Impact[1]	**-14.39**	**4.16**	**-347**	**-21.45**	**14.10**	**-200**	**-12.38**	**16.14**	**380**	**-5.43**	**-2.17**	**-410**	**-16.91**	**6.29**	**-615**
Snow (Day 1)	34.33	22.93	1240	39.41	27.38	1480	30.54	24.86	1460	59.21	11.66	1050	34.04	44.36	2160
Intensity (in/hr)		0.04			0.05			Trace			0.02			0.07	
Snow Impact[1]	**-33.79**	**1.86**	**-867**	**-22.91**	**3.66**	**-640**	**-30.53**	**6.01**	**-340**	**-15.50**	**-3.94**	**-650**	**-5.80**	**2.67**	**-15**
Snow (Day 2)	48.54	13.70	1260	-	-	-	35.98	23.07	1540	60.59	14.41	1185	-	-	-
Intensity (in/hr)		0.05			-			0.05			0.07			-	
Snow Impact[1]	**-19.58**	**-7.38**	**-847**	**-**	**-**	**-**	**-25.09**	**4.22**	**-260**	**-14.11**	**-1.20**	**-515**	**-**	**-**	**-**

1: mi/hr, 2: veh/mi/ln, 3: veh/hr/ln

US 46

At US 46, the average speed under normal conditions varies from 58.7 mi/hr to 63.5 mi/hr with an average speed over the two days of 61.1 mi/hr. At this location speed data were gathered under low (0.02 in/hr) to moderate rain intensity (0.09 in/hr). Under low rain intensity, the average speed is 48.7 mi/hr. Under low/moderate rain intensity, the average speed is 23.7 mi/hr which is significantly lower than the average speed under normal conditions. The rain impact under low rain intensity is 12.4 mi/hr and 37.3 mi/hr under low/moderate rain intensity.

Speed data were also gathered under low snow intensity of 0.05 in/hr and under a trace of snow. Under the 0.05 in/hr snow intensity, the average speed is 36 mi/hr with a snow impact of 25.1 mi/hr. The average speed under trace snow is 30.5 mi/hr with a snow impact of 30.5 mi/hr. The average speed under a trace of snow is lower than the average speed under a 0.05 in/hr snow intensity. These results may be due to the impact of not only the snow intensity, but also to the impact of snow accumulation on the roadway.

I-78

At I-78, the average speed under normal conditions is 74.7 mi/hr. At this location speed data were gathered under low rain intensity of 0.01 and 0.02 in/hr. Under 0.01 in/hr intensity, the average speed is 73.9 mi/hr with a rain impact of 0.8 mi/hr. Under 0.02 in/hr, the average speed is 69.3 mi/hr with a rain impact of 5.4 mi/hr.

Speed data were also gathered under low snow intensity (0.02 in/hr) and low/moderate snow intensity (0.07 in/hr). Under 0.02 in/hr snow intensity, the average speed is 59.2 mi/hr with a snow impact of 15.5 mi/hr. Under 0.07 in/hr snow intensity, the average speed is 60.6 mi/hr with a snow impact of 14.1 mi/hr. The average speed under 0.07 in/hr snow intensity is higher than the average speed under a 0.02 in/hr snow intensity. This may be due to snow accumulation on the roadway.

NJ 22

At NJ 22, the average speed under normal conditions varies from 36.6 mi/hr to 43.1 mi/hr with the average speed over the two days 39.9 mi/hr. At this location speed data were gathered under low and low/moderate rain intensity of 0.02 and 0.07 in/hr, respectively. Under 0.02 in/hr intensity, the average speed is 56.1 mi/hr. This is the only location where speed increased under rain when compared to normal conditions. Under 0.07 in/hr, the average speed is 22.9 mi/hr which is significantly lower than the average speed under normal conditions. The rain impact under 0.02 in/hr rain intensity is 16.9 mi/hr. Speed data were also gathered under low/moderate snow intensity (0.07

in/hr). Under 0.07 in/hr snow intensity, the average speed is 34 mi/hr with a snow impact of 5.8 mi/hr.

Summary of Data under Darkness Conditions

Using the data collected, speed, flow and density were determined under darkness conditions. Darkness was determined at a time during which a high percentage of vehicles used their headlights. Table 8 shows a summary of the speed, density and flow data collected for each of the study locations under each weather conditions and during darkness conditions. The impact of darkness under normal and adverse weather conditions is also shown in Table 8. This darkness impact is determined as the difference between the traffic parameter under lighted condition and a given weather condition and the traffic parameter under darkness with the same weather condition as in the lighted condition.

Overall

Under normal-darkness conditions, with no adverse weather, there is little difference between the speeds for the two days under which data were collected. Under rain-darkness conditions, speeds generally decreased from 0.71 mi/hr at US 46 to 5.2 mi/hr at I-80. Speeds also increased under darkness conditions with an increase of 2.3 mi/hr at I-80, 1.1mi/hr at US 46 and 3.7 at NJ-22.

It is under rain-darkness conditions that the results show varying trends. Speeds decreased by 7.14 and 7.11 mi/hr at NJ 3 (0.22 in/hr) and I-78 (0.11 in/hr), respectively. At the remaining locations, speeds increased from 0.17 mi/hr at NJ 22 under a rain intensity of 0.05 in/hr to 15.5 mi/hr at US 46 under a rain intensity of 0.06 in/hr. Similarly under snow and darkness (snow-darkness) conditions, speeds also increased from 0.19 at NJ 3 under 0.05 in/hr snow intensity to 4.9 mi/hr at NJ 22 under snow intensity of 0.03 in/hr. At I-78, snow-darkness caused a significant decrease in speed of 19.8 mi/hr under a snow-intensity of 0.07 in/hr.

Summary of Data under Sunglare Conditions

Table 9 shows the impact of sunglare at three of the study roadways where sunglare was observed. Compared to the average speed under normal conditions, there is a reduction in speed at I-80 of 10.4 mi/hr, at I-78 of 6.6 mi/hr and at NJ 22 of 20. 6 mi/hr. The table shows that the sunglare impact can be as significant as the rain and snow impact.

Table 8. Summary of Traffic Stream Parameters under Darkness Conditions

	I-80			NJ3			US 46			I-78			NJ22		
	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]
Normal-Darkness (Day 1)	67.19	22.16	1900	61.64	27.10	2140	59.75	20.24	1540	-	-	-	40.31	34.70	2280
Darkness Impact[2]	2.29	-0.95	-160	-1.07	3.71	-100	1.09	-1.87	-460	-	-	-	3.70	-12.38	-90
Normal-Darkness (Day 2)	66.19	22.67	1820	61.21	27.68	2020	62.77	20.12	1660	72.88	14.77	1425	39.43	44.76	2280
Darkness Impact[2]	-5.15	3.68	-220	-0.72	3.64	20	-0.71	4.52	60	-2.97	-1.12	-255	-3.65	8.46	300
Rain-Darkness (Day 1)	61.47	23.66	2020	43.14	35.35	1880	64.20	21.33	1720	66.77	13.11	1275	56.26	24.27	1950
Intensity (in/hr)		0.04			0.22			0.06			0.11			0.05	
Rain-Darkness Impact[2]	2.66	-1.05	-20	-7.14	1.56	-400	15.51	-13.66	-460	-7.11	-0.57	-90	0.17	-0.45	120
Rain-Darkness (Day 2)	55.31	25.65	1560	-	-	-	-	-	-	61.01	15.91	1395	-	-	-
Intensity (in/hr)		0.16		-	-	-	-	-	-		0.01		-	-	-
Rain-Darkness Impact[2]	1.58	0.41	-200	-	-	-	-	-	-	1.80	4.25	345	-	-	-
Snow-Darkness (Day 1)	36.77	22.67	1240	39.60	29.12	1440	39.23	25.97	1560	62.25	8.38	1395	38.97	27.89	1860
Intensity (in/hr)		0.03			0.05			0.05			0.05			0.03	
Snow-Darkness Impact[2]	2.4	-0.27	0	0.19	1.74	-40	3.24	2.91	20	3.04	-3.28	345	4.93	-16.47	-300
Snow-Darkness (Day 2)	-	-	-	-	-	-	-	-	-	40.80	18.12	1110	-	-	-
Intensity (in/hr)	-	-		-	-		-	-		0.07			-	-	
Snow-Darkness Impact[2]	-	-		-	-		-	-		-19.80	3.72		-		
Sunglare	57.01	27.67		-	-		-	-		68.13	16.52		19.25		

1: mi/hr, 2: veh/mi/lane, 3: veh/hr/ln

Table 9. Summary of Traffic Stream Parameters under Sunglare Conditions

Weather Condition	I-80			I-78			NJ 22		
	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]	Speed[1]	Density[2]	Flow[3]
Normal (Average)	67.37	21.07	2170	74.71	15.60	1700	39.85	41.69	2175
Sunglare	57.01	27.67	-	68.13	16.52	-	19.25	-	-
Sunglare Impact	**-10.36**	**6.6**	**-**	**-6.58**	**0.92**	**-**	**-20.6**	**-**	**-**

1: mi/hr, 2: veh/mi/lane, 3: veh/hr/ln

Table 10. Summary of Headway under Various Weather Conditions

Weather Condition	I-80		NJ 3		US 46		I-78		NJ 22	
	Avg[a] (sec)	Avg[b] (ft)	Avg[a] (sec)	Avg[b] (ft)	Avg[a] (sec)	Avg[b] (ft)	Avg[a] (sec)	Avg[b] (ft)	Avg[a] (sec)	Avg[b] (ft)
Normal	2.54	250.59	2.44	222.78	3.13	280.11	3.09	338.46	2.16	126.62
Rain	2.66	209.52	2.33	139.68	2.50	87.00	3.87	393.15	3.28	110.00
Rain Impact	0.13	-41.07	-0.11	-83.10	-0.63	-193.11	0.78	54.69	1.11	-16.62
Rain-Intensity	0.21 in/hr		0.15 in/hr		0.09 in/hr		0.02 in/hr		0.07 in/hr	
Snow	4.56	229.57	3.33	192.70	4.34	228.87	5.21	452.83	2.38	118.92
Snow Impact	2.03	-21.03	0.90	-30.08	1.21	-51.24	2.13	114.37	0.22	-7.70
Snow-Intensity	0.04 in/hr		0.05 in/hr		0.05 in/hr		0.02 in/hr		0.07 in/hr	
Sunglare	2.3	190.61	NA	NA	NA	NA	3.20	319.61	1.80	50.92
Sunglare Impact	-0.31	-59.62	NA	NA	NA	NA	0.11	-18.85	-0.18	-64.37

a: Headway (sec) = Headway (ft/veh)/Speed(ft/sec)
b: Headway (ft/veh) = [1/Density (veh per lane mile)]*5280

Table 10 shows the impact of adverse weather (e.g., rain, snow and sunglare) on driving behavior, in terms of the headway between the following vehicle and its leading vehicle, for the studied locations. The headways defined in Table 10 are based on time (in seconds) and distance (in feet). Under the rain, it was found that the distance headway is generally less than that under normal condition, because of the congestion due to the rain. However, the time headway under the rain increases, besides the locations on NJ 3 and US 46 due to significant congestion (speed reduction of 21.45 and 37.33 mi/hr, respectively, shown in Table 7). Note that both time and distance based headways increase due to the rain impact at the location on I-78 because the congestion impact was very minor (speed reduction only 0.82 mi/hr).

Under snow conditions, it was similarly observed in Table 10 that the distance headway is less than that under normal condition, because of congestion due to the snow. However, the time headway increases in every location, which means the driver become cautious. Note that both time and distance based headways increase due to snow at the location on I-78 because the snow congestion impact is minor (speed reduction of 5.43 mi/hr shown in Table 7).

For collecting sunglare data, the studied locations on NJ 3 and US 46 were excluded because there was no sunglare impact. Minor impact was observed at the locations on I-80 and NJ 22, and it was found that both time and distance based headways decrease due to congestion (speed reduction of 10.36 and 20.6 mi/hr, respectively, shown in Table 8).

In general, adverse weather caused speed reduction, and the reduction in headway. However, it was found that the drivers tended to leave themselves longer time (e.g. increased time based headway) to react potential brakes downstream. In addition, the time headway under the snow is longer than that under the rain, which can be observed in Table 10. More data should be collected in order to quantify the impact of adverse weather on headway for various types of roadways.

Analysis

One of the goals of the research was to develop speed-flow relationships that could be used for predicting speed under various weather and light conditions. At present the Highway Capacity Manual speed-flow relationships are appropriate for lighted and dry conditions. The speed-flow relationships developed in this research could be useable by NJ Transit in estimating expected speeds on bus transit routes under various weather and light conditions.

