ARTERIAL PERFORMANCE MEASUREMENT

USING TRANSIT BUSES AS PROBE VEHICLES

by

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THESIS APPROVAL

The abstract and thesis of Sutti Tantiyanugulchai for the Master of Science in Civil and Environmental Engineering were presented November 7, 2003, and accepted by the thesis committee and the department.

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ABSTRACT

An abstract of the thesis of Sutti Tantiyanugulchai for the Master of Science in Civil and Environmental Engineering presented November 7, 2003.

Title: Arterial Performance Measurement Using Transit Buses as Probe Vehicles

With increasing data availability due to intelligent transportation systems (ITS) deployments, methods for assessing and reporting traffic characteristics and conditions have begun to shift. While previous level of service (LOS) methods were developed for use with limited data, we now have the power to develop and test the use of more specific performance measures tailored to particular locations. Important measures like average speed, travel time, and intersection delay can be used for performance monitoring of the transportation system. These measures are useful for system management, planning and for users. On freeways, these typical performance measures are often estimated directly using data from inductive loop detectors (e.g., time mean speed, occupancy and vehicle counts). For arterials with numerous signalized intersections and access points, performance measures are more challenging due to more complicated traffic control and many origins and destinations. However, within signalized networks, travel time, speed, and other key performance measures can be obtained both directly and indirectly from sources such as automatic vehicle location (AVL) data.

This thesis examines and tests a system for applying AVL data to characterize the performance of an arterial. First, data are extracted from the bus dispatch system (BDS) of the Tri-County Metropolitan Transit District (TriMet), the transit provider for Portland, Oregon. Then, the performance characteristics as described by bus travel on an arterial are compared with ground truth data collected by probe vehicles equipped with global positioning system (GPS) sensors traveling with normal (non-transit) traffic on the same arterial on the same days. Comparisons are drawn between the two methods and some conclusions are drawn regarding the utility of the transit AVL data.

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1. INTRODUCTION

Throughout the past several decades, traffic engineers, planners, researchers, and transportation agencies have expended much effort trying to understand how freeway systems operate. Several key performance measures such as travel time, average speed and delay have been proposed and tested, along numerous freeway miles, documented in numerous publications. Even though these performance measures can be considered successful in describing freeway performance, we still lack solid methods for the analysis of arterials. This is because arterials are characterized by complicated traffic behavior and many more variables than are associated with freeways. Table 1 shows the percentage of roadways in the U.S. categorized by facility type. As indicated, 11.6% of the U.S. lane mileage is contributed by the arterial network, four times more than the freeway system (FHWA, 2002). In addition, more than 40% of the nation's vehicle miles traveled (VMT) occur on arterials, while only 30% occur on freeways.

Table 1: Percentage of Lane Miles and Vehicle Miles Traveled by Facility Type, 2000

U.S.	Total Lane Miles	% Lane Miles	Total VMT (Million)	% VMT
Freeway	250,873	3.1	845,711	30.7
Arterial	952,218	11.6	1,150,012	41.6
Other	7,036,534	85.4	771,645	27.8
Total	8,239,625	100.1	2,767,368	100.1

This suggests that it is important to focus on the management of traffic on arterial facilities in addition to the current heavy focus on freeways.

1.1 Background and Motivation

Since the beginning of intelligent transportation systems (ITS) deployments, there has been heightened interest in providing performance measures along arterials, both in the context of advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS).

For site-specific arterial performance measurement, traffic conditions are now evaluated using test vehicles to collect travel time and delay data (Oppenlander, 1976). However, these studies of travel time and delay are limited temporally and spatially, time consuming and costly. For traffic engineering studies, test vehicles and personnel may often be dispatched to capture traffic movements and collect travel time data for only one peak period on only one day.

With the increasing implementation of ITS, the floating probe vehicle technique can play an important role as an application designed primarily for collecting data in real time. Floating probe vehicles respond to changes in traffic flow as they traverse the network and can transmit location and travel time data to a traffic management center at frequent time intervals on the order of minutes or seconds (Turner et al., 1998). As in the case of a transit fleet, sometimes these potential probe vehicles are already in the traffic stream.

Most existing transit automatic vehicle location (AVL) systems are used primarily for managing transit operations in real time. In Portland, Oregon, the Tri-County Metropolitan Transportation District of Oregon (TriMet) provides transit service in the metropolitan area. During weekdays, more than 600 TriMet buses run along almost every major arterial during the peak periods (TriMet, 2002). Each of these buses is equipped with a bus dispatch system (BDS) which includes AVL, comprised of differential global positioning systems (GPS), automatic passenger counters on most vehicles, wireless communications, and stop-level data archiving capabilities (Strathman et al., 2001). The BDS provides a rich source of accurate time and location information. Since the buses are already in the traffic stream, they are available to be used for the collection of travel time data as probe vehicles. The BDS records bus arrival and departure times at each geo-coded stop, as well as recording the maximum instantaneous speed achieved between stops. As a result, TriMet, the Oregon Department of Transportation (ODOT), and the City of Portland are developing plans to use BDS data for ATMS and ATIS purposes (ODOT, 2003).

1.2 Objectives

Motivated by the ongoing project aimed at implementing the bus probe project in Portland, Oregon, the objective of this study is to design an experiment to determine the statistical relationships between bus travel time and speed and actual traffic conditions. This is performed by comparing transit bus geo-location data and ground truth data collected by GPS instrumented passenger vehicles. This study focuses on establishing the relationship between bus travel behavior and ground truth traffic conditions in one arterial corridor. The study uses two key performance measures–travel time and speed–and uses a statistical analysis to determine the relationships that exist. As a result, the study validates another possible use of automated vehicle location data and confirms the possibility of using transit as probe vehicles on arterials.

1.3 Literature Review

Early efforts to measure roadway performance focused on the freeway system using stationary equipment, such as inductive loop detectors and closed circuit television (CCTV) cameras. More recent studies have included work using the I-880 freeway database located south of Oakland, California (Kwon et al., 2000). The study used single-loop detectors for estimating future travel times on a freeway and found that a linear regression model is beneficial for short-term forecasts of up to 20 min. Another example is a study using inductive loop detectors on a section of westbound Interstate 4 in Orlando, Florida for predicting recurrent congestion with non-linear time series (D'Angello el al., 1999). By testing several traffic parameters, the study found that speed was the best parameter for calibrating a single travel time model which was feasible for an on-line travel time prediction application.

Two example studies used indirect estimation from loop detectors to predict arterial travel time. The first example is a study on a major urban arterial in Roseville, Minnesota using both floating car and loop detector data together with signal timing plans to identify arterial travel time patterns and to generate a simple arterial travel time model (Zhang, 1999). The study yielded satisfactory estimates of link speeds using critical volume to capacity (V/C) ratio and spot speed when traffic conditions are not severe (speed is less than 25 mph and V/C not near 1). Another example arterial travel time study estimated average vehicle speed using intersection loop detector data from the road network of the Clementi town area in Singapore (Xie et al., 2001). This study focused on the use of loop detector data at signalized intersections. The travel time prediction model needed no calibration when the average speed of moving vehicles was used for a short distance traveled. A good summary of the early work on travel time estimation using loop detector data can be found in Sisiopiku and Rouphail (1994).

With the increasing implementation of ITS, the floating probe technique has evolved and overcome past limitations as a travel time data collection system. Probe vehicles are moving sensors responding to changes in traffic flow as they traverse various links on the network and transmit location and travel time data to a traffic information center at a frequent time interval. Probes provide a great potential for improving the estimation accuracy of traffic conditions, especially where no traffic detectors are installed. An example of travel time studies using probe vehicles including the determination of the number of probes necessary for extracting real-time traffic data for advanced traffic management and information systems (ATMIS) is Srinivasan & Jovanis (1996). Hellinga & Fu (1999) performed an assessment of probe vehicle travel time accuracy to address contradictory conclusions from past research regarding sample bias. Another effort was an evaluation of location technology using probe vehicles equipped with global positioning systems (GPS) and cellular phone tracking (Yim & Cayford, 2001). In another case, data from a

California freeway service patrol AVL system were used to develop real-time freeway performance measures in Los Angeles (Moore et al., 2001).

In earlier efforts focusing on the use of transit probes, some researchers have used transit AVL data to develop and explore possible congestion monitoring and transit information uses. For example, Dailey (2001) used transit vehicles traveling on a freeway in the Seattle metropolitan area to provide freeway speed information. In that study, the speed of the probe vehicles was constrained by the flow of the surrounding traffic (Dailey, 2001). In Orange County, Florida, Hall and Vyas (2000) used travel time information obtained from transit probe vehicles and floating cars together with incident locations to locate congestion on the roadway system. The study found that the transit probe was more useful for reporting congestion approaching major intersections since the entire corridor was too large to identify the exact location of an incident. Finally, Williams (2001) used transit probe data to make a comparison with floating probe data collected at outbound bus stops along Route 14 in Portland, Oregon for 22 runs in 3 days. The study introduced the rich transit probe data source in Portland, Oregon and focused on studying travel times between scheduled time points along the route. The study found that the difference between auto travel time and bus travel time diminished as congestion built toward gridlock. This study also found that transit probes can be useful for establishing relationships with actual traffic conditions. His analysis showed the need for expanding the study corridor using a larger sample size. In this way, Williams (2001) is the foundation for this study, which will broaden its coverage to different locations in the Portland Metropolitan area, while incorporating new technology on floating probe vehicles using GPS data.

1.4 Experimental Design

In order to provide performance measures along arterials using transit buses as probe vehicles, first, we raise the question whether transit vehicles can accurately report traffic conditions. After some preliminary investigations, we hypothesized that transit buses can, in fact, represent actual traffic conditions and that there would be statistical relationships between bus travel behavior and actual traffic movements.

In order to test this hypothesis, this study needed data simultaneously describing bus travel behavior and information representing traffic conditions. These two sets of data were required to be consistent in order to facilitate reliable comparison. Table 2 summarizes the details of the experimental design.

The extent to which the travel characteristics of buses are related to those of general traffic is not well understood. Therefore, to examine the relationship between general traffic conditions and bus travel time and speed, a statistical comparison of transit bus data and ground truth data collected by GPS-instrumented passenger vehicle was used in this study. Vehicle trajectories–graphs plotted with vehicle location versus time–of both buses and non-transit test vehicles were produced to measure the differences in travel time and speed. Speed contour plots were also used to observe the precise differences in speed for both types of vehicles traveling along the study corridor. By estimating speeds throughout a road segment at any particular time, speed contours were plotted on a three-dimensional graph using time and location as the *x*- and *y*- axis respectively.

Table 2: Experimental Design Features

Features	**Experiment**
Question	Can buses accurately report actual traffic conditions?
Hypothesis	There are relationships between bus behavior and traffic movements
Requirement	Bus data: • Bus automatic vehicle location data Traffic condition data: • Test vehicle travel time study data Level of consistency: • Same location • Approximately same distance traveled • Same date • Same times • Variety of traffic conditions (peak and off-peak periods)
Comparison	Key performance measures: • Travel time • Speed

To further explore the relationship between bus travel time and general traffic travel time, hypothetical and pseudo bus analyses were also conducted. For this study, hypothetical buses are defined as the buses traveling non-stop and pseudo buses are buses traveling at the maximum speed recorded for each link. Two statistical methods were tested to establish the relationship between test vehicles and buses. First, a preliminary analysis of the relationship between mean speed and mean travel time was tested as a naive method. Later a more robust linear regression was conducted to estimate a more statistically reliable relationship.

The next chapter contains a description of the study corridor and the two sources of data used in this study.

2. DATA

The study location is a 2.5 mi corridor on SE Powell Blvd. in Portland, Oregon. This corridor begins in downtown Portland at SW First Ave., and runs across the Willamette River on the Ross Island Bridge to SE 39th Ave., as illustrated in Figure 1. The corridor serves approximately 50,000 vehicles per day (ODOT, 2001), with peak travel westbound during the A.M. peak and eastbound during the P.M. peak. This study focuses on both the eastbound and westbound directions using BDS and test vehicle data obtained on Thursday Nov. 1, 2001, Saturday Nov. 3, 2001, Wednesday Nov. 7, 2001, and Saturday Nov. 10, 2001. TriMet Route 9 operates on SE Powell Blvd. providing service throughout the study area and will be addressed later in Chapter 3. The next section introduces the components of the TriMet bus dispatch system.

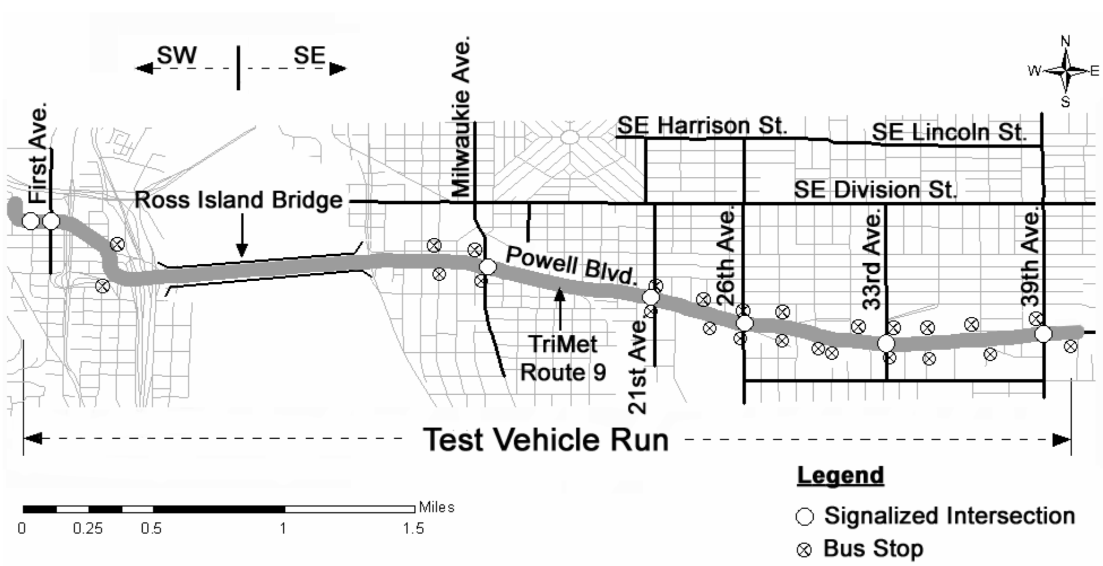


Figure 1: Study Corridor

2.1 Bus Dispatch System Data

The BDS provides a rich data source of transit monitoring information in both real-time and archived formats (Strathman et al., 2001). The BDS system comprises three main components: the GPS satellite system, the real time information system and the data archive system. The GPS satellite system provides vehicle location information feeding into the AVL system in order to monitor vehicle locations in real time. Vehicle location is determined by the on-board computer and transmitted using a real time communication system to the transit dispatch center. The real time component also supports voice and data communication using a mobile radio system. Information is transmitted from the vehicle to the dispatch center either at a regular interval or in response to specific operator initiated events such as route detour, accident or vehicle breakdown. This system is used to ensure that the bus dispatch center is updated with at least the minimum amount of information for tracking and reporting purposes and to provide assistance to bus operators. Finally, the most important part of the BDS that is useful for this study is the archived element. As shown in Figure 2, information regarding bus operational characteristics such as distance traveled, passenger activities, vehicle location (GPS coordinates) and maximum speed achieved on every link traveled, are recorded into storage (a PCMIA memory card) while the bus is in service. The archived data are downloaded to the control system at the garage at the end of day. Such information is extremely valuable and records detailed operating and travel characteristics for every bus which is useful for revealing traffic movements on the arterial system. The next section explains the archived element of the BDS in detail.

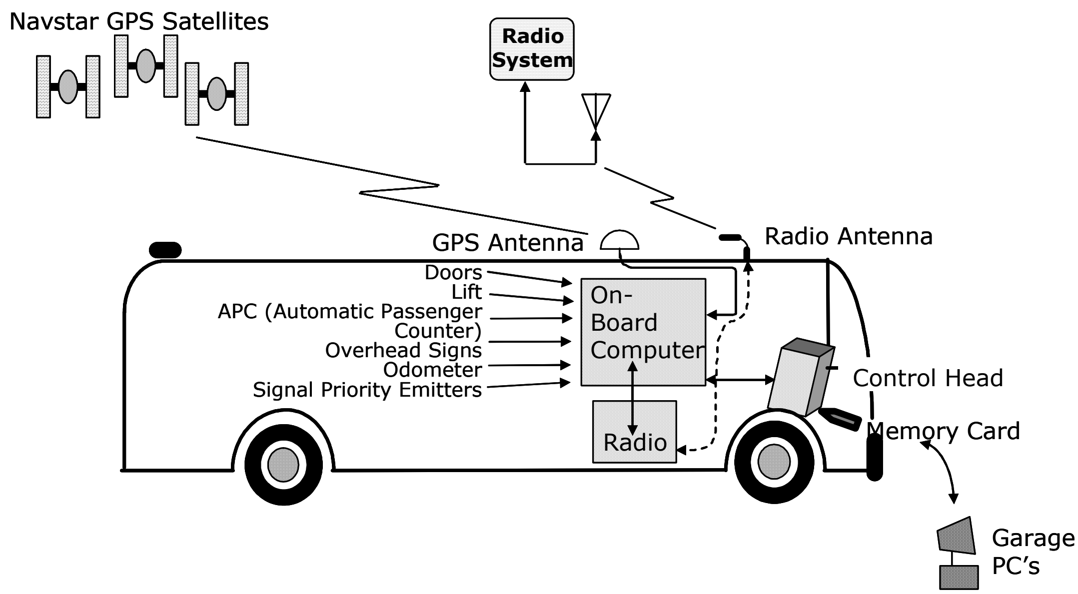


Figure 2: Components of Bus Dispatch System

2.2 Archived Component of BDS

For each bus trip and for each geo-coded stop, the BDS records arrival time, departure time, number of boardings and alightings, and location (in NAD83 state plane *X-Y* coordinates). In addition, the system stores the maximum instantaneous speed achieved between stops. As shown in Figure 3, the position of the GPS-equipped buses is calculated every second, with a spatial accuracy in positioning of plus or minus 10 meters (33 feet). If the bus does not stop at stop *i*, the BDS records the time that the bus is within 30 meters (100 feet) of an accurate location of the next bus stop that is stored on the data card with the schedule as "arrive time." The BDS then records "leave time" when the bus is no longer within 30 meters (100 feet) of the bus stop location. If the bus stops at stop *j*, then the BDS records the time that the door opens as the "arrive time," records the "dwell time" (the difference between door open time and door close time) and records the "leave time" as the time the bus is no longer within 30 meters (100 feet) of the bus stop location (Dueker, 2003). Also

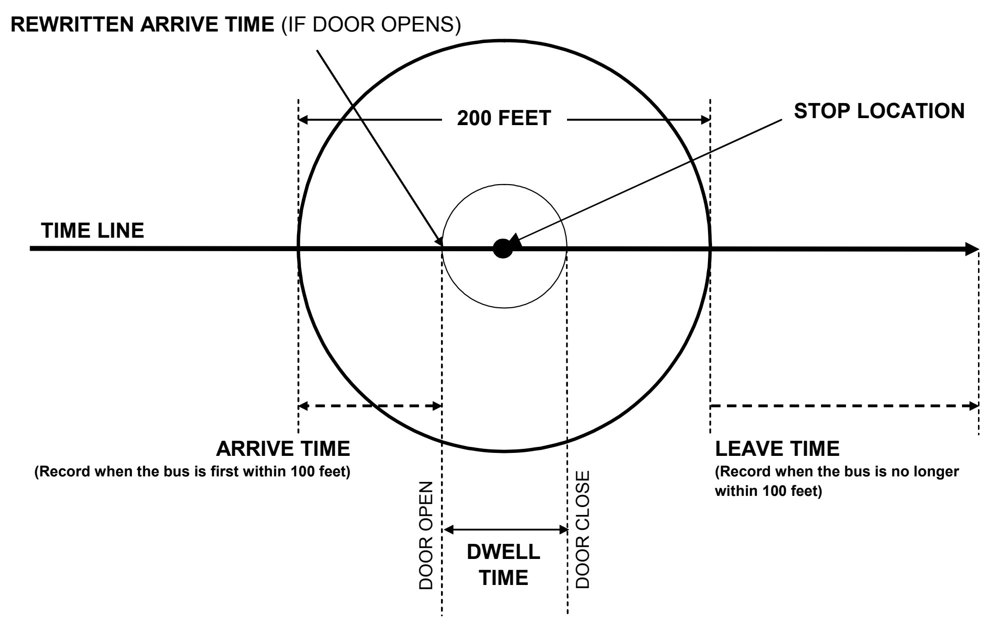


Figure 3: 100-Foot Radius Stop Circle where the BDS Recorded Times and Locations

at each stop where passengers are served, the BDS records the number of boardings and alightings through both doors (El-Geneidy, 2001) using automatic passenger counters (APCs), a pair of infrared beams situated across the front and rear doors of the bus. Table 3 shows examples of BDS data for Bus Route 9 which include:

- Bus trip information such as Service Date, Vehicle Number (unique identification number), Train Number (grouped scheduled trips for a single vehicle), Badge Number (operator identification number), and Direction (0 for outbound and 1 for the inbound direction).
- Travel time information such as Leave Time, Arrive Time, Stop Time (bus scheduled departure time at a given location) and Maximum Speed Recorded between stops.
- Location information such as Pattern Distance (linear scheduled distance measured from the beginning of the route), *X*- and *Y*-Coordinates (geo-coded location of the bus) and Stop Location.
- Passenger activity information such as Dwell Time, Door Open indication, Lift Used indication and Numbers of Passengers Boarding and Alighting.

2.3 Test Vehicle Data

Twelve students were assigned to collect ground truth vehicular travel time data in November, 2001 as shown in Table 4. Test vehicles equipped with GPS receivers connected to laptop computers were dispatched during the study period to collect simultaneous corridor time and location data, later converted into travel time information. The GPS devices were programmed to record each test vehicle's precise location (latitude-longitude) with a time stamp every 3 sec. The distance between

Table 3: Example of BDS Data

Service Date	Vehicle No.	Leave Time	Stop Time	Arrive Time	Train	Badge	Direction	Trip No.	Location ID.	Dwell	Door	Lift	Ons	Offs	Estimated Load	Max Speed	Pattern Distance	X Coordinate	Y Coordinate
01NOV2001	2105	8:53:32	8:49:15	8:53:28	934	285	0	1120	4964	0	0	0	0	0	21	41	10558.58	7644468	676005
01NOV2001	2105	8:55:00	8:51:41	8:54:46	934	285	0	1120	4701	4	0	0	0	1	20	50	15215.05	7649112	676328
01NOV2001	2105	8:56:22	8:52:00	8:55:08	934	285	0	1120	4537	36	3	0	6	0	26	34	15792.35	7649674	676220
01NOV2001	2105	8:57:44	8:53:44	8:57:08	934	285	0	1120	4622	5	2	0	0	1	25	47	18500.66	7652240	675442
01NOV2001	2105	8:58:20	8:54:22	8:57:56	934	285	0	1120	4625	6	2	0	0	1	24	36	19395.29	7653071	675084
01NOV2001	2105	8:59:02	8:54:42	8:58:24	934	285	0	1120	4627	18	2	0	0	10	14	26	19927.71	7653552	674903
01NOV2001	2105	8:59:26	8:55:06	8:59:16	934	285	0	1120	4630	0	0	0	0	0	14	27	20349.21	7653984	674836
01NOV2001	2105	8:59:38	8:55:29	8:59:32	934	285	0	1120	4636	0	0	0	0	0	14	36	20933.38	7654544	674671
01NOV2001	2105	9:00:04	8:55:38	8:59:40	934	285	0	1120	4641	5	1	0	0	0	14	28	21485.01	7655065	674508
01NOV2001	2105	9:00:32	8:56:12	9:00:10	934	285	0	1120	4644	0	0	0	0	0	14	30	21991.62	7655576	674439
01NOV2001	2105	9:01:16	8:56:35	9:00:42	934	285	0	1120	4647	13	1	0	2	2	14	29	22551.43	7656141	674443
01NOV2001	2105	9:01:36	8:57:12	9:01:30	934	285	0	1120	4648	0	0	0	0	0	14	33	23427.98	7657009	674494
01NOV2001	2105	9:02:24	8:58:00	9:01:56	934	285	0	1120	4651	10	2	0	3	2	15	36	24449.92	7658021	674542
01NOV2001	2105	7:08:14	7:07:00	7:07:38	934	285	1	1120	4653	12	2	0	1	2	31	28	54185.67	7657799	674586
01NOV2001	2105	7:08:36	7:07:47	7:08:30	934	285	1	1120	4649	0	0	0	0	0	31	40	55039.00	7656944	674515
01NOV2001	2105	7:08:54	7:08:20	7:08:46	934	285	1	1120	4646	0	0	0	0	0	31	31	55673.27	7656312	674457
01NOV2001	2105	7:09:32	7:08:44	7:08:58	934	285	1	1120	4643	10	2	0	4	0	35	28	56326.76	7655668	674436
01NOV2001	2105	7:10:06	7:09:11	7:09:40	934	285	1	1120	4640	7	2	0	1	1	35	26	56858.53	7655145	674525
01NOV2001	2105	7:10:50	7:10:08	7:10:34	934	285	1	1120	4631	6	2	0	1	0	36	29	57819.60	7654219	674792
01NOV2001	2105	7:11:20	7:10:35	7:11:00	934	285	1	1120	4628	5	2	0	0	1	35	28	58476.58	7653580	674940
01NOV2001	2105	7:11:52	7:11:08	7:11:30	934	285	1	1120	4626	5	2	0	1	0	36	33	59121.09	7652995	675179
01NOV2001	2105	7:12:40	7:11:44	7:12:02	934	285	1	1120	4623	8	2	0	1	0	37	27	59864.31	7652306	675459
01NOV2001	2105	7:14:28	7:14:00	7:13:56	934	285	1	1120	4538	6	2	0	0	1	36	41	62446.05	7649830	676178
01NOV2001	2105	7:14:44	7:14:21	7:14:40	934	285	1	1120	4702	0	0	0	0	0	36	30	63107.28	7649178	676327
01NOV2001	2105	7:16:50	7:17:23	7:16:44	934	285	1	1120	3116	0	0	0	0	0	36	32	68241.22	7644417	676548

two GPS coordinates was estimated using the spherical geometry method (Meridian World Data, 2001). Table 5 shows examples of the test vehicle data.

Table 4: Test Vehicle Data Collection Schedule

Team ID	Task Name	Duration	Date	Start Time	Finish Time
1	Mike/Lara	3 hrs	Wednesday 11/07/01	7:00 A.M.	10:00 A.M.
2	Chie/Monica	3 hrs	Wednesday 11/07/01	7:00 A.M.	10:00 A.M.
3	Renee/Sutti	3 hrs	Thursday 11/1/01	6:00 A.M.	9:00 A.M.
4	Tung/Thac	3 hrs	Thursday 11/1/01	6:30 A.M.	9:30 A.M.
5	AQ/Tu	3 hrs	Saturday 11/3/01	12:00 P.M.	3:00 P.M.
6	Shazia/John	3 hrs	Saturday 11/10/01	12:00 P.M.	3:00 P.M.

Table 5: Example of Test Vehicle Data

Time	Latitude	Longitude	Distance (mi)
7:18:30	45.5003800	122.6750367	0
7:18:33	45.5004500	122.6742367	0.03899
7:18:36	45.5005167	122.6734417	0.038722
7:18:39	45.5005800	122.6726683	0.037655
7:18:42	45.5006417	122.6718900	0.037882
7:18:45	45.5007050	122.6710950	0.038695
7:18:48	45.5007683	122.6702867	0.039336
7:18:51	45.5008333	122.6694683	0.03983
7:18:54	45.5008983	122.6686567	0.039509
7:18:57	45.5009600	122.6678467	0.039404

Two test vehicles were dispatched on the study corridor to collect 3 hours of travel time data between 6:00 A.M. and 10:00 A.M. on Thursday Nov. 1, 2001 and Wednesday Nov. 7, 2001. Further, one test vehicle was dispatched to collect weekend data between 12:00 P.M. and 3:00 P.M. on Saturday Nov. 3, 2001, and Saturday Nov. 10, 2001. Each vehicle contained two students and was dispatched at approximately 10 min headway. The students were instructed to perform standard probe vehicle maneuvers by traveling with the flow of traffic (Turner et al., 1998). Travel time data were thus available for a minimum of 15 runs in each direction (eastbound and westbound) for each weekday, and for 10 runs in each direction for each Saturday.

From the preliminary analysis of vehicle GPS data, *X*-*Y* coordinates were plotted to observe vehicle locations and travel patterns. As shown in Figure 4, some vehicle trips on Saturday Nov. 3 and Saturday Nov. 10 included location errors, placing vehicles outside the roadway network. This accounted for a reduction in data availability of 7.7 percent (7 runs). Such errors were explained by insufficient satellite availability (minimum of three) to calculate precise vehicle locations. Vehicle location data for the weekdays did not contain errors of this type.

Transit AVL data were also obtained from TriMet for the same days and times. Note that the transit data are location-based since the BDS system recorded data at preprogrammed geo-coded stop locations, while the test vehicle GPS data are time-based, recorded at specific time intervals. This study demonstrates how fusing the location-based data with the time-based data can reveal important relations between the two sources. The next chapter describes the analysis of the transit AVL data for determining corridor travel times.