Regression analysis was used to develop speed-flow relationships under each weather and lighting condition studied. Data for I-80 were used as the data gathered on this roadway showed reasonable results and was not impacted by downstream capacity constraints that would impact the measurement of speed at the study location. Four functional forms of the regression model were used including: linear, quadratic, logarithm, and exponential curves. The following provides a discussion of the speed-flow models developed.

Speed-Flow Model under Normal Conditions

For I-80, the difference between the minimum and maximum speed is 26.77 mi/hr with a minimum speed of 55.85 and the maximum speed 82.62 mi/hr. The flow rate varied between 760 and 2220 veh/hr/ln with a difference of 1460 veh/hr/ln. Figure 7 shows the speed-flow relationships using a quadratic regression curve. Table 11 shows the R^2 and the coefficients for the linear, quadratic, logarithm, and exponential regression curves. The quadratic model can be represented as the reduced model that is stated as $S = aF^2 + c$ because the p values of the linear terms are greater than 0.05.

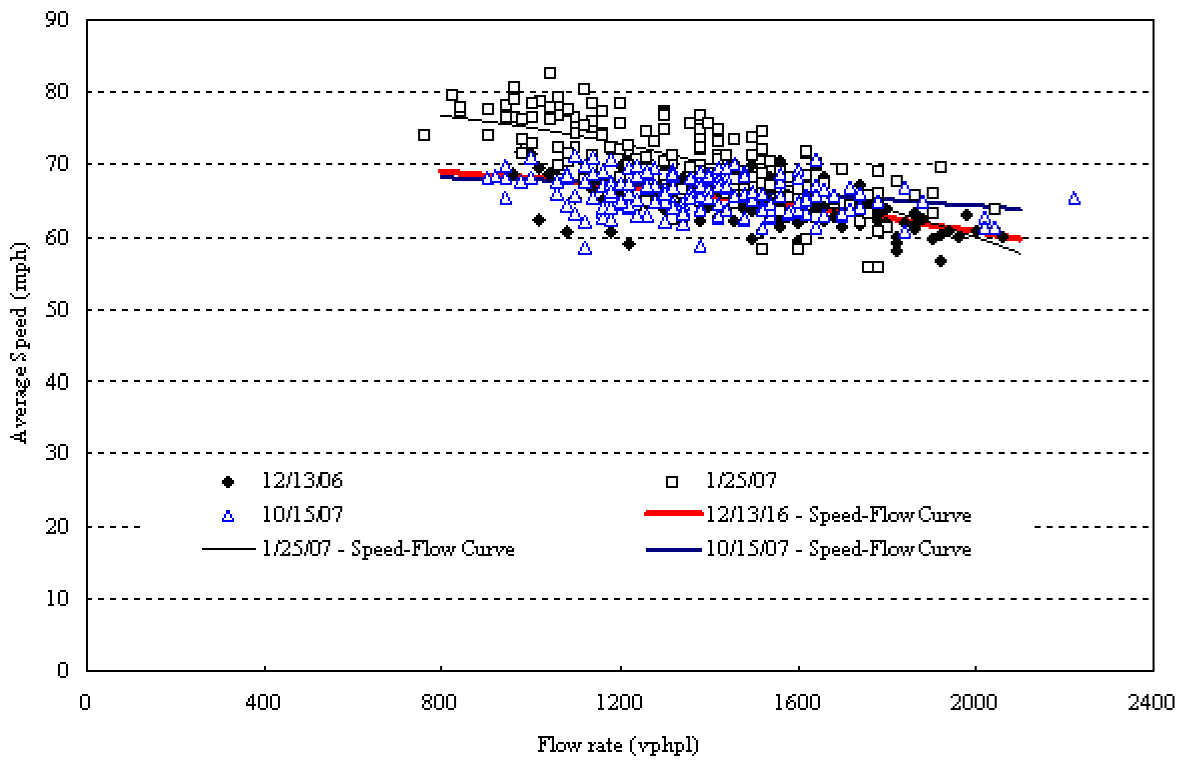


Figure 7. Speed-Flow Curves on I-80 under Normal

Table 11. Regression Forms for I-80 – Normal

Regression Form	Date M/D/Y	R^2	Regression Equations
Linear	12/13/06	0.35	$S= -0.0073F+ 75.7$
	1/25/07	0.51	$S= -0.014F+ 89.5$
	10/15/07	0.11	$S= -0.0036F+ 70.8$
Quad	12/13/06	0.36	$S = -0.0000025F^2+71$
	1/25/07	0.51	$S = -0.0000051F^2+80$
	10/15/07	0.11	$S = -0.0000012F^2+69$
Logarithm	12/13/06	0.34	$S= -10.3Ln(F) + 140.5$
	1/25/07	0.51	$S= -18.5Ln(F) + 203.2$
	10/15/07	0.11	$S= -5.0Ln(F) + 102.1$
Expo	12/13/06	0.35	$S= 76.7e^{-0.0001F}$
	1/25/07	0.50	$S= 92.3e^{-0.0002F}$
	10/15/07	0.11	$S= 71.0e^{-0.00005F}$

<u>Speed-Flow Model under Rain</u>

Figure 8 shows the speed-flow models for two different rain intensities. Under a rain intensity of 0.02 in/hr, the speed range is 22.65 mi/hr with a minimum speed 47.45 and the maximum speed 70.1 mi/hr. Under a rain intensity of 0.20 in/hr, the speed range is 14.81 mi/hr with a minimum speed 41.69 and the maximum speed 56.50 mi/hr. The flow rate range is between 860 and 2100 veh/hr/ln with a difference is 1060 veh/hr/ln for a 0.02 in/hr rain intensity and the flow range is between 860 and 1760 veh/hr/ln with a difference is 900 veh/hr/ln when the rain intensity is 0.20 in/hr. The flow rate range under rain is less than under normal conditions.

The speed range when the rain intensity is 0.02 in/hr (or < 0.1 in/hr) is greater than when the rain intensity is 0.20 in/hr (or > 0.1 in/hr). Figure 8 shows the speed-flow relationships using a quadratic regression curve as the R^2 for the quadratic regression curve is greater than the R^2 for the linear, logarithm, and exponential regression curve. Table 12 shows that the R^2 and the coefficients of the linear, quadratic, logarithm, and exponential regression curve.

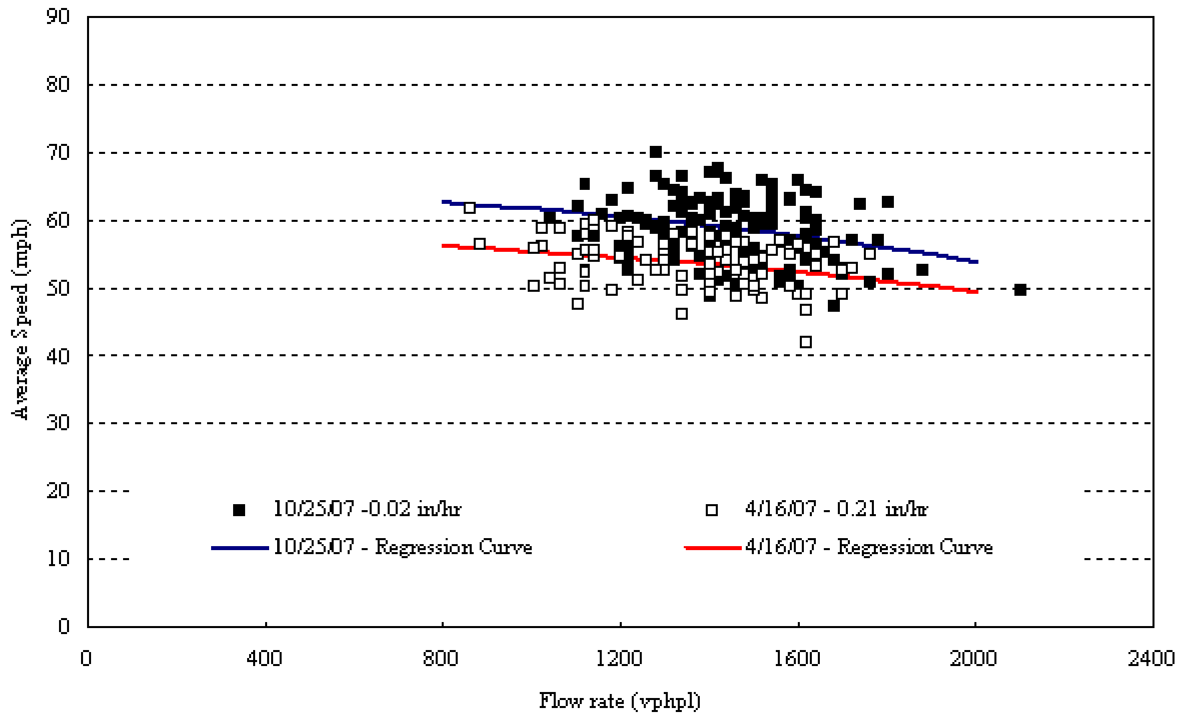


Figure 8. Speed-Flow Curves on I-80 under Rain

Table 12. Regression Forms for I-80 – Rain

Regression Form	Date M/D/Y	R^2	Regression Equations
Linear	10/25/07	0.08	S= -0.0073F+ 69.4
	04/16/07	0.08	S= -0.0047F+ 60.3
Quad	10/25/07	0.08	$S = -0.0000026F^2+65$
	04/16/07	0.08	$S = -0.0000020F^2 +57$
Logarithm	10/25/07	0.07	S= -9.9Ln(F) + 130.45
	04/16/07	0.08	S= -6.1Ln(F) + 98.05
Expo	10/25/07	0.08	$S= 70.6e^{-0.0001F}$
	04/16/07	0.08	$S= 60.6e^{-0.00009F}$

Speed-Flow Model under Snow

Figure 9 shows the speed-flow model for snow on I-80 when the snow intensity is 0.05 in/hr and the roadway was not cleaned and a snow intensity of 0.04 in/hr and the roadway was cleaned. The figure shows the impact of snow accumulation on roadway operations. The speed range is 20.0 mi/hr with a minimum speed of 27.3 and a maximum speed 47.3 mi/hr when the snow intensity is 0.05 in/hr and the road was cleaned. The speed range is 27.1 mi/hr with a minimum speed 38.4 and a maximum speed 65.5 mi/hr when snow intensity is 0.04 in/hr and the road was not cleaned. The flow rate range is between 200 and 1240 veh/hr/ln with a difference of 1040 veh/hr/ln when the snow intensity is 0.05 in/hr and the road was cleaned. The flow rate range is between 40 and 1260 veh/hr/ln with a difference of 1220 veh/hr/ln when the snow intensity 0.04 in/hr and the road was not cleaned. Figure 9 shows the speed-flow relationships using a logarithm regression curve because the R2 of the logarithm regression curve is greater than the R^2 of the linear, logarithm, and exponential regression curve. Table 13 shows that R^2 and the coefficients of the linear, quadratic, logarithm, and exponential regression curve.

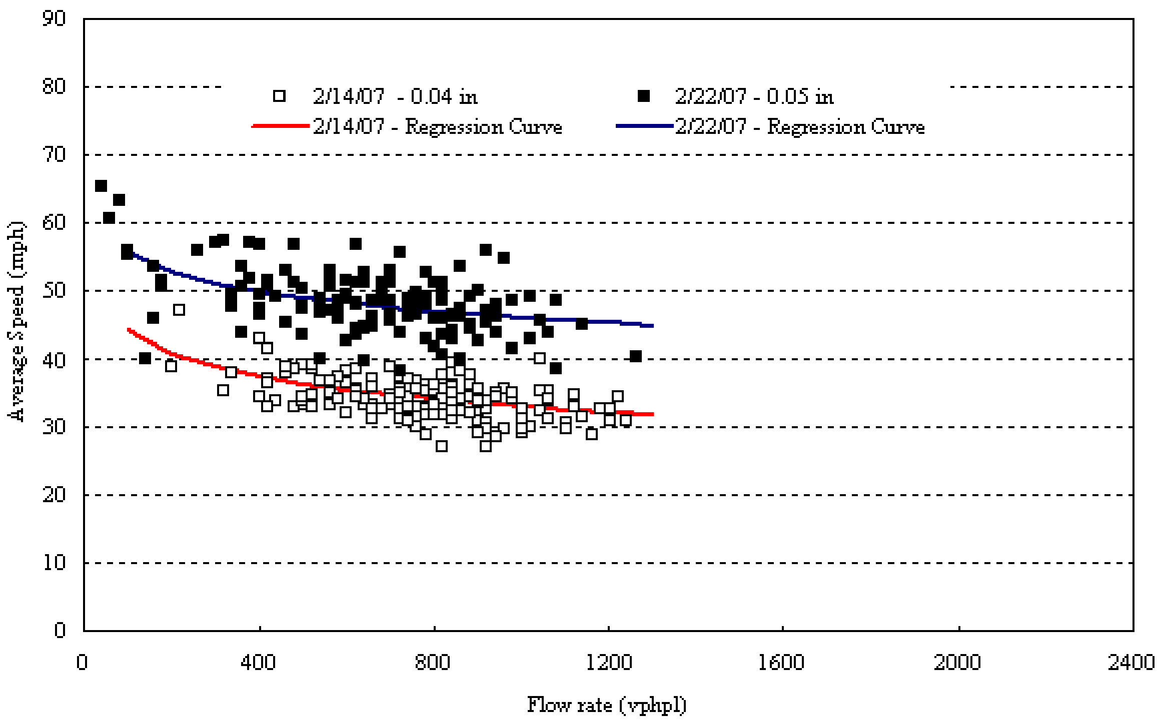


Figure 9. Speed-Flow Curves on I-80 under Snow

Table 13. Regression Forms for I-80 – Snow

Regression Form	Date M/D/Y	R^2	Regression Equations
Linear	02/14/07	0.20	$S= -0.0065F+ 40.1$
	02/22/07	0.22	$S= -0.009F+ 54.3$
Quad	02/14/07	0.17	$S = -0.0000038F^2+40$
	02/22/07	0.17	$S = -0.0000064F^2 +51$
Logarithm	02/14/07	0.24	$S= -4.8Ln(F) + 66.3$
	02/22/07	0.28	$S= -4.2Ln(F) + 75.1$
Expo	02/14/07	0.20	$S= 39.8e^{-0.0002F}$
	02/22/07	0.21	$S= 54.2e^{-0.0002F}$

Speed-Flow Model under Darkness

Data were also gathered under darkness conditions and during normal weather, rain and snow. Figure 10 shows the speed-flow relationship for normal-darkness conditions.

For I-80, the difference between the minimum and maximum speed is 7.79 mi/hr with a minimum speed of 63.4 and a maximum speed 70.9 mi/hr under normal-darkness. The flow rate varied between 1160 and 1900 veh/hr/ln with a difference of 740 veh/hr/ln. Figure 10 shows the speed-flow relationships using a quadratic regression curve. Table 14 shows the R^2 and the coefficients for the linear, quadratic, logarithm, and exponential regression curves. All of the models have the same R^2 of 21%, which indicates that the models do not provide a good fit to the data.

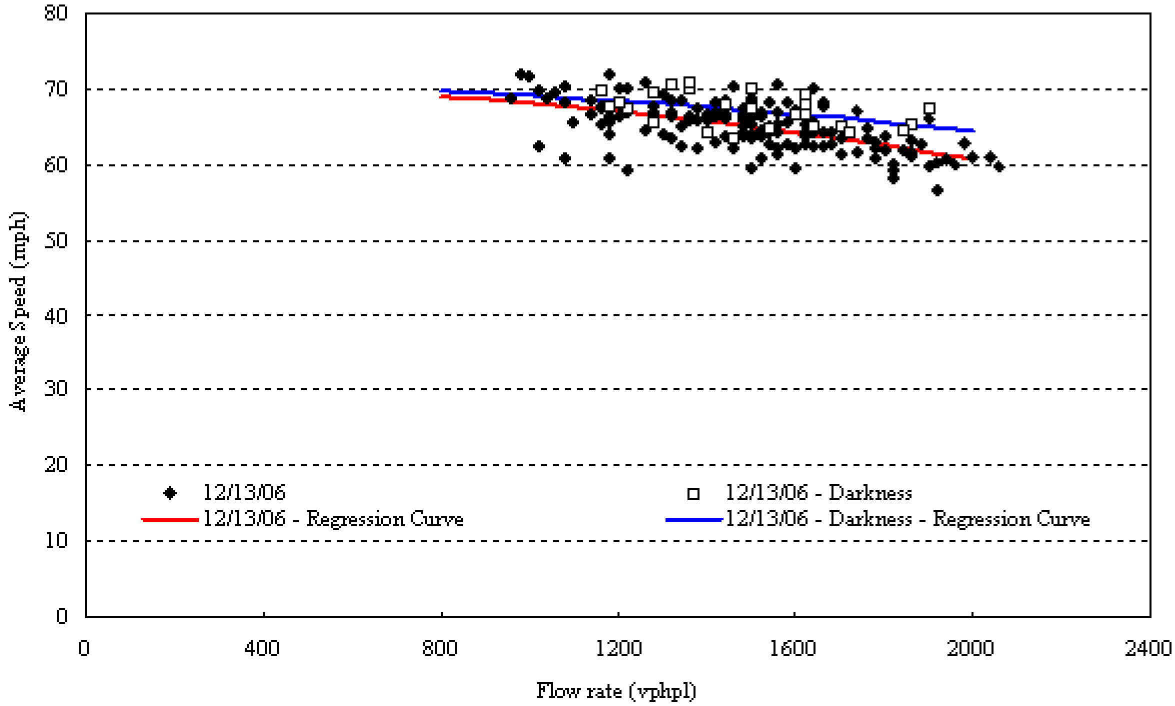


Figure 10. Speed-Flow Curves on I-80 under Normal-Darkness

Table 14. Regression Forms for I-80 – Normal-Darkness

Regression Form	R^2	Regression Equations
Linear	0.21	S= -0.0047F+ 74.2
Quad	0.21	$S = -0.0000016F^2 + 70.6$
Logarithm	0.21	S= -7.08Ln(F) + 118.8
Expo	0.21	$S = 74.5e^{-0.00007F}$

Figure 11 shows the speed-flow models for two rain-darkness conditions. Under a rain intensity of 0.03 in/hr, the speed range is 17.2 mi/hr with a minimum speed 54.9 and a maximum speed 72.5 mi/hr. Under a rain intensity of 0.21 in/hr, the speed range is 7.4 mi/hr with a minimum speed 51.8 and a maximum speed 59.2 mi/hr. The flow rate range is between 920 and 2020 veh/hr/ln with a difference of 1100 veh/hr/ln for a 0.02 in/hr rain intensity and the flow range is between 1040 and 2020 veh/hr/ln with a difference is 980 veh/hr/ln when the rain intensity is 0.20 in/hr. Table 15 shows that the R^2 and the coefficients of the linear, quadratic, logarithm, and exponential regression curve. The table shows that for speed-flow models, the data for 4/16/2007 provided a better fit than the data for 10/25/2007.

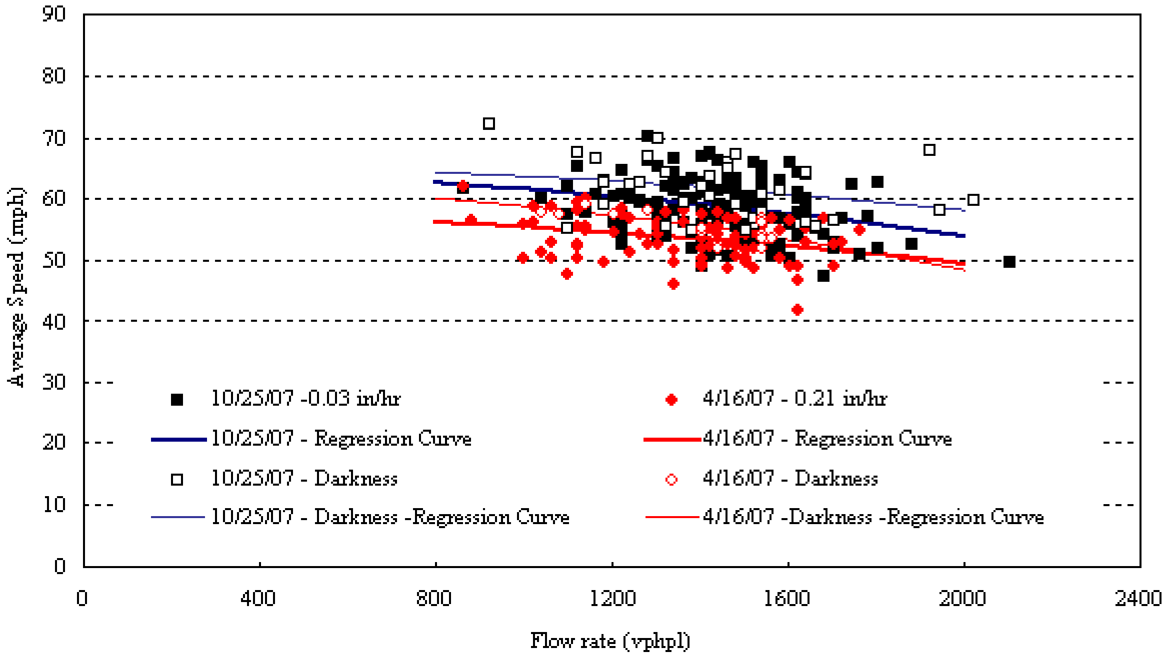


Figure 11. Speed-Flow Curves on I-80 under Rain-Darkness

Table 15. Regression Forms for I-80 – Rain-Darkness

Regression Form	Date M/D/Y	R^2	Regression Equations
Linear	10/25/07	0.09	S= -0.0062F+ 70.5
	04/16/07	0.54	S= -0.0090F+ 67.9
Quad	10/25/07	0.09	$S = -0.0000019F^2 + 65$
	04/16/07	0.54	$S = -0.0000034F^2 + 62.1$
Logarithm	10/25/07	0.11	S= -9.7Ln(F) + 132.4
	04/16/07	0.54	S= -11.7Ln(F) + 140.4
Expo	10/25/07	0.09	$S= 70.6e^{-0.0001F}$
	04/16/07	0.53	$S= 69.3e^{-0.0002F}$

Figure 12 shows the speed-flow model for snow-darkness conditions on I-80 when the snow intensity is 0.03 in/hr. The speed range is 17.4 mi/hr with a minimum speed of 39.8 and a maximum speed 57.2 mi/hr when the snow intensity is 0.03 in/hr. The flow rate range is between 260 and 820 veh/hr/ln with a difference of 560 veh/hr/ln when the snow intensity is 0.03 in/hr. Figure 12 shows the speed-flow relationships using a logarithm regression curve because the R^2 of logarithm regression curve is greater than the R^2 of the linear, logarithm, and exponential regression curve. Table 16 shows that the R^2 and the coefficients of the linear, quadratic, logarithm, and exponential regression curve.

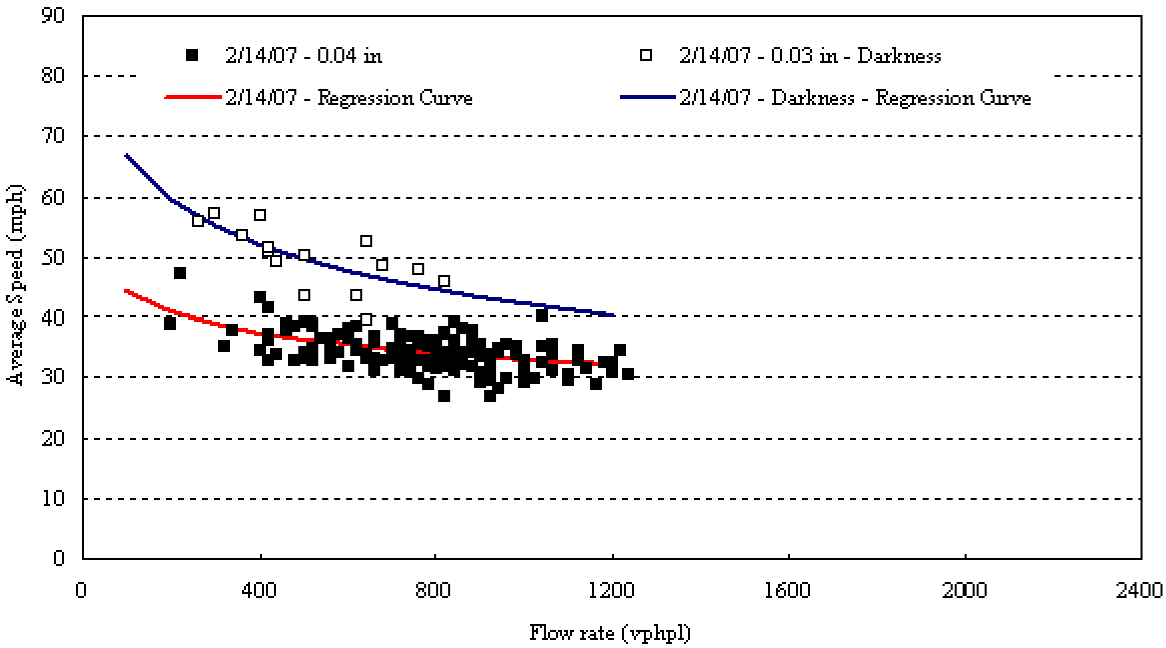


Figure 12. Speed-Flow Curves on I-80 under Snow-Darkness

Table 16. Regression Forms for I-80 – Snow-Darkness

Regression Form	R^2	Regression Equations
Linear	0.44	S= -0.020F+ 60.4
Quad	0.03	$S = -0.000001F^2+37.5$
Logarithm	0.50	S= -10.7Ln(F) + 116.2
Expo	0.42	$S= 61.3e^{-0.0004F}$

Speed-Flow Model under Sunglare

Figure 13 shows the speed-flow relationship under sunglare and normal conditions. The speed range is 11.1 mi/hr with a minimum speed 49.8 and a maximum speed 60.9 mi/hr under sunglare conditions. Under normal conditions the speed range is 12.8 mi/hr with a minimum speed 58.4 and a maximum speed 71.2 mi/hr under normal conditions. The flow rate range is between 1320 and 2120 veh/hr/ln with a difference of 800 veh/hr/ln under sunglare conditions. Under normal conditions, the flow rate range is between 900 and 2220 veh/hr/ln with a difference is 1320 veh/hr/ln. Figure 13 shows the speed-flow relationships using a logarithm regression curve. The logarithm curve had the largest R^2 compared to the linear, logarithm, and exponential regression curve as shown in Table 17.