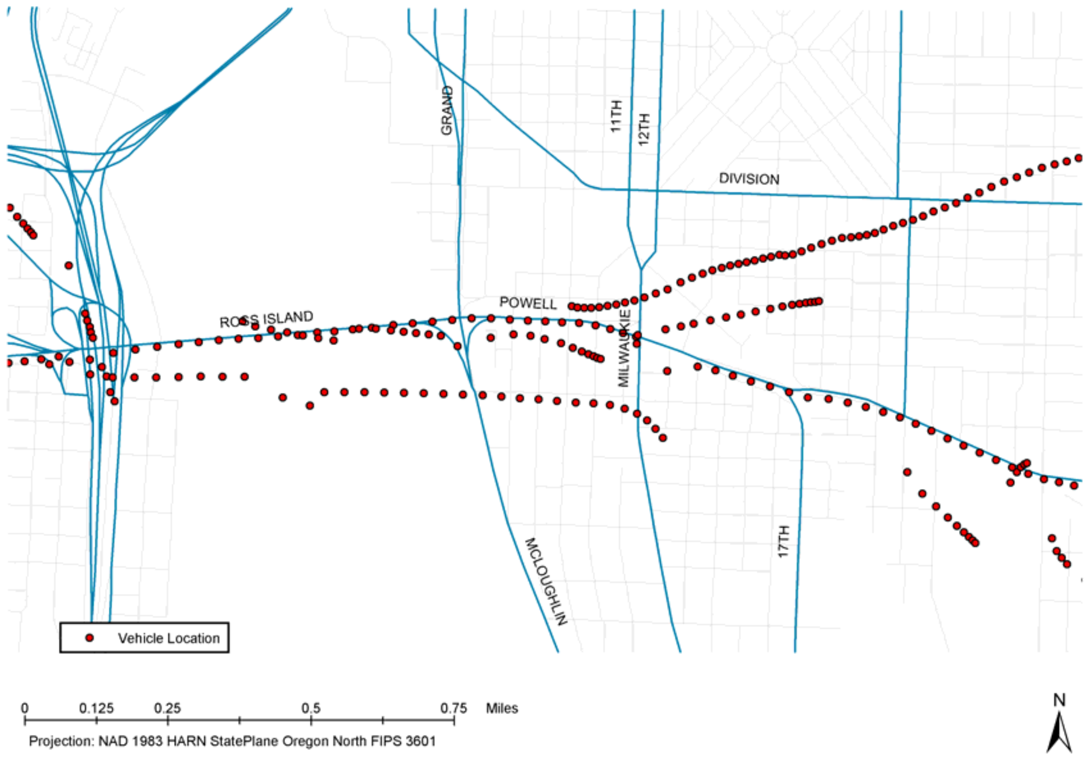


Figure 4: Examples of Vehicle Locations Due to Insufficient Satellite Availability

3. BUS PROBE ANALYSIS

For the transit probe investigation, TriMet bus Route 9 was selected for analysis on SE Powell Blvd. as shown in Figure 5. Route 9 is designated by TriMet as a "frequent service" route with headways of 15 min or less between the Gresham Transit Center and downtown Portland. TriMet provides approximately 80 trips per direction per day on Route 9 including several "limited trips," which provide express service during peak periods by skipping stops at specific locations. The study corridor between a time point at SW 1st Ave. & SW Arthur St. and a time point at SE Powell Blvd. & SE 39th Ave. (see Figure 1) includes 13 eastbound and 12 westbound stops. In the study corridor during the field experiment, TriMet provided a scheduled mean trip time of 10.7 min, with trip times ranging between 8 min during the off-peak and 13 min during the peak. On Nov. 1, 2001, the mean observed dwell time in the eastbound direction was 12.1 sec with an average of

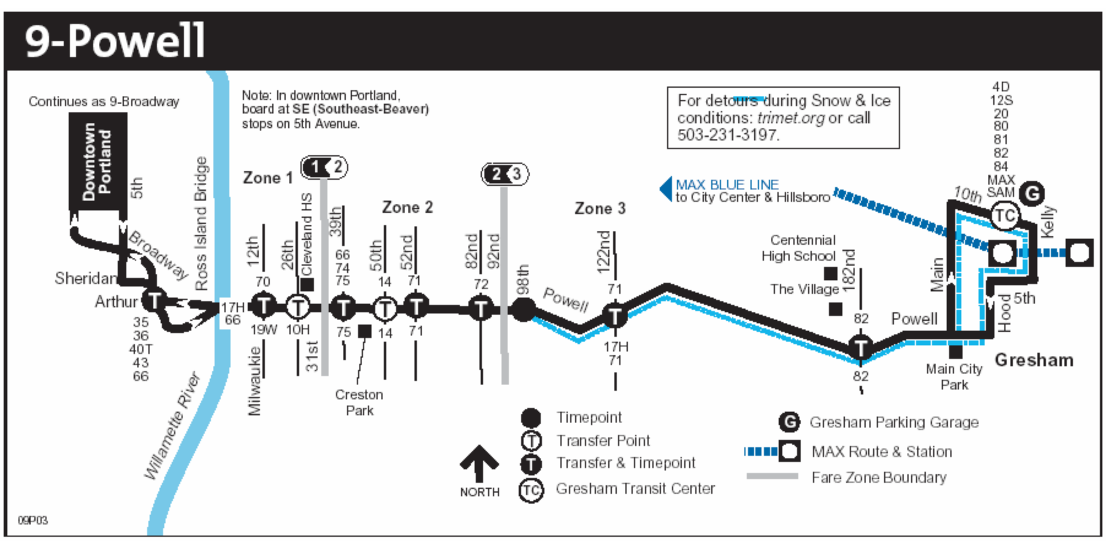


Figure 5: Bus Route 9 Service Map

3 passenger boarding and 3 passenger alighting movements per stop served in the study corridor. The buses stopped at an average of 6 stops to serve passengers. Bus data on Nov. 7, 2001 indicated similar results for all previously observed elements (mean observed dwell time of 13 sec, average of 3 passenger boarding and alighting movements and 7 served stops) as shown in Table 6. In the westbound direction, observations indicated similar patterns of these observed elements on Nov. 1 and Nov. 7, and this similarity also prevailed in the case of Saturday data on Nov. 3, 2001 and Nov. 10, 2001. Since the data collected on these study days represent bus travel on the corridor during the weekday morning peak period and the weekend midday period, for easy demonstration purposes, the rest of the thesis will focus on two scenarios, the morning peak period (Wednesday Nov. 7, 2001 and Thursday Nov. 1, 2001) and the off-peak period (Saturday Nov. 3 and Saturday Nov. 10, 2001)

Table 6: Bus Passenger Activities

Eastbound

	No. of Runs	Mean Dwell Time	Average		Average No. Served Stops
			Boarding	Alighting	
Thursday Nov. 1, 2001	15	12.1	3	3	6
Saturday Nov. 3, 2001	12	10.3	2	2	7
Wednesday Nov. 7, 2001	15	13.3	3	3	7
Saturday Nov. 10, 2001	10	11.7	2	2	6

Westbound

	No. of Runs	Mean Dwell Time	Average		Average No. Served Stops
			Boarding	Alighting	
Thursday Nov. 1, 2001	19	16.0	3	2	8
Saturday Nov. 3, 2001	12	11.7	2	2	6
Wednesday Nov. 7, 2001	16	15.7	3	3	9
Saturday Nov. 10, 2001	11	12.0	2	2	5

for both directions. This meets one of the study objectives which is to concentrate on periods with varying traffic conditions. The next section describes the preliminary analysis using bus trajectories.

3.1 Time-Space Diagram

Figure 6 illustrates a preliminary investigation of the BDS data using eastbound vehicle trajectories plotted on a time-space diagram. The bus trajectories were constructed by plotting the cumulative distance the bus traveled on the *y*-axis and time on the *x*-axis. A trajectory contains all of the information necessary to completely describe a vehicle's movement on the roadway (Daganzo, 2000). A

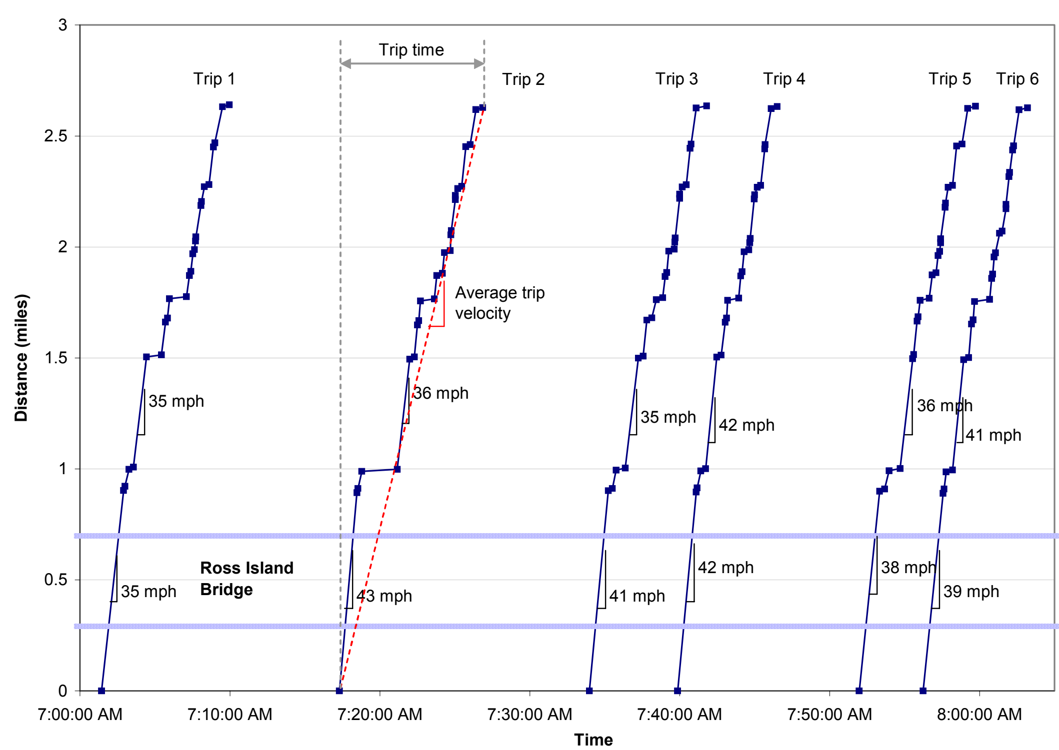


Figure 6: Example of Bus Trajectories on Time-Space Diagram

trajectory's slope at any time *t* is the average bus speed at that time on that route segment as labeled next to selected trajectory lines. Vehicle stops are also shown as horizontal segments. The Ross Island Bridge is illustrated with two stripes at the beginning of the trajectory (for the eastbound direction). Key performance measures like vehicle trip time, average speed or delay can also be derived from the trajectory. Total trip time is visible as time difference between the beginning and the end of trajectory and average speed is the slope of the line connecting these two points. Delay at any point is the horizontal distance between the actual trajectory and the scheduled or free flow trajectory.

To better understand the trajectories' details, Figure 7 shows sample bus movements in a stop circle. Figure 7(a) shows a trajectory where the bus arrives at the bus stop at arrive time t_1, is reported to have stopped for time T (dwell time) to serve passengers, and leaves the bus stop at leave time t_2. Arrive time is recorded when the bus is within 100 feet of an accurate location of the next bus stop stored on the bus data card and is overwritten by the time the door opens if passenger activity was present (Dueker, 2003). Leave time is the time recorded when the bus is no longer within that 100 feet of the bus stop location. Dwell time is reported as the time that the door is open. In reality this is only an approximate representation of the actual bus movement, shown as a dashed line. Figure 7(b) presents another trajectory where the bus does not stop to serve passengers. Time T' between arrive and leave time (t_1' and t_2' consecutively) is observed to be shorter than T. The distance

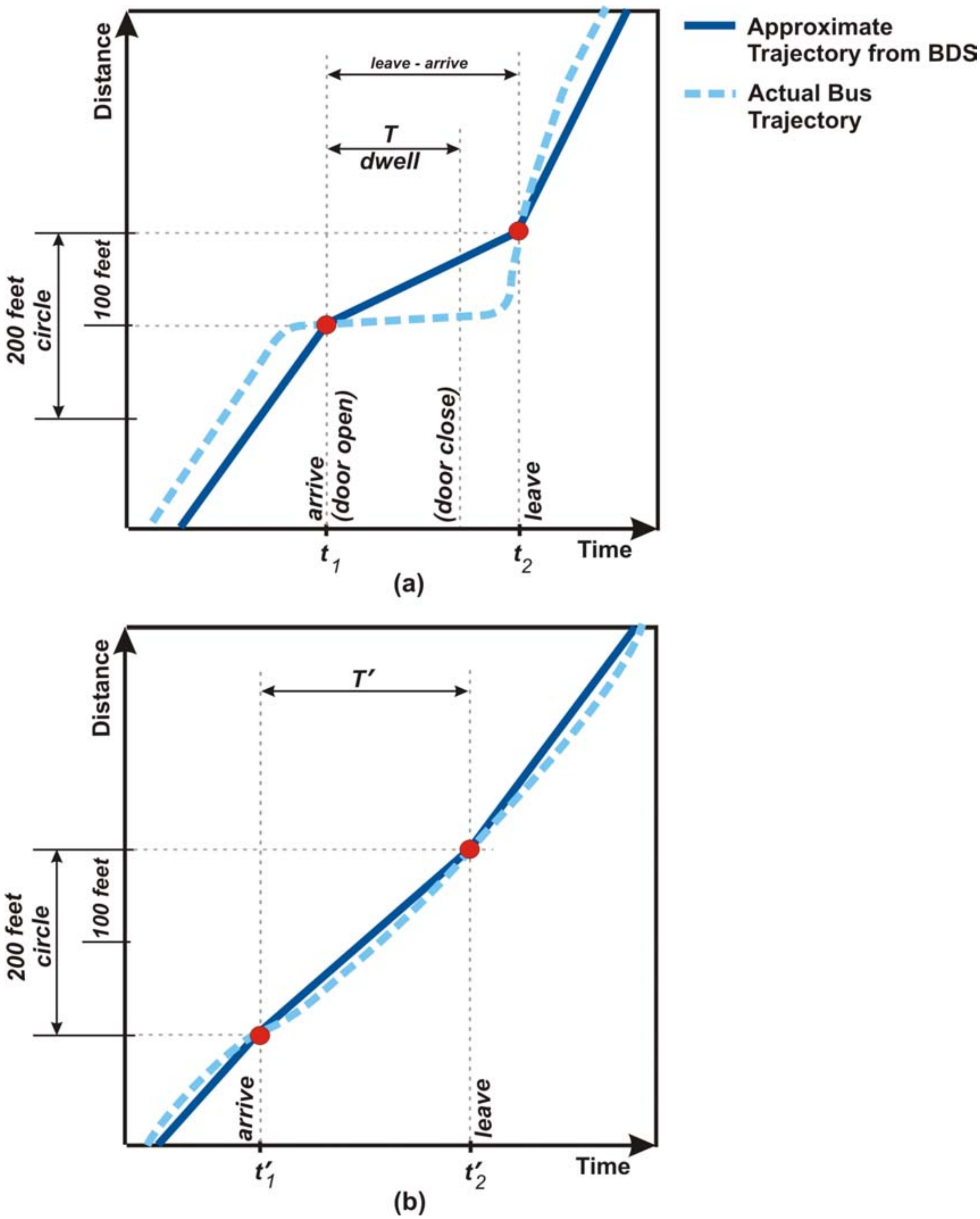


Figure 7: Sample Bus Trajectories (a) When Bus Stops and (b) When Bus Does Not Stop