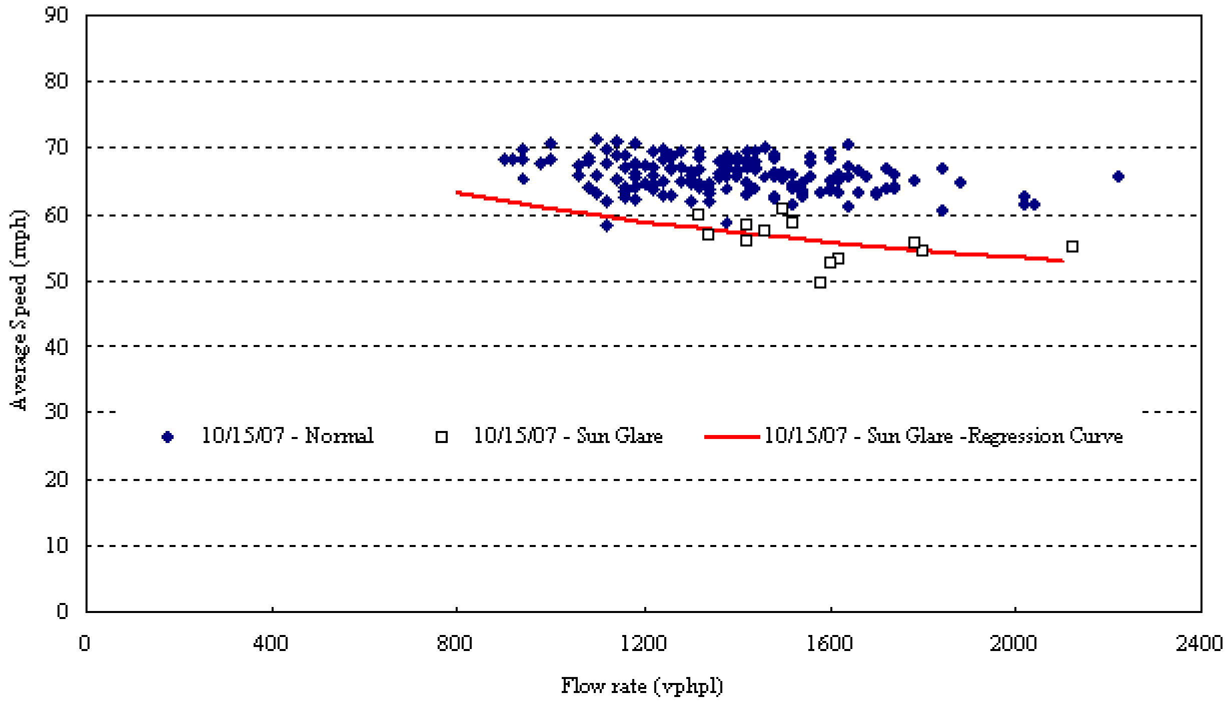


Figure 13. Speed-Flow Curves on I-80 under Sunglare

Table 17. Regression Forms for I-80 – Sunglare

Regression Form	R^2	Regression Equations
Linear	0.17	S= -0.0062F+ 66
Quad	0.15	$S = -0.0000017F^2+61$
Logarithm	0.19	S= -10.6Ln(F) + 134
Expo	0.16	$S= 66.3e^{-0.0001F}$

Results and Findings

The objective of the research was to identify the impacts of adverse weather conditions on traffic parameters. The weather conditions considered for study included rain, snow, darkness and sunglare. The study results are summarized below:

- The goal of the study was to gather two days of data at each location and under each weather condition. In general, there were small differences between the average speeds for the two days of data.

- Under rain conditions, the reduced speeds range from 0.82 mi/hr to 37 mi/hr. The rain impact was found to not only be a function of the rain intensity, but also a function of the presence of downstream congestion.

- Under snow conditions, the reduced speeds range from 5.8 mi/hr to 33.8 mi/hr. The research showed that the snow impact is attributed to the snow intensity as well as the snow accumulation and whether the roadway has been plowed.

- Under normal weather and darkness conditions, there is little difference between the speeds for the two days under which data were collected. In general the reduced speeds range from 0.71 mi/hr to 52 mi/hr.

- Under rain and darkness conditions, the reduced speeds generally range from 7.11 mi/hr to 7.14 mi/hr.

- Similarly under snow and darkness conditions, the increased speeds range from 0.19 to 4.9 mi/hr. At one location snow and darkness caused a significant speed reduction of 19.8 mi/hr.

- Under sunglare, the reduced speeds range from 6.6 mi/hr to 20. 6 mi/hr showing that the sunglare impact can be as significant as the rain and snow impact.

The analysis showed that there were also conditions where speeds increased. At NJ 22 speeds increased under rain conditions by 16 mi/hr. The impact of adverse weather was seen to be a function not only of the rain or snow intensity, but also a function of the roadway condition. Wet roadways or snow covered roadways had a greater impact on traffic conditions, than the intensity of the rain or snow. These results can be used also to adjust transit schedules during adverse weather conditions.

It was found that the drivers tended to leave themselves longer time (e.g. increased time based headway) to react potential brakes downstream. In addition, the time headway under the snow is longer than that under the rain, which can be observed in Table 10.

Table 18. Impact of Speed Comparisons under Rain and Snow (Unit: mi/hr)

		I-80		NJ3		US 46		I-78		NJ 22	
		Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Speed (mi/hr)	Rain Impact	-8.56 to -13.64	1.09 to 6.93	-12.05 to -21.45	1.96 to 0.81	-37.33 to -12.38	4.51 to 9.91	-0.82 to -5.43	0.45 to -0.88	16.24 to -16.91	1.62 to -3.24
	Snow Impact	-33.04 to -18.83	-0.94 to 1.29	-22.91	3.22	-30.53 to -25.09	-0.32 to 3.91	-15.50 to -14.11	1.54 to 6.80	-5.80	-2.42
Density (veh/mi/ln)	Rain Impact	3.64 to 4.16	-0.23 to 0.29	10.07 to 14.10	2.36 to 2.06	41.84 to 16.14	9.28 to 15.40	-1.92 to -2.17	-0.75 to -0.72	-16.97 to 6.29	-6.75 to -1.81
	Snow Impact	1.86 to -7.38	2.72 to 1.25	3.66	6.21	6.01 to 4.22	3.68 to 3.32	-3.94 to -1.20	-0.17 to -0.12	2.67 to -16.97	-3.29 to -6.75
Flow (veh/hr/ln)	Rain Impact	-67 to -347		160 to -200		-60 to 380		-335 to -410		-345 to -615	
	Snow Impact	-867 to -847		-640		-340 to -260		-650 to -515		-15	

TRANSIT OPERATION UNDER ADVERSE WEATHER

The relationship between bus travel time and weather conditions was investigated and discussed in this section. The discussion started by introducing the available data sources, methodology adopted for bus travel time collection and processing. The results are concluded at the end of this section.

Methodology

The weather and bus APC data were collected to investigate the variation of bus travel time under adverse weather. The results can be used to understand the impact of weather to transit schedule adherence and delay, and maybe applied to improve the transit schedule.

<u>Data Collection Plan</u>

APC Data

Bus Route 62 of NJ Transit operating in Essex, Union and Middlesex counties in New Jersey was selected as the study route for this project. Eight buses running along this route were equipped with APC devices and NJ Transit provided the scheduled arrival times on the timetable. Bus service is provided both inbound and outbound for the studied OD pair between Newark's Penn Station and Woodbridge Center Mall. The APC data was collected consecutively from 4 quarters (e.g., January, April, June, and September) in 2002. In this study, the January Pick (from January to April) in 2002 was retrieved from the APC database by NJ Transit. All attributes in each APC record that might be related to this project are summarized in Table 19.

Weather Data

Hourly weather information was obtained from the National Climatic Data Center (NCDC) website which provides historic weather information at selected locations. The Newark International Airport Station in NJ was selected as the observation station because it is the closest the study route. The weather information includes weather type (e.g., normal, rain, snow), hourly temperature (e.g., dry bulb temperature), precipitation (e.g., rainfall and snowfall), and sky conditions (e.g., visibility and wind speed). The attributes of the data available from NCDC are listed in Table 20. Only the weather type variable was used for the statistical analyses in this study.

Table 19. APC Data

Variable	Description
Sched. Run Time	Scheduled run time of the bus in the entire trip
Actual Run Time	Actual run time of the bus trip
Sched. Start	Scheduled start time of the trip
Sched. End	Scheduled end time of the trip
Actual Start	Actual start time of the trip
Actual End	Scheduled end time of the trip
Time Of Day	Starting time of the trip
Transit Day	Date of the service
Open Time	Recorded bus door opening time
Close Time	Recorded bus door closing time
Stop Description	Stop description
Stop Sequence	A unique number attached to all intended stops along the route. It has a value of 10 at the origin and increases in increments of 10 for subsequent stops.
Time Point ID	Time Point indicator number
Direction	Service direction (Inbound or Outbound)
Trip Status	Trip status (Start or End)
Lat.	Latitude
Long.	Longitude
On	Number of boarding passengers at a stop
Off	Number of alighting passengers at a stop
Stop Distance	Travel distance between two consecutive stops
Dwell Time	The bus door open time at any particular time-point. They are derived from the original data as, the cumulative time that the vehicle halted at all intermediate stops.
Leave Psgr Load	Number of onboard passengers when the bus leaves a stop
Arrive Psgr Load	Number of onboard passengers when the bus arrives a stop
Leg Time	Inter-stop travel time. The difference of door open time at a subject stop and door close time at previous stop.
Origin	Origin of the trip
Destination	Destination of the trip
Pattern ID	4-digit number associated with each pattern in each pick data file.
Trip Index	Unique index associated with a trip

Table 20. Weather Data Provided by NCDC

Date	Time	Station Type	Maintenance indicator	Sky Condition
Precip.Total	Visibility	Weather Type	Dry Bulb Temp (F)	Dew Point Temp (F)

Selection of Study Sections

Bus Route 62 starts from Newark's Penn Station and ends at Perth Amboy, traveling a total distance of 29.5 miles. There are 17 major stops or Time Points (TPs) along the bus route. The first 6 of these TPs were selected to be included in the study as shown in Figure 14. The stops were chosen using sample size considerations, and because they are located within a 10-mile radius of the weather observation station, Newark International Airport Station. The TPs sequence for the studied trips is listed in Tables 21 and 22. Buses attributed to the same trip (e.g., inbound or outbound) serve the same number and sequence of TPs.