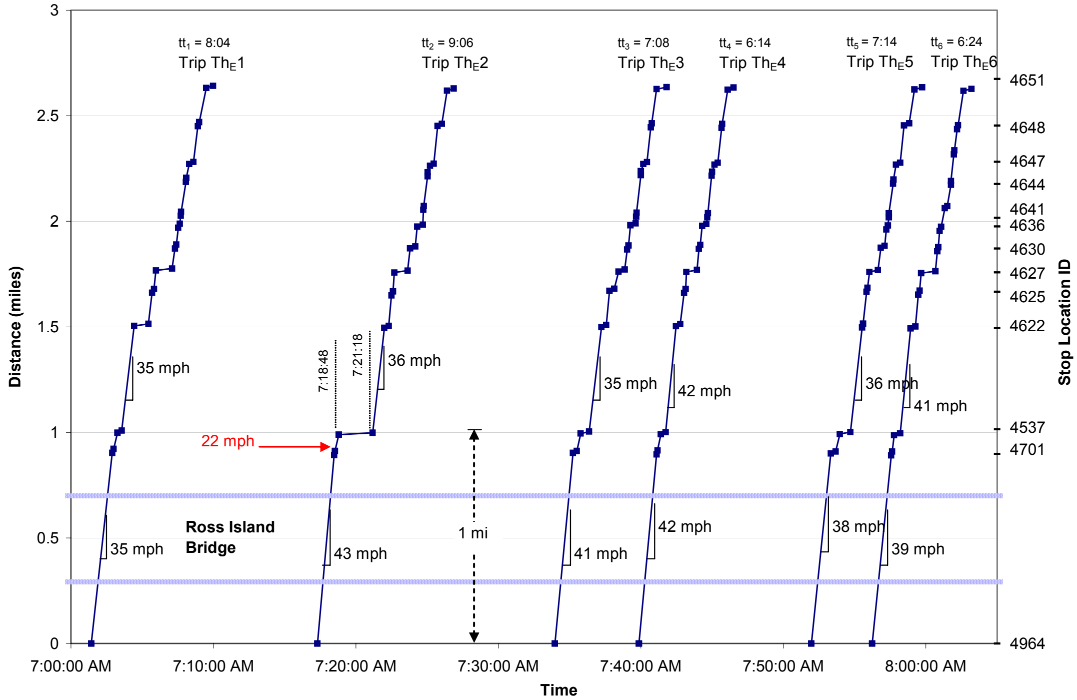
traveled inside the stop circle was included in the trajectories as indicated. The next section describes the preliminary analysis of eastbound bus data, followed by analysis of westbound bus data and the portion of bus data on the Ross Island Bridge.

3.2 Eastbound Direction Analysis

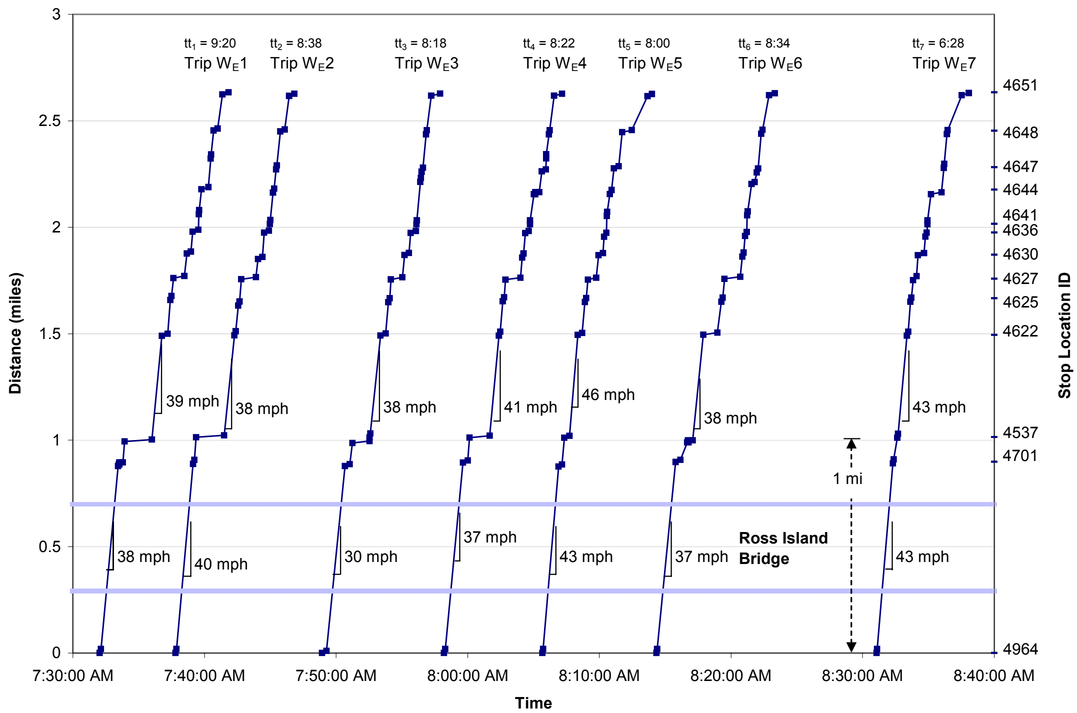
Figures 8 and 9 illustrate example bus trajectories for the weekday morning peak period and weekend off-peak period respectively. Each trajectory shown in each figure describes an individual bus traveling eastbound (outbound) and the Ross Island Bridge is illustrated with two stripes, between 0.3 and 0.7 mi from the west end of the corridor (SW First Ave.). On the secondary (right-hand) *y*-axis, in both Figures 8 and 9, the stop locations along the route are shown from stop 4964 between SW Natio Pkwy. and the Ross Island Bridge to stop 4651 at the corner of SE Powell Blvd. and SE 39th Ave. These stop locations are also listed in Table 7.

The bus trajectories illustrated in Figures 8(a), 8(b), 9(a) and 9(b) are sample eastbound trips on all four study days. As shown in these figures, the small horizontal segments reflect bus movement within the stop circles, matching stop locations on the secondary *y*-axis. The difference between the first location and last location projected on the *x*-axis is the total trip time (run time).

Focusing on Thursday Nov. 1, 2001, the mean run time was 7:46 min and varied (in the morning peak between 6:00 and 9:30 A.M.) between 5:12 and 10:24 min. In Figure 8(a), passenger activity can be observed to be high at a particular stop

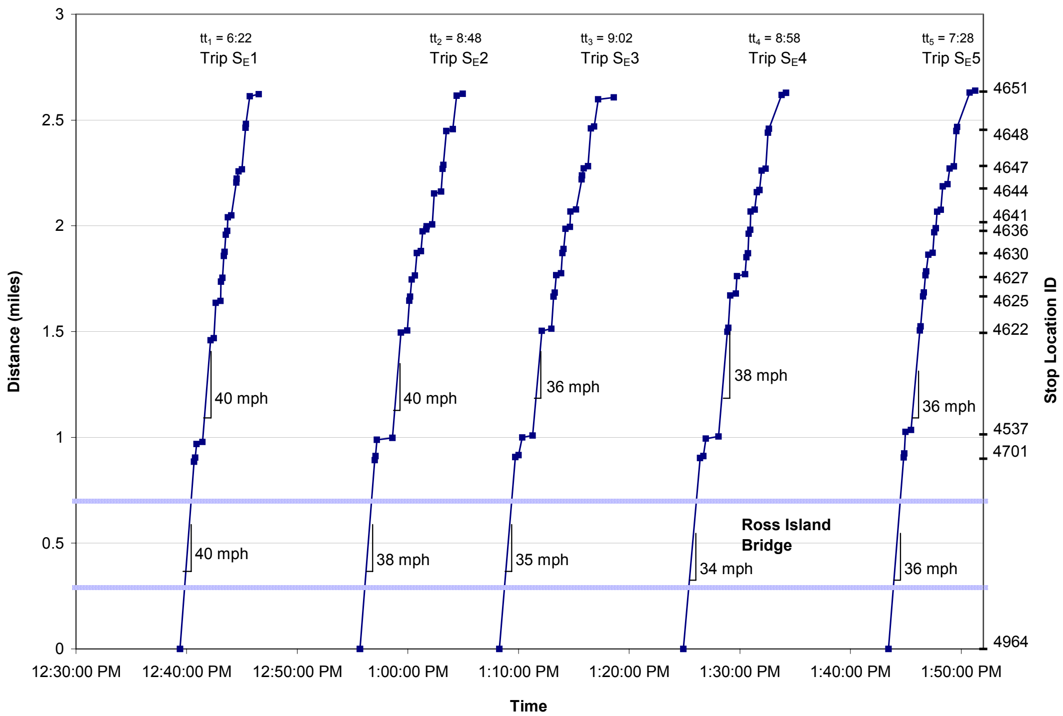


(a)

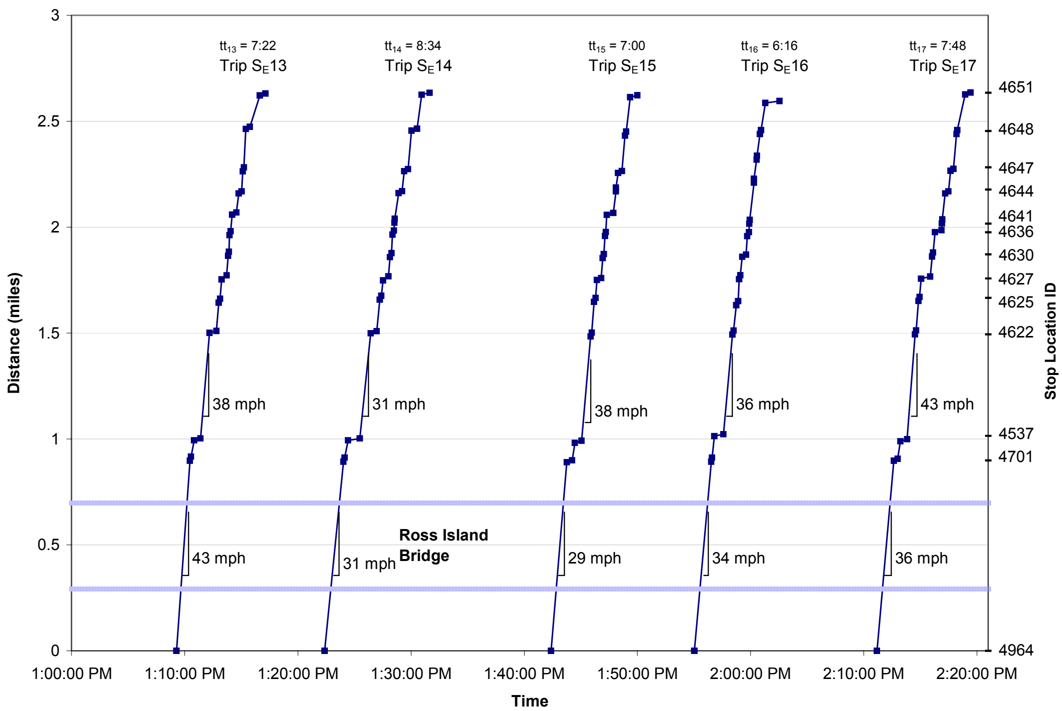


(b)

Figure 8: Eastbound (Outbound) Bus Trajectories on (a) Thursday Nov. 1, 2001 and (b) Wednesday Nov. 7, 2001



(a)



(b)

Figure 9: Eastbound (Outbound) Bus Trajectories on (a) Saturday Nov. 3, 2001 and (b) Saturday Nov. 10, 2001

Table 7: Bus Route 9 Stop Locations

Eastbound		Westbound	
Stop ID	**Location**	**Stop ID**	**Location**
4964	Natio Pkwy / Ross Island Bridge *	4653	SE Powell Blvd. / SE 39th *
4701	SE Powell Blvd. / SE 9th	4649	SE Powell Blvd. / SE 36th
4537	SE Powell Blvd. / SE Milwaukie *	4646	SE Powell Blvd. / SE 34th
4622	SE Powell Blvd. / SE 21st	4643	SE Powell Blvd. / SE 33rd
4625	SE Powell Blvd. / SE 24th	4640	SE Powell Blvd. / SE 31st
4627	SE Powell Blvd. / SE 26th	4631	SE Powell Blvd. / SE 28th
4630	SE Powell Blvd. / SE 28th	4628	SE Powell Blvd. / SE 26th
4636	SE Powell Blvd. / SE 29th	4626	SE Powell Blvd. / SE 24th
4641	SE Powell Blvd. / SE 31st	4623	SE Powell Blvd. / SE 21st
4644	SE Powell Blvd. / SE 33rd	4538	SE Powell Blvd. / SE Milwaukie *
4647	SE Powell Blvd. / SE 34th	4702	SE Powell Blvd. / SE 9th
4648	SE Powell Blvd. / SE 36th	3116	SW Kelly / SW Corbett *
4651	SE Powell Blvd. / SE 39th *		

Note: * Timepoint is a specific stop where a bus is scheduled to be at a certain time

location. Specifically, bus trips Th_E1, Th_E2, Th_E4, Th_E5 and Th_E6 had long dwell times at stop 4627, located at the corner of SE Powell Blvd. and SE 26th Ave. The mean total dwell time for all stops throughout the corridor was 73 sec. The trajectories also show that the buses were traveling at a mean speed of 40 mph at the beginning of the corridor (over the bridge to stop 4537). However, at the end of the trip, the trajectories show variations on corridor travel time for all buses while trajectories show that the buses were traveling with similar patterns between each stop pair. Since these buses traveled through the study corridor in the eastbound direction which had lower traffic volumes in the morning peak, the bus corridor travel time varied more directly with passenger activities or dwell time. As observed in Figure 8(a), it appears that high passenger activity levels resulted in higher bus runtime. For example, bus trip Th_E2 spent the longest travel time of 9:06 min to traverse the corridor due to the long activity at stop 4537. Bus trip Th_E1 also spent 8:04 min with two long passenger activities at stops 4622 and 4627.