Table 21. Sequence of Time Points for Studied Route (Outbound)

Time Point	Location	Distance to Start Point (mi)
1	PENN STATION BUS LANES	0.00
2	BROAD ST & BRANFORD PL	3.77
3	NWK AIRPORT TERM A	7.14
4	NWK AIRPORT TERM B	9.67
5	NWK AIRPORT TERM C	10.81
6	BRAOD ST & JERSEY ST	13.74

Table 22. Sequence of Time Points for Studied Route (Inbound)

Time Point	Location	Distance to Start Point (mi)
1	BRAOD ST & JERSEY ST	0.00
2	NWK AIRPORT TERM A	3.56
3	NWK AIRPORT TERM B	4.00
4	AIRPORT TERM C	4.51
5	BROAD ST & BRANFORD PL NWK	8.40
6	PENN STATION BUS LANES	9.07

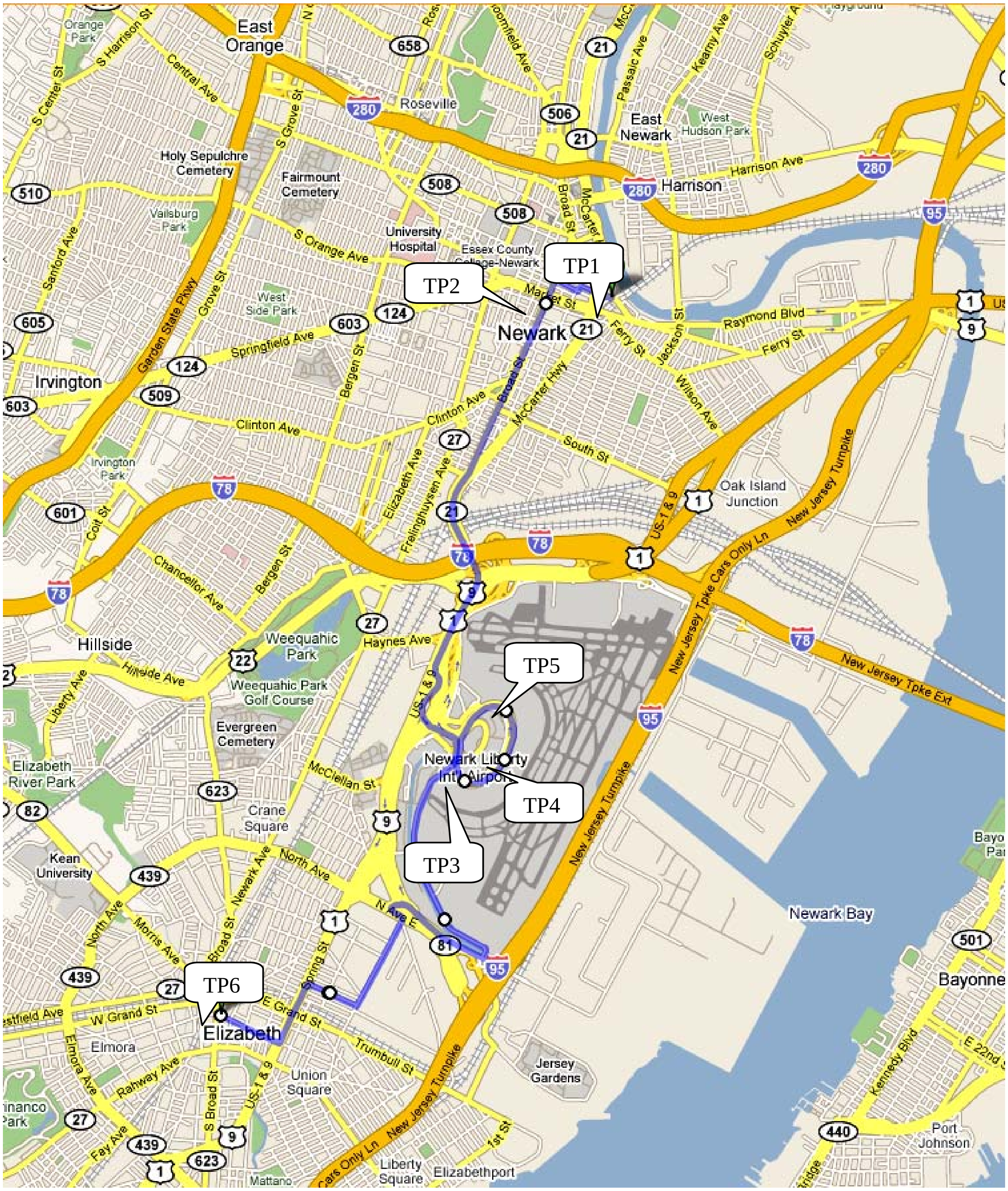


Figure 14. Configuration of Bus Route 62

Data Screening and Processing

There are many items recorded in the APC dataset for each bus trip. Records that were missing or incorrect in the raw data file were identified and removed from the database.

Different problems experienced while processing the APC data and their corresponding solutions are itemized below:

The problems experienced in collected APC data:

a) Duplicate records.
b) Unreasonable arrival times for stops.
c) Inconsistent data (e.g., open vs. close time, scheduled vs. actual running time).
d) Times recorded in different formats (e.g., hour/minute/second, minutes).

The corresponding solutions to the above problems:

a) Delete duplicate records.
b) Use actual arrival times at non-problematic TPs to interpolate the appropriate arrival time at the problematic TPs.
c) Correct the wrong information.
d) Unify the format of all time indices.

After processing the original APC dataset, the weather data need was mapped to the APC dataset for analysis with the use of unique indexes among the two different datasets. For example, "month/date/hour" was used to merge weather data with the APC data, and "month/date/trip/time point ID" was used to calculate data (e.g., travel time between each time point, arrival time difference) with the merged APC weather data. After merging the collected data including the bus arrival times, numbers of boarding and alighting passengers at all TPs, weather information, schedule time, and accumulated dwell times between pairs of TPs, database with weather and schedule information was ready for analysis data.

Data Analysis

As shown in Table 23, the mapped APC weather data was categorized into 3 weather groups, normal (no precipitation), rain, and snow, and two different time periods, peak and off-peak. The heavy traffic volume direction during the peak period was of concern in this study. Vehicles traveling from Broad St. and Jersey St. to Newark's Penn Station (e.g., inbound) during the AM peak period are defined as traveling in the peak traffic direction, while the PM peak direction is out of Newark's Penn Station (e.g., outbound). The peak inbound period is from 6:00 AM to 9:00 AM, and 4:00 PM to 7:00 PM for outbound. More than 80 percent of the data represent normal weather for both inbound and outbound trips.

Table 23. Number of Trips under Different Time Periods and Weather Conditions

Direction	Weather Condition	Peak[1]	Off-peak	Total
TP 1 to TP 6 (Outbound)	Normal	34 (89%)	133 (83%)	167 (84%)
	Rain	2 (5%)	18 (11%)	20 (10%)
	Snow	2 (5%)	9 (6%)	11 (6%)
Total		38	160	198
TP 6 to TP 1 (Inbound)	Normal	29 (97%)	127 (85%)	156 (87%)
	Rain	0 (0%)	14 (9%)	14 (8%)
	Snow	1 (3%)	9 (6%)	10 (6%)
Total		30	150	180

[1]: Peak period outbound from 4:00PM to 7:00PM; Peak period inbound from 6:00 AM to 9:00 AM.

There are no exclusive bus lanes on the study route. The difference between the actual travel time and the scheduled travel time can be calculated by the bus actual arrive time minus the schedule time. Therefore, negative values indicate that the bus arrived earlier than scheduled and positive values show that the bus arrived late.

Figures 15 and 16 show the distribution of the differences between the actual and scheduled arrival times for outbound and inbound trips, respectively. Figure 15 indicates that a greater percentage of buses arrived late when it rained in comparison with snow and normal weather. Also, a relative high percentage of snow condition had a long delay (e.g. arrived 14 mins late) compared to normal and rain. By comparing the three highest percentages under different weather conditions in Figure 16, is obvious that snow causes more delays rain or normal weather. Figure 17 shows the distribution of the differences between the actual and schedules arrival times at each TP.

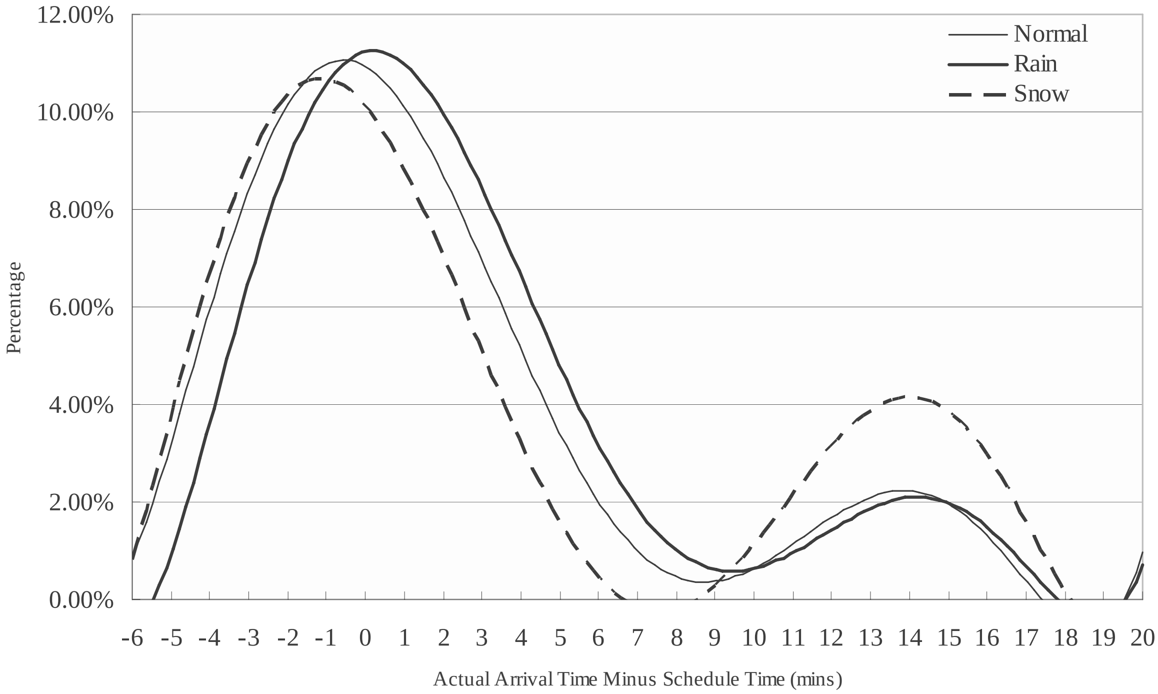


Figure 15. Distribution of the Difference between Actual and Scheduled Arrival Times for Outbound Trips

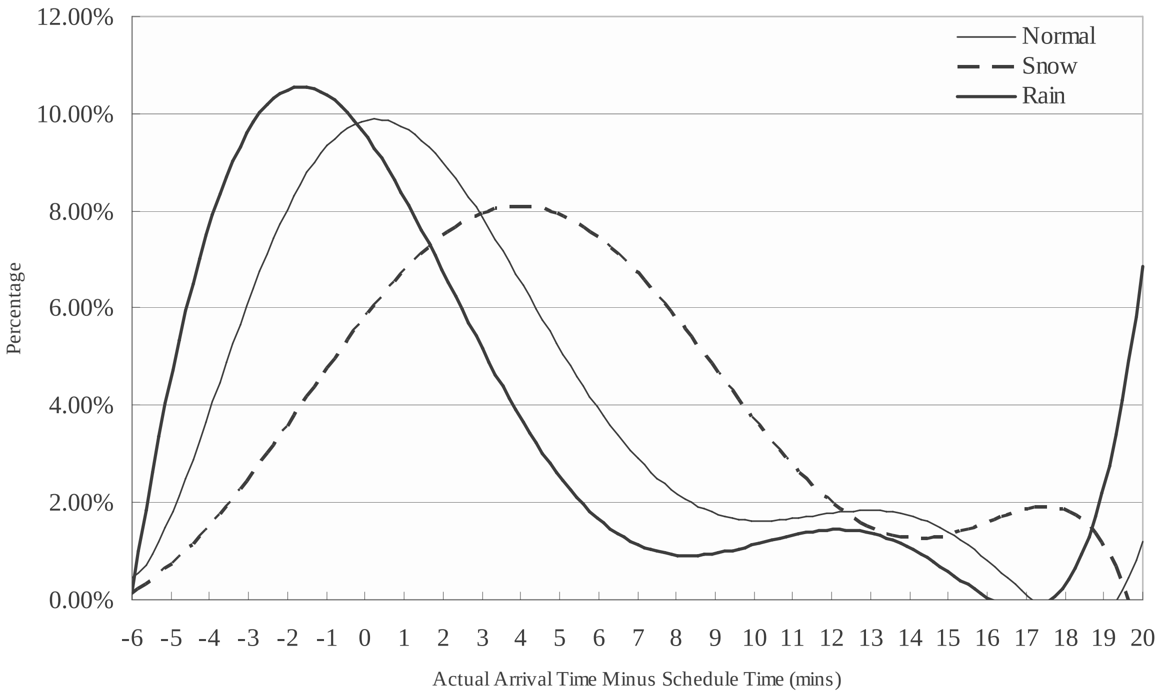
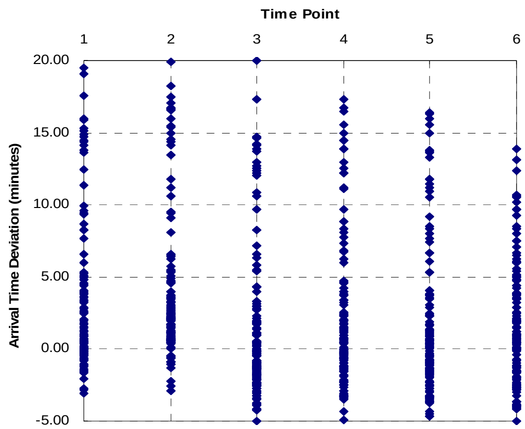
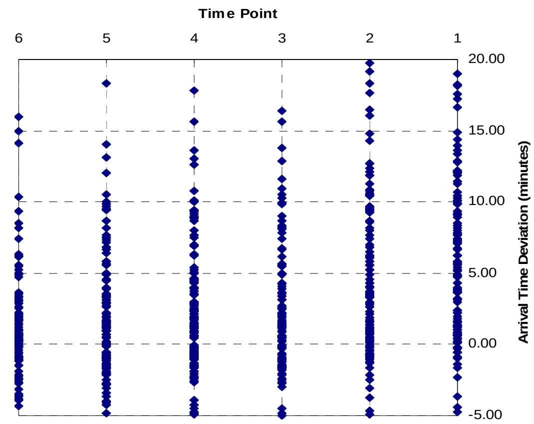