As shown in Figure 8(b), the sample Wednesday Nov. 3, 2001 bus trajectories were observed to be similar to the previous study day with a mean run time of 8:05 min, varying between 6:12 and 9:50 min. Passenger activity was also found to be high at stop 4537 located at the corner of SE Powell Blvd. and SE Milwaukie Ave. The bus trajectories show that the long dwell time at stop 4537 occurred only on the earlier bus trips, specifically bus trip W_E1, W_E2, W_E3 and W_E4, ranging between 0:34 min on Bus Trip W_E4 and 1:39 min on Bus Trip W_E2. Figure 8(b) also indicates that passenger activity times decreased on later trips e.g., W_E5, W_E6 and W_E7 as the morning peak period was ending. On Wednesday Nov. 3, the mean dwell time for all stops throughout the corridor was 96 sec. The trajectories, again, show that the buses were traveling on the bridge (the beginning of the corridor) at a higher mean speed of 38 mph compared to a corridor speed, after the bridge, of 19 mph. This illustrates the effects of numerous stops located on the east end of the corridor resulting in slower bus speed due to the delay from pulling in and out of those stops, which is characterized as lost time due to acceleration and deceleration.

For the off-peak period study, bus data on Saturday Nov. 3, 2001 and Saturday Nov. 10, 2001 indicate a variation in corridor travel time due to passenger activities. However, there are no signs of extreme passenger boardings and alightings, which results in lower mean dwell times per served stop, as reflected previously in Table 6. On Nov. 3, 2001, the mean total dwell time combined from all stops throughout the corridor was 68 sec. and was 60 sec. on Nov. 10, 2001. These indicate lower passenger activities on Saturday off-peak periods compared to the morning peaks on Wednesday and Thursday.

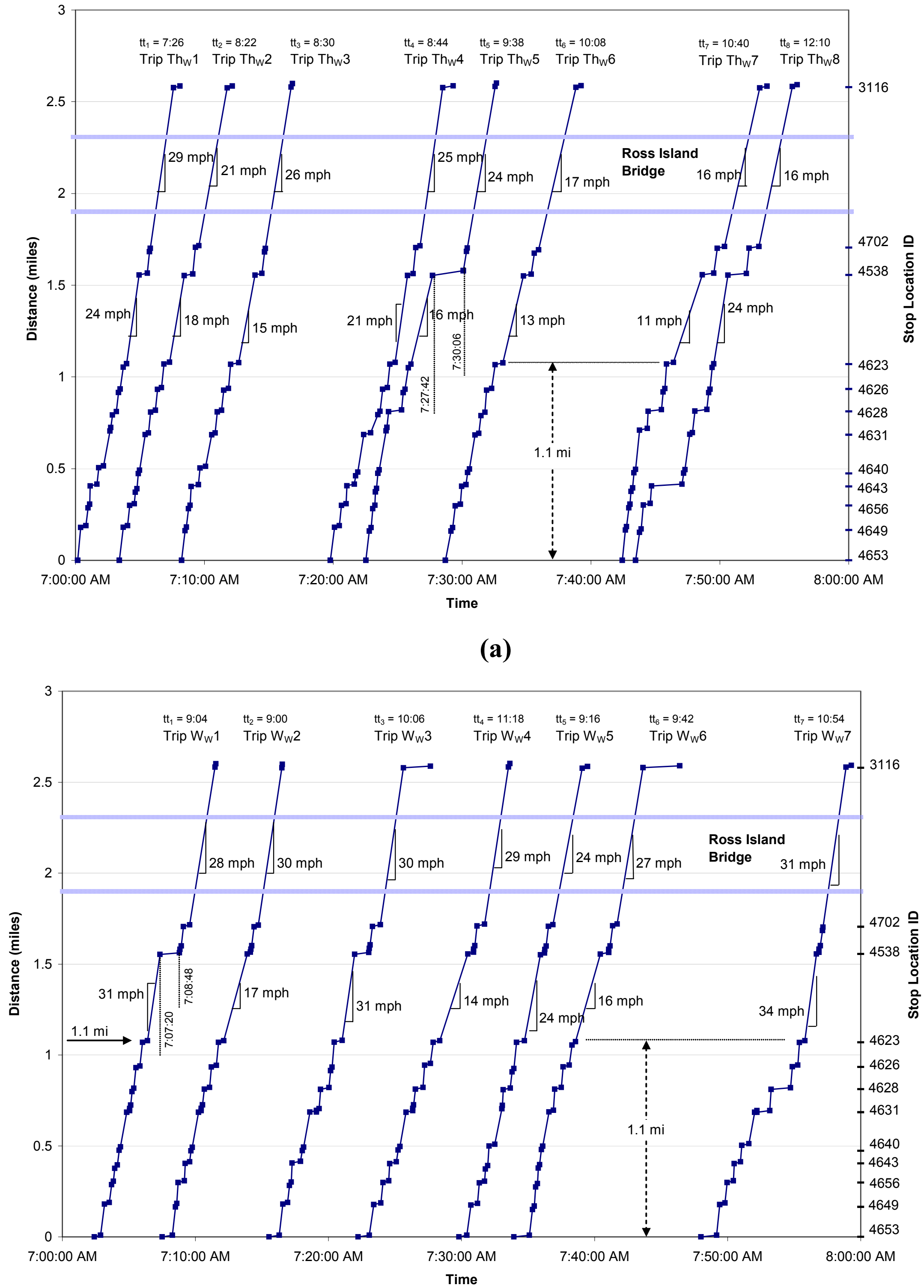
Figures 9(a) and 9(b) illustrate sample eastbound bus trajectories on Saturday Nov. 3, 2001 (total of 12 trips) and Saturday Nov. 10, 2001 (total of 10 trips) respectively. As stated earlier, trajectories on both figures show small nearly horizontal lines describing stop periods which confirm that during Saturday off-peak periods, there were fewer passenger movements. In Figure 9(a), bus trajectories depict higher speeds at the beginning of the run (from the west end, over the bridge to the middle of corridor at stop 4622) with the mean speed on the bridge of 37 mph (varying between 34 and 40 mph). The mean run time for the entire corridor was 7:37 min and varied between 5:08 and 9:16 min. Also in Figure 9(b), bus trajectories show similar patterns with higher speeds on the west end of corridor. The mean speed on the bridge was 36 mph, slightly lower compared to the first Saturday, varying between 29 and 43 mph. The mean run time was slightly higher at 7:43 min, varying between 6:16 and 9:52 min.

One benefit of using vehicle trajectories is the ability to pinpoint specific locations and times that vehicle behavior changes. As shown in Figure 8(a), an example of this benefit is in the case of bus trip Th_E2 where we can easily observe a change in bus performance. As shown in Figure 8(a), at distance 1 mi, bus trip Th_E2 was traveling at 22 mph after the bridge and stopped for a long period (2:30 min at stop 4537). The bus data indicate a dwell time of 54 sec, with 5 passenger boardings and 3 alightings. According to TriMet's Route 9 schedule, stop 4537 is a time point with a prescribed departure time. In order to keep up with the bus schedule, an operator who arrives at this stop early must wait and depart on schedule. Operators are prohibited from departing early according to TriMet policy. However, in this case, the bus arrived at stop 4537 at 7:18:48 A.M., which was 2:48 min after the scheduled stop time of 7:16:00 A.M. There would be no need for waiting, rather the operator needed to rush in order to catch up with the schedule. This long dwell time can potentially be explained by the stop location near a signalized intersection (a nearside stop located east of SE Milwaukie Ave.). After bus trip Th_E2 closed the door and departed from stop 4537, it reached a signalized intersection at the same time the signal phase changed to red and had to wait until the next cycle before it could leave the stop circle. This resulted in the additional recorded stop time of approximately 1:00 min. This is reasonable considering that there is a 110-second traffic signal cycle at this intersection (Koonce, 2003). The westbound bus analysis will be described in the next section.

3.3 Westbound Direction Analysis

For the westbound direction, an investigation was again conducted using vehicle trajectories as shown in Figures 10 and 11. There are 12 stops along the inbound route, from stop 4653 at the corner of SE Powell Blvd. and SE 39th Ave. to stop 3116 between SW Kelly Ave. and SW Corbett Ave. The Ross Island Bridge is marked with two stripes, between 1.9 and 2.3 mi from the east end of the corridor. For the weekday study (Thursday Nov. 1 and Wednesday Nov. 7, 2001), morning peak traffic traveled inbound toward downtown Portland, resulting in higher demand on the transit system as indicated by higher passenger activities and resulting in longer bus run times.

Figure 10(a) illustrates sample westbound bus trajectories on Thursday Nov. 1, 2001. The bus mean run time was 9:24 min and varied (in the morning peak between 6:00 and 9:30 A.M.) between 7:26 and 13:12 min. In Figure 10(a), bus run times were observed to increase from approximately 7 min to 12 min. Figure 10(a) also shows that passenger activities on bus trips Th_W4, Th_W5, Th_W6, Th_W7 and Th_W8 resulted in longer dwell times compared to the other three trips and that dwell times on these bus trips were increasing over time, i.e., bus trips Th_W7 and Th_W8 had longer dwell times than the rest. The mean dwell time for the corridor was 127 sec. The trajectories show that the buses were traveling at a mean speed of 13 mph at the beginning of their trips (east end of the corridor before the bridge). However, when the trajectories are observed in detail, they show that the buses were traveling with slightly different patterns. Between 7:00 and 7:15 A.M., buses were traveling at a mean speed of 14.5 mph with steady movement for bus trips Th_W1, Th_W2 and Th_W3. Five minutes later, bus movements along the corridor changed. Between 7:20 and 7:40 A.M., the trajectories for bus trips Th_W4, Th_W5, Th_W6, Th_W7 and Th_W8 were



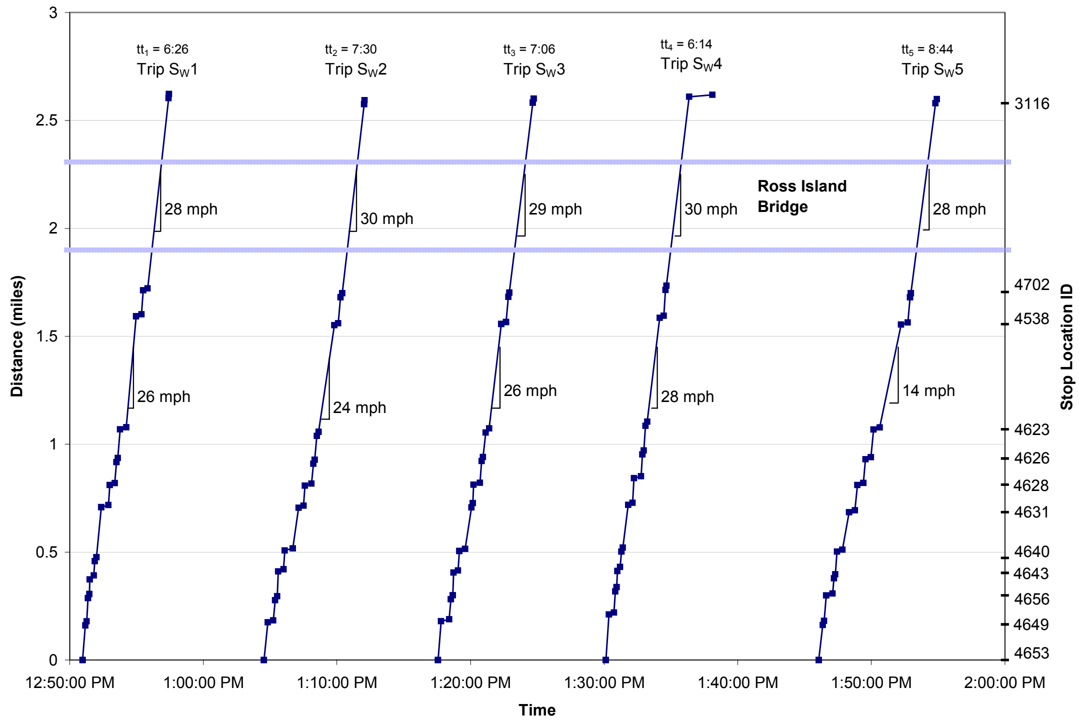
(b)

Figure 10: Westbound (Inbound) Bus Trajectories on (a) Thursday Nov. 1, 2001 and (b) Wednesday Nov. 7, 2001

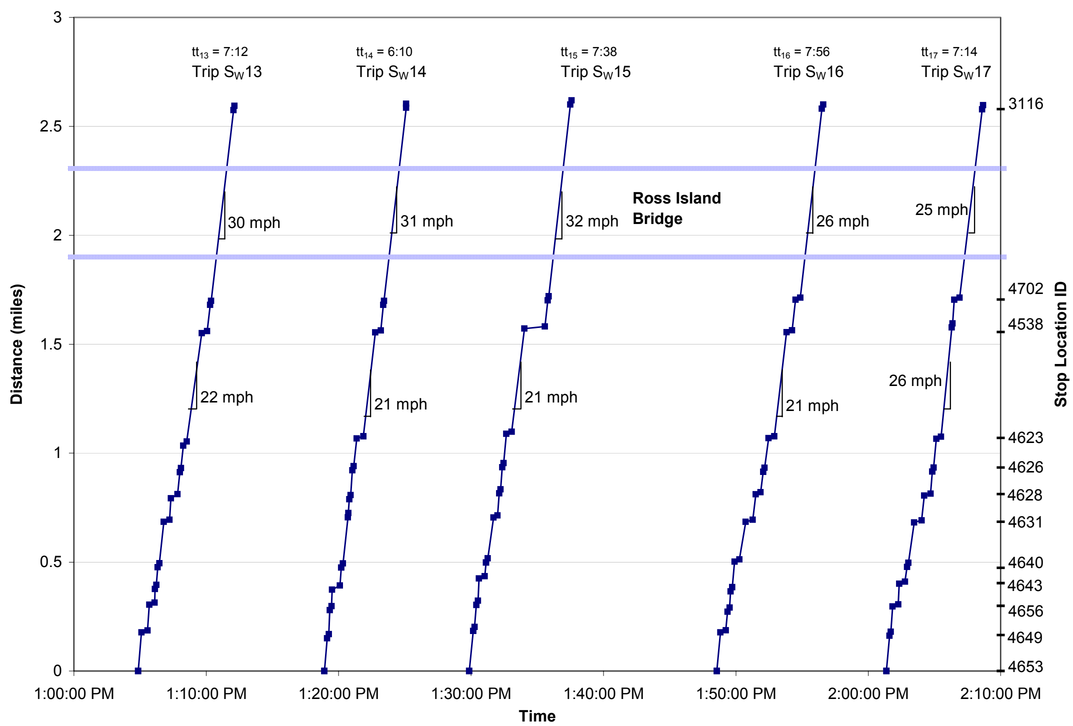
observed to be fuzzy indicating that there were variations in bus speeds with a lower mean speed of 12 mph. This can be explained by changes in traffic conditions when the morning peak began. As observed in Figure 10(a) this confirms that buses spent more time traversing the study corridor after this time. For example, bus trip Th_W1 required 7:26 min to traverse the corridor while trip Th_W2, Th_W3 and Th_W4 spent 8:22, 8:30 and 8:44 min respectively and the bus run times continued to increase for the remaining bus trips as indicated in the figure.

Figure 10(b) also shows sample inbound bus trajectories for Wednesday Nov. 7, 2001. The mean run time was 9:46 min and varied between 7:46 and 11:22 min. In Figure 10(b), run times increased from approximately 9 min to 11 min. Average total dwell time combined from all stops throughout the corridor was 140 sec. which was the highest of all study days and directions. The figure also shows the impact of passenger activity, i.e., bus W_W4 and W_W7 spent more time at stops compared to the other buses resulting in very long run times (11:18 and 10:54 respectively). The impact of passenger activities can be explained clearly by focusing on a comparison between bus trips W_W4 and W_W7. As shown in Figure 10(b), both buses spent approximately 11 min to traverse the study corridor. The trajectory of bus trip W_W4 shows a much lower speed on the route compared to trip W_W7. However, the total dwell time for bus trip W_W4 was 158 sec. which was lower than bus trip W_W7 for 46 sec., resulting in approximately the same overall trip time.

Saturday data were analyzed using the same methodology as shown in Figures 11(a) and 11(b). Midday weekend off-peak traffic resulted in bus trajectories



(a)



(b)

Figure 11: Westbound (Inbound) Bus Trajectories on (a) Saturday Nov. 3, 2001 and (b) Saturday Nov. 10, 2001

from all stops throughout the corridor was 72 sec. On Saturday Nov. 10, 2001, as shown in Figure 11(b), the trajectories indicate small variations in total run time and nearly the same travel speed on the corridor and on the bridge for all buses. The mean run time was 7:13 min, ranging between 5:04 and 9:14 min. Passenger activities were low with the mean total dwell time for all stops throughout the corridor of 62 sec.

For the westbound direction, the benefits of using vehicle trajectories to pinpoint changes in vehicle behavior can also be shown as detailed in Figures 10(a) and 10(b). The first example is the case of bus trip Th_W5 in Figure 10(a). We can easily observe a change in the bus's performance graphically. As shown in the figure, at distance 1.1 mi, bus Th_W5 was traveling at 16 mph and stopped for a long period (2:24 min at stop 4538). In this case, the bus arrived at stop 4538, which is a time point, at 7:27:42 A.M., earlier than the stop time 7:30:00 A.M. by 2:18 min. We also found a very long dwell time of 1:33 min (from door open to door close) without any passenger movement (zero boarding and alighting). This high stop time highlights the issue of stop location on this corridor. Since bus stops are usually located near signalized intersections (including stop number 4538, a nearside (upstream from intersection) stop located east of SE Milwaukie Ave.), after bus trip Th_W5 closed the door and departed stop 4538, it reached a signalized intersection at the same time the signal phase changed to red and had to wait until the next cycle before it could leave the stop circle. This resulted in an additional recorded stop (dwell time 1:33 min) during which the driver was waiting to keep up with the schedule and a total stop time (2:24 min) before the bus could continue moving downstream.

Another example is the case of the bus trajectories shown in Figure 10(b) where bus trip W_W1 was traveling at 31 mph and stopped for a long period (1:28 min at stop 4538). Bus trip W_W2 was traveling at a lower speed of 17 mph and stopped for a shorter period at the same stop. Since this stop is a nearside stop, bus W_W1 traveled at a higher speed and arrived at stop 4538 at the same time the signal phase changed to red and had to wait until the next cycle before it could leave the stop circle. This resulted in a longer recorded stop time even though the dwell time and number of passengers boarding and alighting were low, e.g., 13 sec dwell time, 2 boardings, and 1 alighting. Bus W_W2 traveled at a slower speed, stopped, and completed its passenger activity when the signal was still green so the bus was able to continue downstream without any additional waiting time. This emphasizes the benefits of using vehicle trajectories in detecting vehicle behavior in detail especially at the stop level. The next section describes characteristics of buses traversing the bridge portion of the study corridor.

3.4 Buses on the Bridge

Recognizing that transit vehicles have different operating characteristics than other vehicles in the traffic stream, it was hypothesized that transit speed could appear similar to other vehicles on the Ross Island Bridge. This bridge has no shoulders and its approaches are bottlenecks, so traffic is usually flowing freely on the bridge. In fact, transit speeds on the bridge were observed to be nearly constant and always higher than the average overall bus speed on the route. As shown in Table 8, the mean bus speed on the bridge was approximately 37.3 mph in the eastbound direction and was 26.5 mph in the westbound direction, while the average corridor bus speeds were 20.8 mph and 19.3 mph in eastbound and westbound direction respectively. This indicates that more or less free flow traffic conditions prevailed on the bridge. This information will be useful and explained further in Chapter 6. The next chapter describes the analysis of the test vehicle data for determining corridor travel times.

Table 8: Bus Mean Speeds

Eastbound Direction

	Bus Mean Speed (mph)			
	Thurs. Nov. 1	**Wed. Nov. 7**	**Sat. Nov. 3**	**Sat. Nov. 10**
On the Bridge	38	38	37	36
Entire Corridor	21	20	21	21

Westbound Direction

	Bus Mean Speed (mph)			
	Thurs. Nov. 1	**Wed. Nov. 7**	**Sat. Nov. 3**	**Sat. Nov. 10**
On the Bridge	21	29	28	28
Entire Corridor	17	16	22	22

4. TEST VEHICLE ANALYSIS

The previous chapter showed how vehicle trajectories can help describe bus movements along the study corridor. In this chapter, with the same methodology using time-space diagrams, we can also describe vehicle movement using vehicle trajectories.

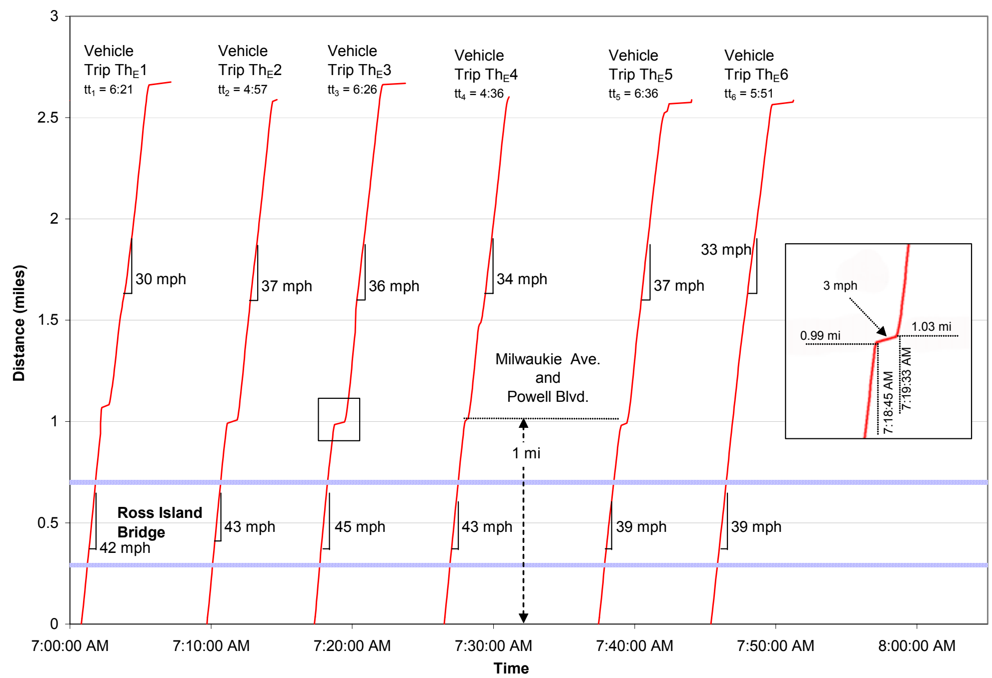
From the test vehicle data obtained from the GPS devices collected on Nov. 1, 3, 7 and 10, 2001, the distance between two reported locations was estimated using the spherical geometry method (Meridian World Data, 2001). This method calculates distance on the circular path along the surface of the Earth between two locations using Latitude-Longitude coordinates. For the test vehicle data available, Table 9 summarizes the numbers of runs for all four study days. Test vehicle trajectories were plotted as shown in Figures 12(a) and 13(a) for preliminary analysis. The mean test vehicle corridor speed and the mean test vehicle travel times were analyzed and will be described later in this chapter. The test vehicle preliminary analysis using time-space diagram will be explained in the next section.

Table 9: Test Vehicle Number of Runs

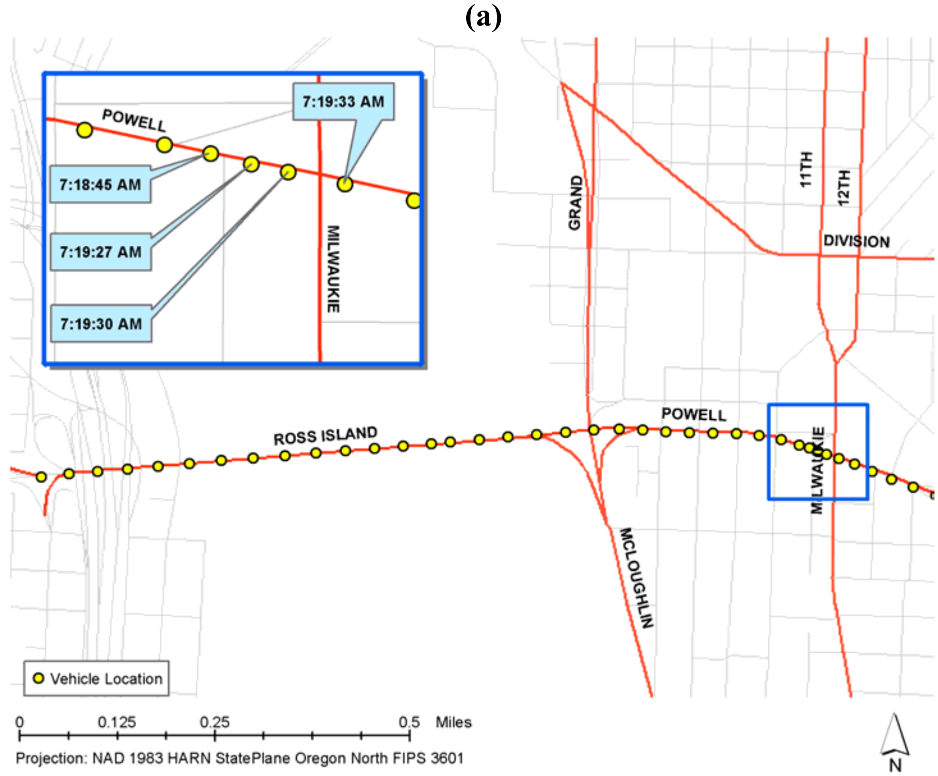
	Number of Test Vehicle Trips			
	Thursday Nov. 1	**Wednesday Nov. 7**	**Saturday Nov. 3**	**Saturday Nov. 10**
Eastbound Direction	15	16	3	5
Westbound Direction	15	18	7	5

4.1 Vehicle Trajectories

Test vehicle trajectories were constructed by plotting the cumulative distance the test vehicle traveled on the *y*-axis and time on the *x*-axis. Figure 12(a) shows examples of eastbound test vehicle trajectories on Thursday Nov. 1, 2001. From the trajectory slopes, it is shown that the test vehicles experienced stop-and-go traffic conditions along the corridor. As shown in Figure 12(a), for example, the inset for vehicle Trip Th_E3 shows that the test vehicle decelerated at distance 0.99 mi, stopped for a short period, and then accelerated to the vehicle's desired speed of 36.0 mph. The inset also shows that between distance 0.99 mi at 7:18:45 A.M. and distance 1.03 mi at 7:19:33 A.M. vehicle 3 traveled at 3.0 mph. This was observed to be where the vehicle arrived at a signalized intersection. As detailed in Figure 12(b), at 7:18:45 A.M., the test vehicle arrived at a signalized intersection between SE Powell Blvd. and SE Milwaukie Ave. at the end of a queue. The vehicle waited for approximately 0:42 min, appeared at the next location, 0.01 mi downstream, at 7:19:27 A.M. and then accelerated toward the intersection at 7:19:30 A.M. From Figure 12(b), it was clear that the vehicle began accelerating after the signal phase turned green and the queue diminished by observing the increasing gap between vehicle locations through time. This behavior was observed at the same location for several more vehicle trips, e.g., test vehicle trips Th_E1, Th_E2, Th_E4 and Th_E5. However, test vehicle decelerations occurred at slightly different locations, since each vehicle reached the end of the queue formed at that intersection at a different location.



(a)

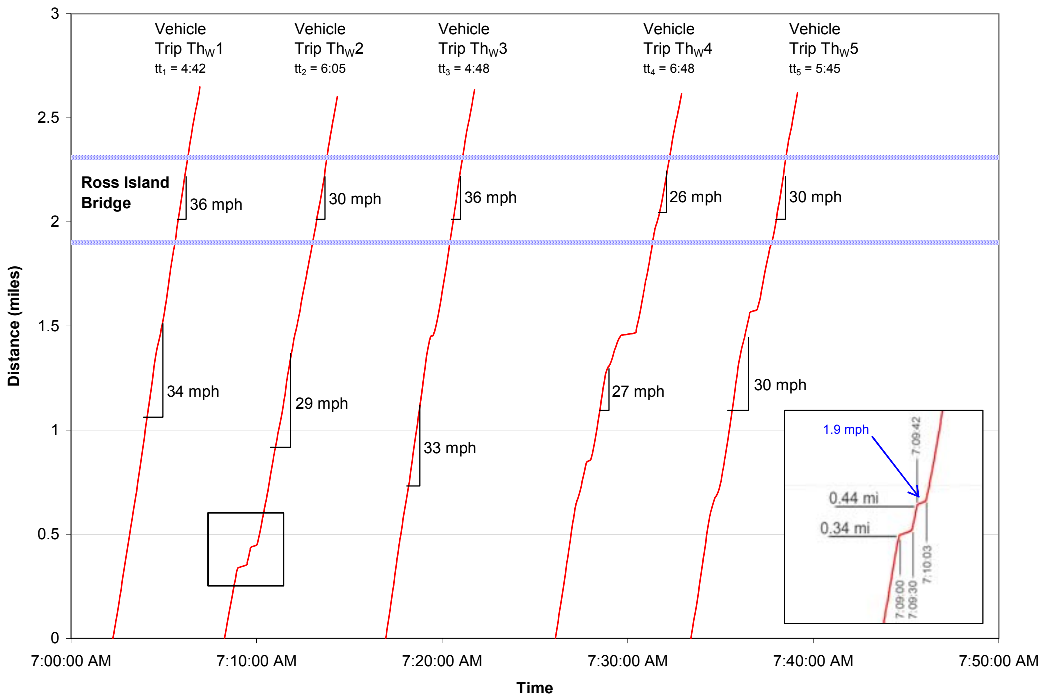


(b)