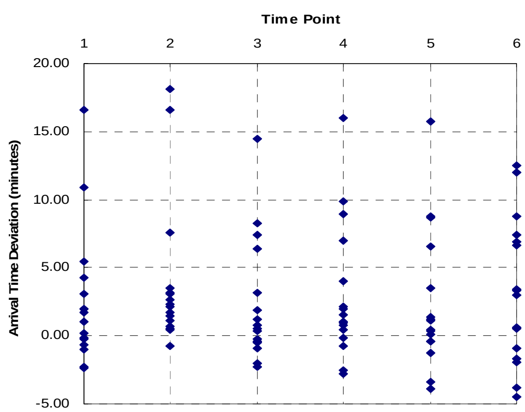
Figure 16. Distribution of the Difference between Actual and Scheduled Arrival Times for Inbound Trips



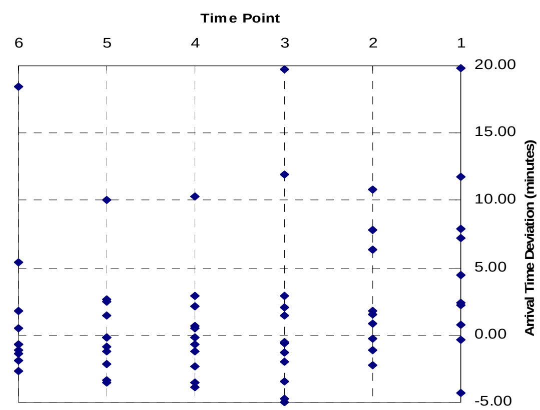
Outbound trip - Normal



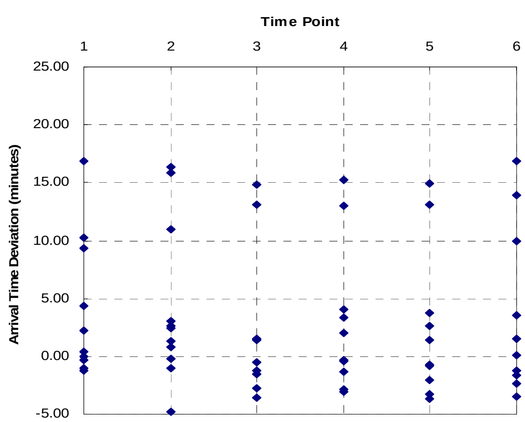
Inbound trip - Normal



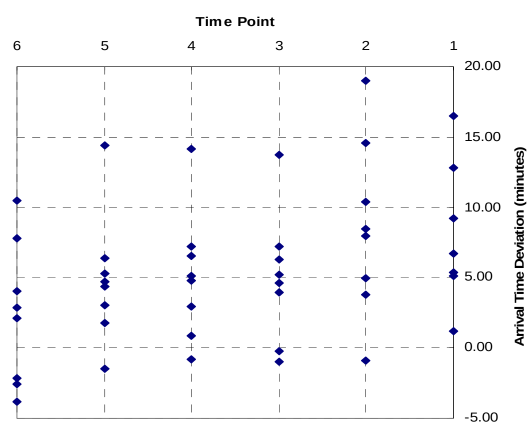
Outbound trip - Rain



Inbound trip - Rain



Outbound trip - Snow



Inbound trip - Snow

Figure 17. Distribution of the Difference between Actual and Scheduled Arrival Times at Each Time Point

The average differences between actual and scheduled time at each TP are shown in Table 24, and the numbers are in minutes. The overall average differences of transit arrival times indicates that in general rain increases total delays by about 40%, while snow may increases them by 80% above what can be expected under normal weather conditions.

Table 24. The Average Differences between Actual and Scheduled Arrival Times at Each Time Points (min)

Outbound	TP1	TP2	TP3	TP4	TP5	TP6	Total
Normal	2.70	3.42	0.96	1.59	1.07	1.17	10.92
Rain	2.02	3.22	1.90	2.43	1.92	2.62	14.10
Snow	3.70	4.75	1.44	2.69	2.28	3.36	18.22
Inbound	**TP6**	**TP5**	**TP4**	**TP3**	**TP2**	**TP1**	**Total**
Normal	1.00	1.43	2.04	1.74	4.11	4.98	15.29
Rain	0.24	2.33	2.29	1.99	5.14	8.15	20.14
Snow	1.88	3.83	4.08	3.25	5.78	7.95	26.77

To study the difference between the actual travel time and scheduled times under different weather conditions (e.g., normal, rain, snow) at each TP, the cumulative travel time of the outbound trip for the entire day is shown in Figure 18. The cumulative travel time was calculated by summing the travel time (e.g. bus door opening time at the current TP minus bus door closing time at the previous TP) and the dwell time from APC data at each TP. One can see that buses leaving late arrival times at the beginning TPs can catch up at later TPs under normal weather. However, the cumulative travel time is hard to be made up under rain. Due to the limited snow records, the cumulative travel time under snow were not shown a result similar to that for rain.

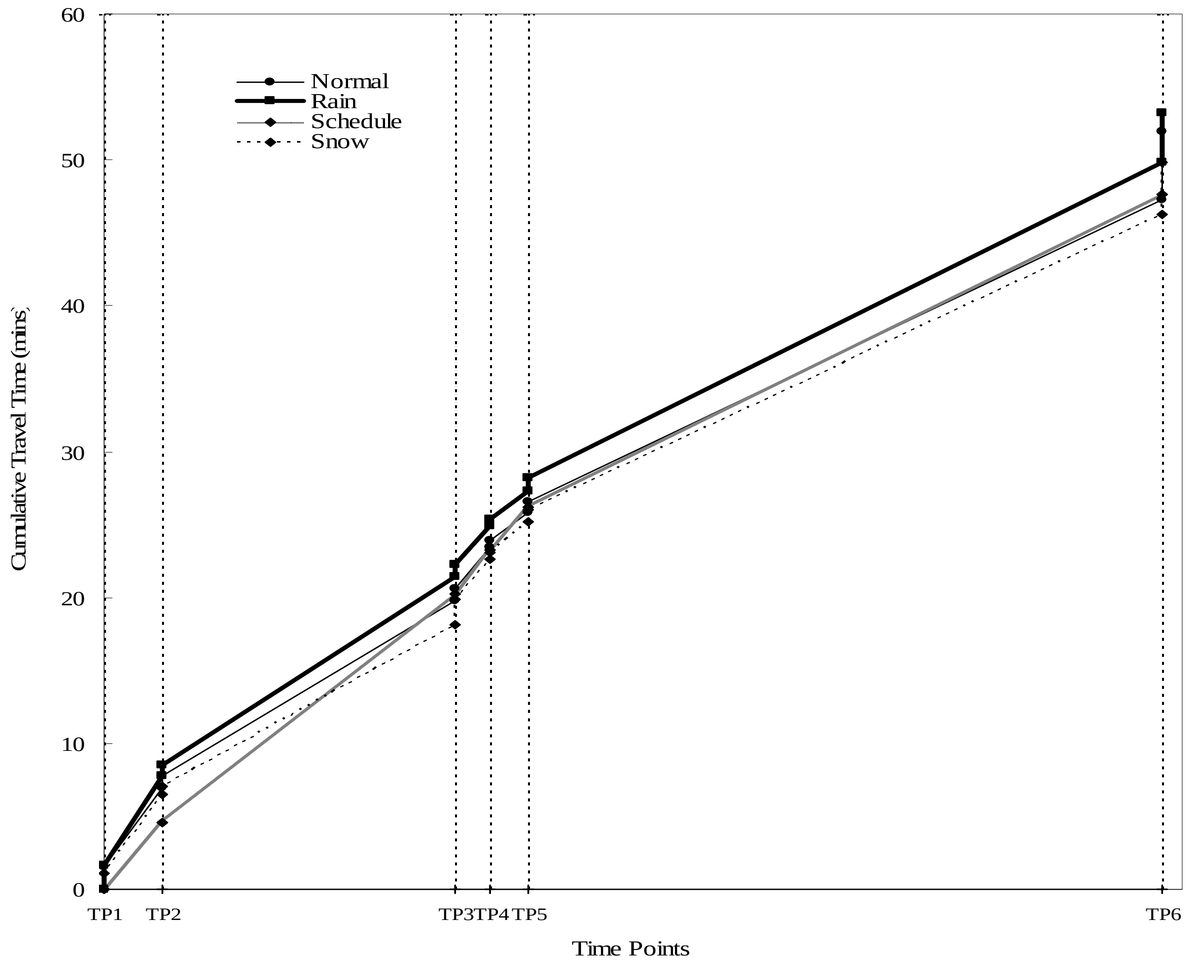


Figure 18. Cumulative Travel Time vs. Distance from Starting Time Point

To further analyze how travel time is impacted by various weather conditions, statistical analysis (e.g., t-test, Levene's test) was used and the results are shown in the following tables. The mean and standard deviation values were calculated to analyze the travel time between each pair of TPs, and the significance level, denoted as the p-value, was used to evaluate the difference of the mean and standard deviation. Tables 25, 26, and 27 compare the results of the outbound trip considering the entire day, just the peak period, and just the off-peak period, all under normal weather, rain and snow. The distances between the TP pairs 3-4 and 4-5 are very close, and the travel times between those points were not considered in the statistical analysis.

To calculate the differences of means for records under different weather conditions, consider the null hypothesis that there is no difference between the population means. Let $\overline{X}_1$ and $\overline{X}_2$ be the sample means obtained from two random samples of sizes, n_1 and n_2, drawn from respective populations having means μ_1 and μ_2, and standard deviations σ_1 and σ_2. To test the null hypothesis that the samples come from the same population (e.g., $\mu_1 = \mu_2$, $\sigma_1 = \sigma_2$), we use the variable given by

$$t = \frac{\overline{X}_1 - \overline{X}_2}{S_{\overline{X}_1 - \overline{X}_2}} \tag{3}$$

where $S_{\overline{X}_1 - \overline{X}_2} = S_P \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$

The distribution of the test statistic is approximated as being an ordinary Student's t distribution with $n_1 + n_2 - 2$ degree of freedom. Note that S_P is a pooled variance which can be calculated by a weighted average, where the weights are the respective degrees of freedom:

$$S_P = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \tag{4}$$

where S_1^2 and S_2^2 are the sample variance calculated from the random samples.