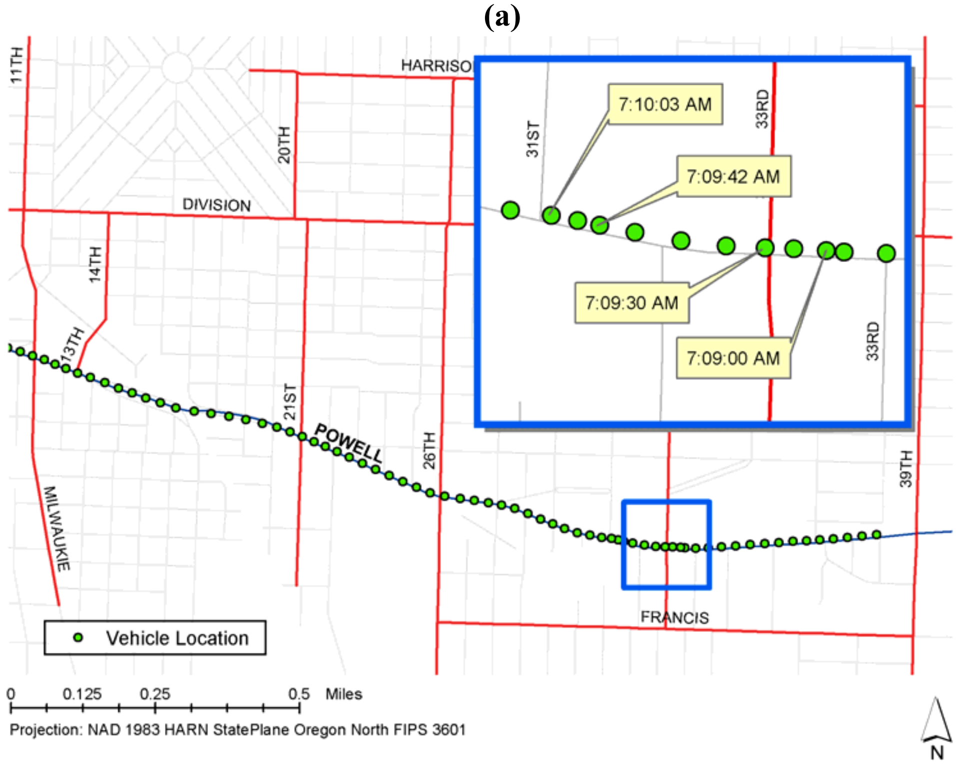
Figure 12: Example of Test Vehicle Investigation Eastbound: Thursday Nov. 1, 2001 Using (a) Time-Space Diagram and (b) Geo-Coded Vehicle Locations

Another example of this preliminary analysis is the case of test vehicles traveling in the westbound direction on the same day, Thursday Nov. 1, 2001. As shown in Figure 13(a), test vehicles traveled westbound from SE 39th Ave. toward downtown Portland with a mean corridor speed of 27.2 mph, ranging between 20.7 mph and 33.8 mph. The inset in Figure 13(a) indicates that test vehicle trip Th_W2 decelerated at distance 0.34 mi at 7:09:00 A.M., stopped for a short period, and at 7:09:30 A.M. accelerated back to 22.6 mph. Test vehicle trip Th_W2 repeated this pattern at distance 0.44 mi at 7:09:42 A.M. As shown in the inset, test vehicle trip Th_W2 decelerated, traveled at 1.9 mph before accelerating to the previous speed at distance 0.46 mi at 7:10:03 A.M. This was observed to be where the vehicle arrived at a signalized intersection. As shown by the vehicle geo-locations in Figure 13(b), at 7:09:00 A.M., the test vehicle arrived at a signalized intersection between SE Powell Blvd. and SE 33rd Ave. at the end of a queue. The vehicle waited and then accelerated at 7:09:30 A.M. when the queue discharged after the signal phase turned green. This behavior was repeated again at the next signalized intersection between SE Powell Blvd. and SE 31st Ave.

The test vehicle trajectories on Wednesday Nov. 7, 2001, Saturday Nov. 3, 2001 and Saturday Nov. 10, 2001 were also analyzed for both eastbound (a) and westbound (b) directions. These vehicle trajectories can be found in Appendix A. From the vehicle trajectories, it was observed that at several intersections, e.g., between SE Powell Blvd. and SE Milwaukie Ave., SE 26th Ave. and SE 33rd Ave., test vehicle trajectories show the same behavior repeatedly as vehicles decelerated,



(a)



(b)

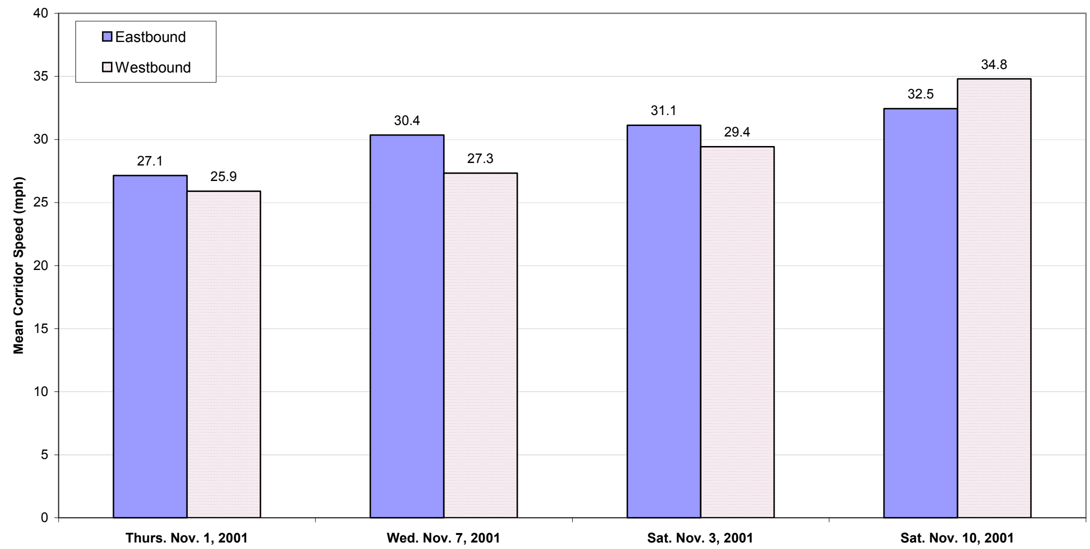
Figure 13: Example of Test Vehicle Investigation Westbound: Thursday Nov. 1, 2001 Using (a) Time-Space Diagram and (b) Geo-Coded Vehicle Locations

traveled at very low speeds and accelerated back to their desired speeds. This also reinforces that time-space diagrams are helpful tools for defining hot spots on arterials. The next section describes the analysis of the test vehicle data for determining corridor speed and travel times.

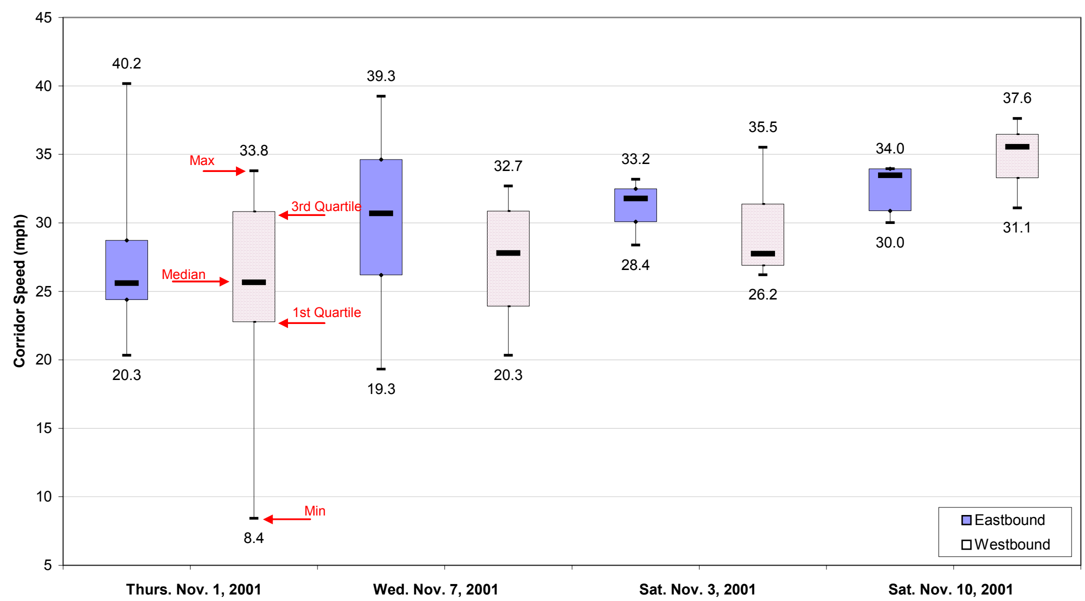
4.2 Test Vehicle Speeds and Travel Times

Test vehicle speeds and travel times were calculated using distances between two locations and time differences generated from the previous section. Figures 14(a) and 15(a) are bar charts illustrating the mean test vehicle speeds and the mean test vehicle travel times for both directions on all study days. In order to illustrate the distributions of speeds and travel times, Figures 14(b) and 15(b) also show box plots of test vehicle corridor speed and corridor travel time respectively. Each box plot captures the variation in each data set (described as one direction over one study day) by summarizing information between the first and the third quartiles as a rectangle. The median is shown by a bar within the box, and the minimum and maximum are shown at the ends of the lines extended from the first and the third quartile respectively.

As can be seen from the bar chart in Figure 14(a), the average speeds for all study days of the test vehicle were similar, varying between 26 mph and 35 mph, and were found to be higher in the eastbound (off peak) direction. However, referring to Figure 14(b), the box plots reflect the fact that there were variations in corridor speeds occurring across study days as a result of traffic conditions. As shown in the

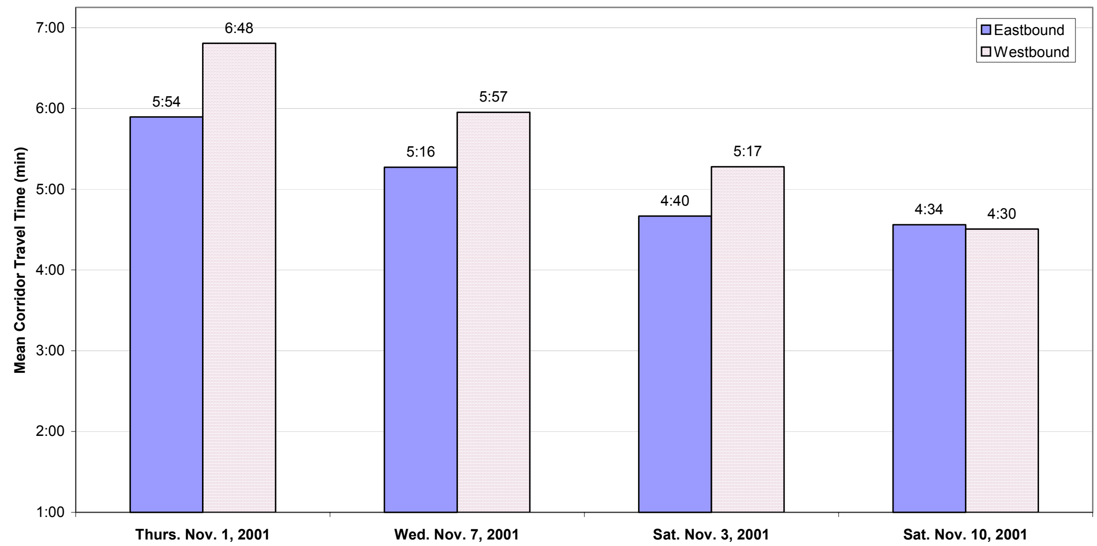


(a)

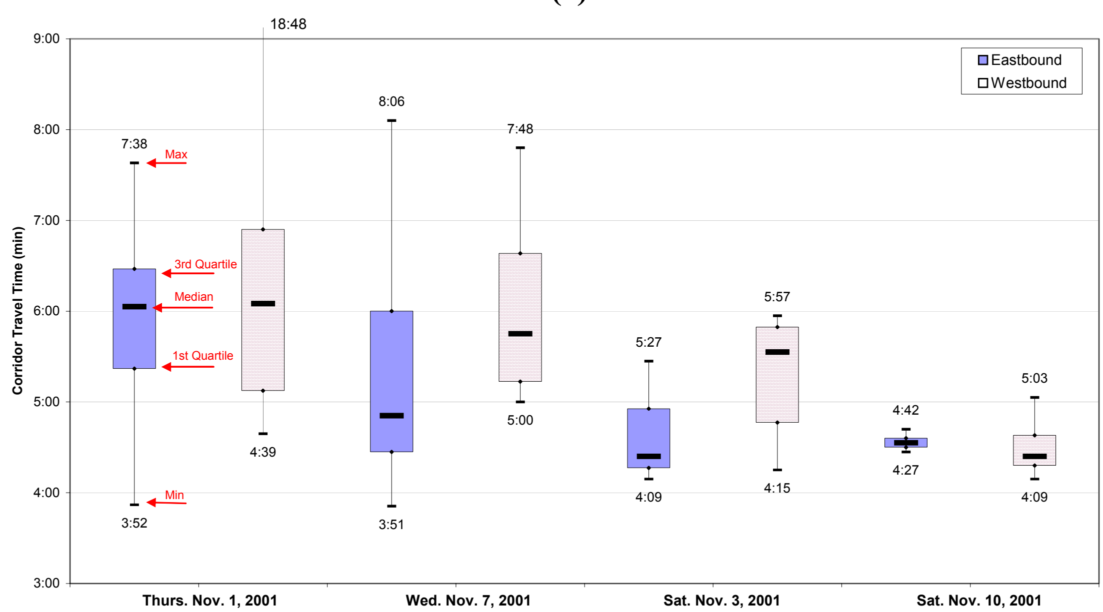


(b)

Figure 14: Test Vehicle Corridor Speeds



(a)



(b)

Figure 15: Test Vehicle Corridor Travel Times

figure, the range of the lines between a pair of minimum and maximum values on Thursday Nov. 1 and Wednesday Nov. 7 is longer than the others from the Saturday off-peak period for both directions. Standard deviations of test vehicle speeds on weekdays (Thursday and Wednesday) in eastbound and westbound directions were 5.3 and 5.2 mph respectively while the weekend standard deviations were found to be lower as 2.1 and 4.3 mph in both directions respectively.

The mean test vehicle travel times were found to vary slightly between the two directions as shown in Figure 15(a). The mean travel times for both directions on all study days were between 4:30 and 6:48 min with some variations as shown by the box plots in Figure 15(b). Test vehicle travel time varied somewhat throughout the study period each day. However, higher variations of vehicle mean travel times can be observed more clearly on weekdays (Thursday and Wednesday) compared to weekends (Saturday) with travel time standard deviations of 1:08 and 2:24 min on the weekdays and 0:23 and 0:41 min on the weekends in eastbound and westbound direction respectively. This indicates that effects from traffic conditions are more pronounced on weekdays.

Now that we have examined corridor speed and travel time, we will examine these two traffic parameters on the bridge as explained in the next section.