To calculate the variances of two different random samples under various weather conditions, let S_1^2 and S_2^2 be the samle variances from the first and second random samples, respectively. The null hypothesis is assumed two population variances are equal ($\sigma_1^2 = \sigma_2^2$), and the ratio of two sample variances can be calculated by

$$F = \frac{S_1^2 / \sigma_1^2}{S_2^2 / \sigma_2^2} = \frac{S_1^2}{S_2^2} \tag{5}$$

Note that Equation 5 follws F-distribution with $n_1 - 1$ numerator degrees of freedom and $n_2 - 1$ denominator degrees of freedom.

The null hypothesis is that the population means are equal or that their difference is zero (null). If the p-value of the standard deviation is greater than 0.05, the null hypothesis of equal difference is rejected. The p-values of t statistic in Table 25 indicate that the differences of the data for each pair of TP are not quite significant. In Table 24, the p-values of the mean were not all than 0.05 (e.g., 95% confidence interval), which means that there was no significant evidence indicating differences between normal vs. rain and normal vs. snow. The mean travel times between each TP pair under rain were all greater than under normal weather. However, they were relatively close to the snow.

Table 25. Actual Outbound Travel Times under Different Weather Conditions (Entire Day)

	TP 1-2		TP 2-3		TP 5-6	
	Mean (N)	**Stdev (N)**	**Mean (N)**	**Stdev (N)**	**Mean (N)**	**Stdev (N)**
Normal – min	5.45 (167)	2.06 (167)	11.99 (167)	2.24 (167)	20.65 (167)	6.08 (167)
Rain – min	6.17 (20)	2.46 (20)	12.94 (20)	2.92(20)	21.60 (20)	6.69 (20)
Significance (p-value)	0.15	0.13	0.09	0.10	0.51	0.62
Snow – min	5.43 (11)	2.74 (11)	11.09 (11)	3.33 (11)	20.28 (11)	7.09 (11)
Significance (p-value)	0.98	0.13	0.21	0.14	0.85	0.61

N: Number of trips

In Table 26, there was a significant difference between the TP 2-3 pair. One can tell because the p-values of mean for both normal vs. rain and normal vs. snow were less than 0.05. Note that the differences of the data between TP 5-6 were quite significant under different weather conditions. The overall mean travel times under rain and snow were greater than those under normal weather. The number of records was relatively small under rain and snow during the peak period.

Table 26. Actual Outbound Travel Times (Peak Period)

	TP 1-2		TP 2-3		TP 5-6	
	Mean (N)	**Stdev (N)**	**Mean (N)**	**Stdev (N)**	**Mean (N)**	**Stdev (N)**
Normal – min	6.70 (34)	2.95 (34)	12.12 (34)	1.28 (34)	20.57 (34)	5.51 (34)
Rain – min	10.69 (2)	0.04 (2)	9.83 (2)	3.62 (2)	25.02 (2)	0.78 (2)
Significance (p-value)	0.07	0.20	0.03*	0.01*	0.27	1.01E-04*
Snow – min	5.95 (2)	1.63 (2)	7.50 (2)	5.49 (2)	14.48 (2)	0.38 (2)
Significance (p-value)	0.73	0.57	4.59E-05*	2.85E-04*	0.13	5.04E-05*

N: Number of trips
**: The comparison result is significant*

The number of trips with APC data during the off-peak period was greater than that during the peak period. In Table 27, the mean travel times under rain and snow were all greater than that under normal weather condition. However, the difference of the data for each TP was not quite significant during the off-peak period for all weather conditions, except for the comparison between normal weather vs. snow at TP1-2.

Table 27. Actual Outbound Travel Times (Off-Peak Period)

	TP 1-2		TP 2-3		TP 5-6	
	Mean (N)	Stdev (N)	Mean (N)	Stdev (N)	Mean (N)	Stdev (N)
Normal – min	5.13 (133)	1.63 (133)	11.96 (133)	2.43 (133)	20.67 (133)	6.23 (133)
Rain – min	5.67 (18)	2.03 (18)	13.28 (18)	2.74 (18)	21.22 (18)	6.96 (18)
Significance (p-value)	0.21	0.19	0.03*	0.48	0.73	0.52
Snow – min	5.32 (9)	3.00 (9)	11.99 (9)	2.48 (9)	21.57 (9)	7.25 (9)
Significance (p-value)	0.76	3.89E-03*	0.93	0.68	0.68	0.60

N: Number of trips
**: The comparison result is significant*

Tables 28, 29, and 30 compare the results for the inbound trips considering the entire day, just the peak period, and just the off-peak period, all under normal, rain and snow. The same analyses of the outbound trips were used in the comparisons of the inbound data. The distances between the TP pairs of 5-4 and 4-3 were relatively short and the travel times between those points were not considered in the statistical analysis.

In table 28, the mean travel times under rain and snow were generally greater than or close to those under normal weather. However, there was no significant evidence indicating differences between normal vs. rain and normal vs. snow and no differences of the data for each pair of TP, except for the normal vs. rain between TP 2-1.

Table 28. Actual Inbound Travel Times (Entire Day)

	TP 6-5		TP 3-2		TP 2-1	
	Mean (N)	Stdev (N)	Mean (N)	Stdev (N)	Mean (N)	Stdev (N)
Normal – min	19.16 (156)	7.60 (156)	14.88 (156)	3.78 (156)	4.96 (156)	1.28 (156)
Rain – min	18.19 (14)	6.57 (14)	14.93 (14)	3.71 (14)	6.25 (14)	5.86 (14)
Significance (p-value)	0.64	0.74	0.96	0.47	0.02*	6.85E-06*
Snow – min	22.63 (10)	7.45 (10)	14.82 (10)	2.14 (10)	5.19 (10)	1.20 (10)
Significance (p-value)	0.16	0.97	0.96	0.40	0.57	0.53

N: Number of trips
**: The comparison result is significant*

The numbers of trips were relatively small under snow during the peak period direction, and no records were available under rain in Table 29. Therefore, an analysis of the difference from the data under different weather conditions was not possible.

The results in Table 30 were similar to the trend in Table 27 with greater travel times under rain and snow for each pair of TPs. However, there were no significant differences between normal vs. rain and normal vs. snow. The differences of the data for each pair of TPs were not significant during the off-peak period, except for the normal vs. rain at TP 2-1.

Table 29. Actual Inbound Travel Times (Peak Period)

	TP 6-5		TP 3-2		TP 2-1	
	Mean (N)	**Stdev (N)**	**Mean (N)**	**Stdev (N)**	**Mean (N)**	**Stdev (N)**
Normal – min	17.82 (29)	7.12 (29)	15.97 (29)	3.47 (29)	5.33 (29)	1.34 (29)
Rain – min	NA	NA	NA	NA	NA	NA
Significance (p-value)	NA	NA	NA	NA	NA	NA
Snow – min	10.55 (1)	NA	10.55 (1)	NA	5.30 (1)	NA
Significance (p-value)	0.32	NA	0.62	NA	0.98	NA

N: Number of trips

Table 30. Actual Inbound Travel Times (Off-Peak Period)

	TP 6-5		TP 3-2		TP 2-1	
	Mean (N)	**Stdev (N)**	**Mean (N)**	**Stdev (N)**	**Mean (N)**	**Stdev (N)**
Normal – min	19.47 (127)	7.70 (127)	14.63 (127)	3.82 (127)	4.87 (127)	1.25 (127)
Rain – min	18.19 (14)	6.57 (14)	14.93 (14)	3.71 (14)	6.25 (14)	5.86 (14)
Significance (p-value)	*0.55*	*0.81*	*0.78*	*0.42*	*0.02**	*2.68E-05**
Snow – min	23.97 (9)	6.49 (9)	14.50 (9)	1.99 (9)	5.18 (9)	1.27 (9)
Significance (p-value)	*0.09*	*0.56*	*0.92*	*0.32*	*0.48*	*0.90*

N: Number of trips
**: The comparison result is significant*

Results and Findings

In this study, NJ Transit's APC data was used to analyze the differences between scheduled and actual travel times under different weather conditions. Though there were some inconsistent records in the APC data, the APC unit has demonstrated its effectiveness to collect detailed bus operational information (e.g., open/close time, dwell time, etc). The data and the procedure discussed in this study (e.g., weather information, actual travel times between each pair of TPs, schedule time at TPs) can generate accurate information for data analyses.

After evaluating the bus travel time from the collected APC data, it was shown that buses operating with late arrival times at the beginning TPs can catch up at later TPs under normal weather condition. However, the cumulative travel time could be hard to catch up to under rain. The mean travel times between each pair of TPs under rain were generally greater than under normal weather. The significance level or p-values generated in the statistical analyses showed that the differences of the travel time means for each pair of TPs are not quite significant in most situations. A reason for this result could be the fact that the number of trips under adverse weather was very small.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The potential applications of the study results will help in exploring the weather impact on speed, density, headway, and capacity on different type of roadways and transit travel time and schedule adherence. The immediate extensions of this research include but are not limited to (1) estimating delay and travel time to assist the public in making decisions on when to travel and by what route or mode under adverse weather; (2) incorporating the estimated delay and potential congested locations due to adverse weather and developing network-wide adaptive traffic control strategies; and (3) assessing the operational performance and identifying bottlenecks of existing transportation infrastructure under adverse weather.

The areas of further research include:

- Use GIS to develop models based on seasonal variations in sun direction and the impact of sunglare on drivers at select New Jersey roadways.
- Although over 80 hours of data were collected in this research, more data is needed at each location in order to isolate weather impacts that are free from daily and seasonal variation in traffic patterns.
- The collected data and the speed-flow models developed suggest that it may be possible to use the data to implement advanced traveler information systems where drivers are informed of expected travel times as they travel.
- Autoscope was the primary data collection tool used in this research. The limitations of autoscope, as used, are the need to capture video data. The video data proved to be difficult to capture in the absence of an existing overpass at the location of study. To capture more data, further research is needed to determine the potential use of alternative data collection methods including road traffic microwave sensors (RTMS).
- The data indicate speed and flow patterns, as well as bus travel times, differ under adverse weather conditions. Using the data collected, more research is needed to provide NJ Transit with information how to adjust bus transit schedules and provide passengers with accurate information.
- The collected data indicate the impact of adverse weather on driving behavior. More data should be collected in order to quantify that impact on vehicle headways for various traffic volumes and types of roadways.
- The transit data used in the research were limited to certain types of roadways. More research is needed to identify the impacts of adverse weather on transit for a variety of roadway types not currently studied in this research.
- The impact of adverse weather on bus dwell times could be determined.

- A more intensive data collection effort and analysis may determine bus driver behavior under adverse weather conditions.

- A detailed analysis based on a significantly greater amount of data may identify locations or route segments that are susceptible to congestion or incidents only under adverse weather conditions.

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APPENDIX-A

Table A-1. Summary of Traffic Stream Parameters for Study Locations

Weather Condition	I-80			NJ 3			US 46			I-78			NJ 22		
	Speed[2]	Density[3]	Flow[4]	Speed[2]	Density[3]	Flow[4]	Speed[2]	Density[3]	Flow[4]	Speed[2]	Density[3]	Flow[4]	Speed[2]	Density[3]	Flow[4]
Normal (Day 1)	64.90	23.11	2060	62.71	23.39	2240	58.66	22.11	2000	73.56	15.32	1720	36.61	47.08	2370
Normal (Day 2)	71.34	18.99	2040	61.93	24.04	2000	63.48	15.60	1600	75.86	15.88	1680	43.08	36.30	1980
Normal (Day 3)	65.86	21.12	2220		-	-		-	-		-	-		-	-
Average	**67.37**	**21.07**	**2170**	**62.32**	**23.71**	**2120**	**61.07**	**18.85**	**1800**	**74.71**	**15.60**	**1700**	**39.85**	**41.69**	**2175**
Rain (Day 1)	58.81	24.71	2040	50.27	33.79	2280	23.74	60.69	1740	73.88	13.68	1365	56.09	24.72	1830
Intensity (in/hr)		0.02			0.02			0.09			0.01			0.02	
Rain Impact	**-9.31**	**3.64**	**-67**	**-12.05**	**10.07**	**160**	**-37.33**	**41.84**	**-60**	**-0.82**	**-1.92**	**-335**	**16.24**	**-16.97**	**-345**
Rain (Day 2)	53.73	25.23	1760	40.87	37.81	1920	48.69	34.99	2180	69.28	13.43	1290	22.94	47.98	1560
Intensity (in/hr)		0.21			0.15			0.02			0.02			0.07	
Rain Impact[1]	**-14.39**	**4.16**	**-347**	**-21.45**	**14.10**	**-200**	**-12.38**	**16.14**	**380**	**-5.43**	**-2.17**	**-410**	**-16.91**	**6.29**	**-615**
Snow (Day 1)	34.33	22.93	1240	39.41	27.38	1480	30.54	24.86	1460	59.21	11.66	1050	34.04	44.36	2160
Intensity (in/hr)		0.04			0.05			Trace			0.02			0.07	
Snow Impact[1]	**-33.79**	**1.86**	**-867**	**-22.91**	**3.66**	**-640**	**-30.53**	**6.01**	**-340**	**-15.50**	**-3.94**	**-650**	**-5.80**	**2.67**	**-15**
Snow (Day 2)	48.54	13.70	1260	-	-	-	35.98	23.07	1540	60.59	14.41	1185	-	-	-
Intensity (in/hr)		0.05			-			0.05			0.07			-	
Snow Impact[1]	**-19.58**	**-7.38**	**-847**	**-**	**-**	**-**	**-25.09**	**4.22**	**-260**	**-14.11**	**-1.20**	**-515**	**-**	**-**	**-**

1 Difference between the average normal condition and the rain/snow data.
2: mi/hr, 3: veh/mi/lane, 4: veh/hr/ln

Table A-2. Speed Comparisons under Darkness and Sunglare Conditions (Unit: mi/hr)

	I-80		NJ3		US 46		I-78		NJ22	
	Avg	Std. Dev.	Avg	Std. Dev	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Normal-Darkness (1)	67.19	2.24	61.64	1.96	59.75	2.74	-	-	40.31	4.28
Difference [2]	2.29	-0.82	-1.07	-0.40	1.09	0.09	-	-	3.70	-0.94
Normal-Darkness (2)	66.19	4.24	61.21	2.16	62.77	2.85	72.88	2.40	39.43	5.41
Difference [2]	-5.15	-0.54	-0.72	-0.30	-0.71	-0.75	-2.97	-1.06	-3.65	0.22
Rain-Darkness (1)	61.47	4.82	43.14	2.90	64.20	3.36	66.77	4.32	56.26	4.94
Intensity (in/hr)	0.04	0.04	0.22	0.22	0.06	0.06	0.11	0.11	0.05	0.05
Difference [2]	2.66	0.26	-7.14	-1.47	15.51	-9.68	-7.11	1.07	0.17	-1.88
Rain-Darkness (2)	55.31	9.17	-	-	-	-	61.01	5.05	-	-
Intensity (in/hr)	0.16	0.16	-	-	-	-	0.01	0.01	-	-
Difference [2]	1.58	-1.23	-	-	-	-	1.80	0.72	-	-
Snow-Darkness (1)	36.77	2.3	39.60	4.73	39.23	2.70	62.25	4.42	38.97	3.77
Intensity (in/hr)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03
Difference [2]	2.4	-0.68	0.19	-0.90	3.24	-4.33	3.04	0.08	4.93	0.99
Snow-Darkness (2)	-	-	-	-	-	-	40.80	6.97	-	-
Intensity (in/hr)	-	-	-	-	-	-	0.07	0.07	-	-
Difference [2]	-	-	-	-	-	-	-19.80	-2.63	-	-
Sunglare	57.01	3.50	-	-	-	-	68.13	2.07	19.25	4.68

2 Difference between the rain/snow data for the same date under light conditions and the rain/snow data under darkness.

Table A-3. Impact of Speed Comparisons under Rain and Snow (Unit: mi/hr)

		I-80		NJ3		US 46		I-78		NJ 22	
		Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Speed (mi/hr)	Rain Impact	-8.56 to -13.64	1.09 to 6.93	-12.05 to -21.45	1.96 to 0.81	-37.33 to -12.38	4.51 to 9.91	-0.82 to -5.43	0.45 to -0.88	16.24 to -16.91	1.62 to -3.24
	Snow Impact	-33.04 to -18.83	-0.94 to 1.29	-22.91	3.22	-30.53 to -25.09	-0.32 to 3.91	-15.50 to -14.11	1.54 to 6.80	-5.80	-2.42
Density (veh/mi/ln)	Rain Impact	3.64 to 4.16	-0.23 to 0.29	10.07 to 14.10	2.36 to 2.06	41.84 to 16.14	9.28 to 15.40	-1.92 to -2.17	-0.75 to -0.72	-16.97 to 6.29	-6.75 to -1.81
	Snow Impact	1.86 to -7.38	2.72 to 1.25	3.66	6.21	6.01 to 4.22	3.68 to 3.32	-3.94 to -1.20	-0.17 to -0.12	2.67 to -16.97	-3.29 to -6.75
Flow (veh/hr/ln)	Rain Impact	-67 to -347		160 to -200		-60 to 380		-335 to -410		-345 to -615	
	Snow Impact	-867 to -847		-640		-340 to -260		-650 to -515		-15	

Table A-4. Summary of Density Data for Study Locations (Unit: veh/mi/ln)

	I-80		NJ3		US 46		I-78		NJ22	
	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Normal (Day 1)	23.11	4.61	23.39	4.32	22.11	5.70	15.32	3.72	47.08	15.65
Normal (Day 2)	18.99	4.70	24.04	4.11	15.60	4.08	15.88	3.10	36.30	10.04
Normal (Day 3)	21.12	4.02	-	-	-	-	-	-	-	-
Average	**21.07**	**4.44**	**23.71**	**4.22**	**18.85**	**4.89**	**15.60**	**3.41**	**41.69**	**12.84**
Rain (Day 1)	24.71	4.21	33.79	6.58	60.69	14.17	13.68	2.65	24.72	6.10
Intensity (in/hr)	0.02	0.02	0.02	0.02	0.09	0.09	0.01	0.01	0.02	0.02
Rain Impact [1]	**3.64**	**-0.23**	**10.07**	**2.36**	**41.84**	**9.28**	**-1.92**	**-0.75**	**-16.97**	**-6.75**
Rain (Day 2)	25.23	4.73	37.81	6.27	34.99	20.29	13.43	2.69	47.98	11.03
Intensity (in/hr)	0.21	0.21	0.15	0.15	0.02	0.02	0.02	0.02	0.07	0.07
Rain Impact [1]	**4.16**	**0.29**	**14.10**	**2.06**	**16.14**	**15.40**	**-2.17**	**-0.72**	**6.29**	**-1.81**
Snow (Day 1)	22.93	7.16	27.38	10.43	24.86	8.57	11.66	3.24	44.36	9.55
Intensity (in/hr)	0.04	0.04	0.05	0.05	Trace	Trace	0.02	0.02	0.07	0.07
Snow Impact [1]	**1.86**	**2.72**	**3.66**	**6.21**	**6.01**	**3.68**	**-3.94**	**-0.17**	**2.67**	**-3.29**
Snow (Day 2)	13.70	5.69	-	-	23.07	8.21	14.41	3.29	-	-
Intensity (in/hr)	0.05	0.04	-	-	0.05	0.05	0.07	0.07	-	-
Snow Impact [1]	**-7.38**	**1.25**	**-**	**-**	**4.22**	**3.32**	**-1.20**	**-0.12**	**-**	**-**

1 Difference between the average normal condition and the rain/snow data.

Table A-5. Density Comparisons under Darkness and Sunglare Conditions (Unit: veh/mi/ln)

	I-80		NJ3		US 46		I-78		NJ22	
	Avg	Std. Dev.	Avg	Std. Dev	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Normal-Darkness (1)	22.16	3.64	27.10	5.26	20.24	4.31	-	-	34.70	12.35
Difference [2]	-0.95	-0.97	3.71	0.93	-1.87	-1.39	-	-	-12.38	-3.30
Normal-Darkness (2)	22.67	4.53	27.68	3.86	20.12	3.15	14.77	2.65	44.76	11.53
Difference [2]	3.68	-0.17	3.64	-0.25	4.52	-0.93	-1.12	-0.45	8.46	1.48
Rain-Darkness (1)	23.66	4.74	35.35	5.22	21.33	4.35	13.11	3.23	24.27	6.89
Intensity (in/hr)	0.04	0.04	0.22	0.22	0.06	0.06	0.11	0.11	0.05	0.05
Difference [2]	-1.05	0.53	1.56	-1.36	-13.66	-15.94	-0.57	0.58	-0.45	0.80
Rain-Darkness (2)	25.65	3.83	-	-	-	-	15.91	3.75	-	-
Intensity (in/hr)	0.16	0.16	-	-	-	-	0.01	0.01	-	-
Difference [2]	0.41	-0.90	-	-	-	-	4.25	0.51	-	-
Snow-Darkness (1)	22.67	6.41	29.12	8.26	25.97	8.56	8.38	3.10	27.89	10.05
Intensity (in/hr)	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03
Difference [2]	-0.27	-0.75	1.74	-2.17	2.91	0.36	-3.28	-0.13	-16.47	0.49
Snow-Darkness (2)	-	-	-	-	-	-	18.12	5.47	-	-
Intensity (in/hr)	-	-	-	-	-	-	0.07	0.07	-	-
Difference [2]	-	-	-	-	-	-	3.72	2.18	-	-
Sunglare	27.67	5.15	-	-	-	-	16.52	3.18	103.73	20.84

2 Difference between the rain/snow data for the same date under light conditions and the rain/snow data under darkness.

Table A-6. Impact of Density Comparisons under Rain and Snow (Unit: veh/mi)

	I-80		NJ3		US 46		I-78		NJ 22	
	Avg	Std. Dev.	Avg	Std. Dev	Avg	Std. Dev.	Avg	Std. Dev.	Avg	Std. Dev.
Rain Impact	3.64 to 4.16	-0.23 to 0.29	10.07 to 14.10	2.36 to 2.06	41.84 to 16.14	9.28 to 15.40	-1.92 to -2.17	-0.75 to -0.72	-16.97 to 6.29	-6.75 to -1.81
Snow Impact	1.86 to -7.38	2.72 to 1.25	3.66	6.21	6.01 to 4.22	3.68 to 3.32	-3.94 to -1.20	-0.17 to -0.12	2.67 to -16.97	-3.29 to -6.75

Table A-7. Maximum Observed Flow Rate Comparisons under Normal, Rain, Snow(Unit: veh/hr/ln)

	I-80	NJ3	US 46	I-78	NJ22
Normal (1)	2060	2240	2000	1720	2370
Normal (2)	2040	2000	1600	1680	1980
Normal (3)	2220	-	-	-	-
Average	2170	2120	1800	1700	2175
Rain(1)	2040	2280	1740	1365	1830
Intensity (in/hr)	0.02	0.02	0.09	0.01	0.02
Difference [1]	-67	160	-60	-335	-345
Rain (2)	1760	1920	2180	1290	1560
Intensity (in/hr)	0.21	0.15	0.02	0.02	0.07
Difference [1]	-347	-200	380	-410	-615
Snow (1)	1240	1480	1460	1050	2160
Intensity (in/hr)	0.04	0.05	Trace	0.02	0.07
Difference [1]	-867	-640	-340	-650	-15
Snow (2)	1260	-	1540	1185	-
Intensity (in/hr)	0.05	-	-	0.07	-
Difference [1]	-847	-	-260	-515	-

1 Difference between the average normal condition and the rain/snow data.

Table A-8. Maximum Observed Flow Rate Comparisons under Darkness and Sunglare Conditions (Unit: veh/hr/ln)

	I-80	NJ3	US 46	I-78	NJ22
Normal-Darkness (1)	1900	2140	1540	-	2280
Difference [2]	-160	-100	-460	-	-90
Normal-Darkness (2)	1820	2020	1660	1425	2280
Difference [2]	-220	20	60	-255	300
Rain-Darkness (1)	2020	1880	1720	1275	1950
Intensity (in/hr)	0.04	0.22	0.06	0.11	0.05
Difference [2]	-20	-400	-460	-90	120
Rain-Darkness (2)	1560	-	-	1395	-
Intensity (in/hr)	0.16	-	-	0.01	-
Difference [2]	-200	-	-	345	-
Snow-Darkness (1)	1240	1440	1560	1395	1860
Intensity (in/hr)	0.03	0.05	0.05	0.05	0.03
Difference [2]	0	-40	20	345	-300
Snow-Darkness (2)	-	-	-	1110	-
Intensity (in/hr)	-	-	-	-75	-
Difference [2]	-	-	-	-	-
Sunglare	2120	-	-	1380	2430

2 Difference between the rain/snow data for the same date under light conditions and the rain/snow data under darkness.

Table A-9. Impact of Maximum Observed Flow Rate Comparisons under Rain and Snow (Unit: veh/hr/ln)

	I-80	NJ3	US 46	I-78	NJ 22
Rain Impact	-67 to -347	160 to -200	-60 to 380	-335 to -410	-345 to -615
Snow Impact	-867 to -847	-640	-340 to -260	-650 to -515	-15