4.3 Test Vehicles on the Bridge

In the previous section, we described the analysis of test vehicles on the overall corridor and now we will focus on the bridge portion of the study area. To examine vehicle performance on the Ross Island Bridge, test vehicle speeds were analyzed over the bridge portion of the corridor (length 0.4 mi) for all study days. The mean test vehicle speeds are presented in Table 10 together with the mean test vehicle corridor speeds from the previous section. Referring to the details in Table 10, the mean test vehicle speeds on the bridge varied between 41 and 49 mph in the eastbound direction and between 31 and 45 westbound. Test vehicle speeds on the bridge were found to be higher than the average route speed by factors of approximately 1.5 and 1.3 in the eastbound and westbound direction respectively. Together with the observation of bus speeds on the bridge explained earlier in section 3.4, this confirms that traffic conditions on the bridge were better than the overall conditions along the route and will be further discussed in Chapter 6.

Table 10: Test Vehicle Speeds

Eastbound

	Test Vehicle Mean Speed (mph)			
	Thursday Nov. 1	**Wednesday Nov. 7**	**Saturday Nov. 3**	**Saturday Nov. 10**
On the Bridge	41.4	48.5	40.7	47.2
Entire Corridor	27.1	30.4	31.1	32.5

Westbound

	Test Vehicle Mean Speed (mph)			
	Thursday Nov. 1	**Wednesday Nov. 7**	**Saturday Nov. 3**	**Saturday Nov. 10**
On the Bridge	31.0	39.7	39.4	44.9
Entire Corridor	25.9	27.3	29.4	34.8

Now that we have examined speed and travel time for the overall corridor and the bridge section of the study area, we note that the conditions vary between the test vehicles and the buses. Next we will describe modifications needed to extract useful data from the bus trajectories.

5. TEST SCENARIOS: ALTERNATIVE USES OF BDS DATA

This chapter explores the bus and test vehicle comparison using a speed contour plot as a visual aid. As shown in Figure 16, Portland Metropolitan Area freeway map is filled with colored bars representing speed ranges on each freeway segment where green represents free flow speed, yellow for slower speed and red for very slow or congested speed. In order to understand more about bus and test vehicle movement along the study corridor, vehicle location and speed measured along the route were plotted on top of the study area map using the same color concept as the freeway speed map. As shown in Figure 17(a), the colors shown on the map

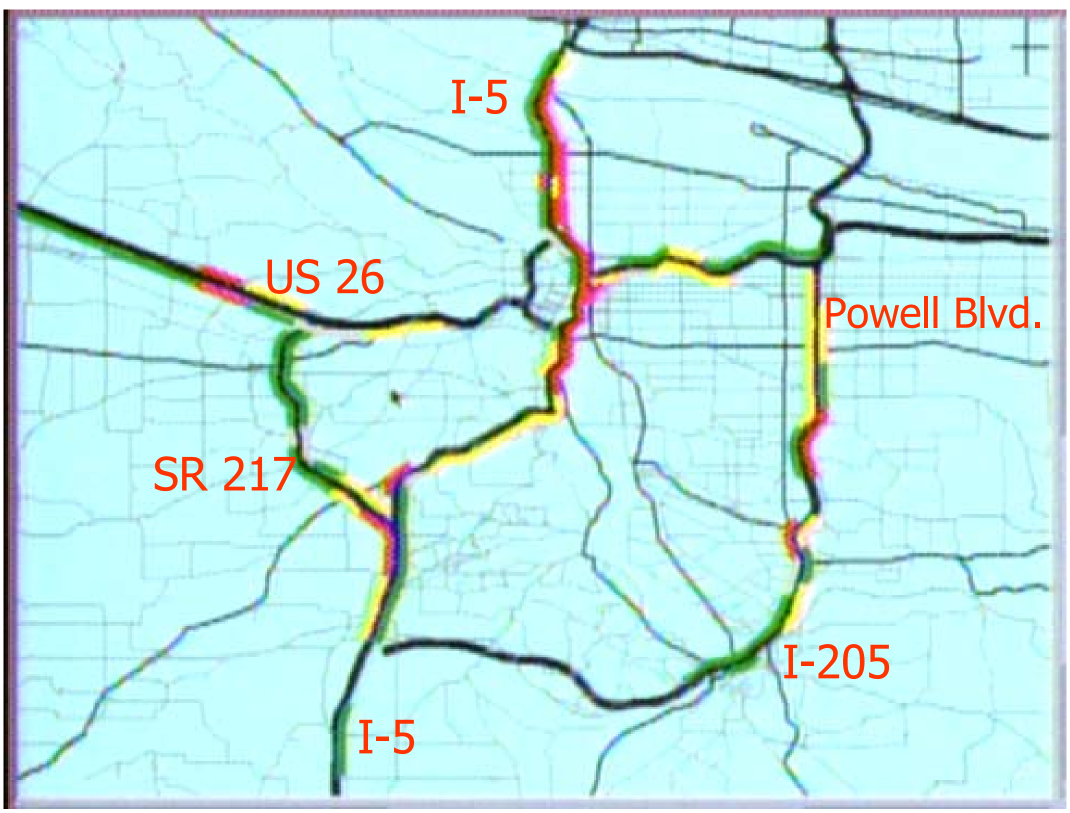
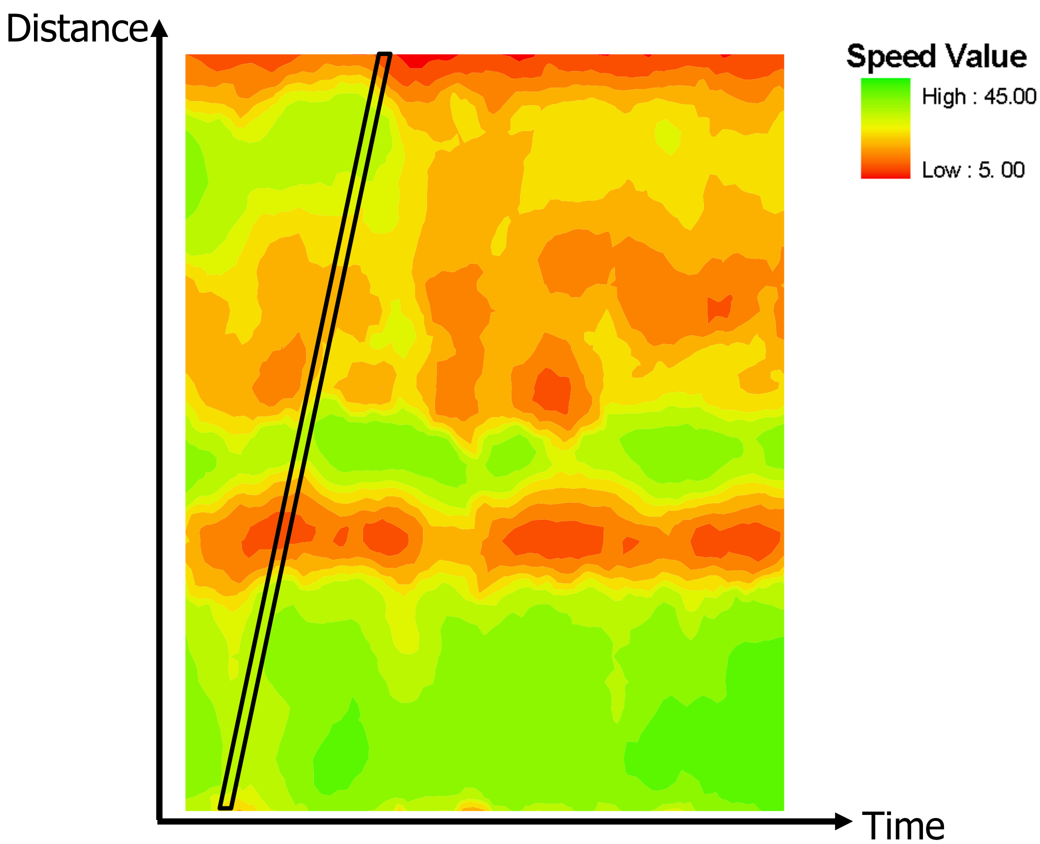


Figure 16: Portland Speed Map Showing Speed on Freeways in Portland Metropolitan Area

(a)



(b)

Figure 17: Speed Contour Plot in Two Dimensions

represent speed measured on particular segments of the corridor. The combination of these speed colors over the time interval studied at locations along the corridor can form a speed surface plot where the *x*-axis is time and the *y*-axis is distance over the corridor as shown in Figure 17(b). This speed surface delivers the characteristics of the vehicle movements along the corridor over time in a diagonal direction as travel distance increases and time proceeds. This can be a useful tool to describe the changes of traffic conditions at locations distances over time by observing the change of the color. Next, a further experiment using the three-dimensional speed contour will be explained.

5.1 Three-Dimensional Speed Contour

Now that we have created a speed surface reflecting the traffic conditions over space and time, further analysis is conducted toward representing actual traffic conditions on a three-dimensional (3-D) diagram.

To further understand the relationship between buses and test vehicles, a 3-D speed contour technique was used to assist in visualizing the speed differences between the buses and the test vehicles spatially and temporally. As shown in Figure 18, 3-D speed contour plots for buses and test vehicles were generated applying not only color to represent the speed but also the depth of the surface with speed on the *z*-axis. The area between each pair of known data points was estimated using a geographic information system (GIS) statistical interpolation method called "Kriging" (Longley, Goodchild, Maguire, & Rhind, 2001).

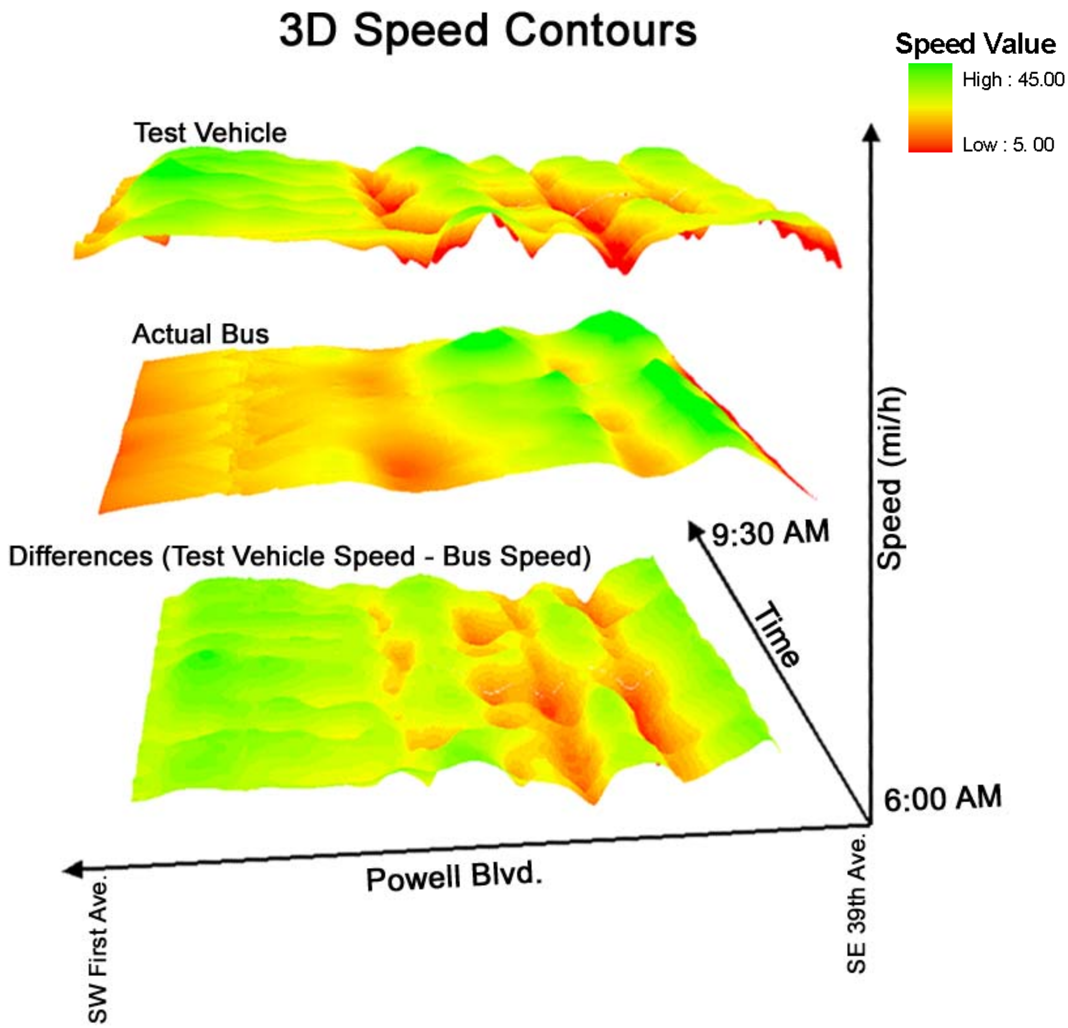


Figure 18: Example Three-Dimensional Speed Contour Plot

The speed contour diagram shows that the test vehicle speed changed smoothly on the surface due to the availability of data every 3 sec while the changes in bus speeds were more coarse since the numbers of bus data points were limited to stop locations. The concave surface reflects slower traffic conditions compared to other patterns on the surface. As vehicle *i* or bus *j* traverses through distance and time in a diagonal direction on the surface, concave and convex surface features describe the varying traffic conditions resulting from deceleration and acceleration. A concave surface feature, as an example, indicates that a vehicle faced queued traffic downstream and accordingly decelerated. A steep slope on the surface represents a faster change in speed of the vehicle. After the lowest point on the surface, traffic conditions began to return to unqueued conditions as the vehicle accelerated. By viewing the differences between the two speed surfaces, one can locate specific locations and times that the test vehicles experienced conditions that were different from those experienced by the buses.

In order to establish the relationship between test vehicles and buses, we could assume that the difference between both vehicles' characteristics, like speed, at every location on the study route should be constant. These constant differences can be shown with a smooth surface representing a steady speed differential between the two surfaces, the test vehicle and bus speed contour plots. However, Figure 18 shows that such differences do not exist between both vehicle types since the difference surface shown in this figure is not rigidly smooth as we hypothesized. This indicates that the buses and test vehicles might not provide a sufficient pair of variables to establish the relationship and we need to develop some alternatives that would fit with test vehicle better than the bus. The next section explains some alternative bus trajectories created from the available BDS data.

5.2 Conceptual Buses

Toward developing an algorithm to relate the bus data to actual traffic conditions, experiments using the bus data were conducted including hypothetical, pseudo and modified pseudo bus scenarios. Non-transit vehicles do not decelerate and accelerate to serve passengers, so the hypothetical bus concept constructs a potential non-stop bus trajectory by subtracting the dwell times from the actual trajectory. Figure 19 shows examples of actual and conceptual buses' trajectories from Thursday, Nov. 1, 2001. The resulting non-stop trajectory shown in Figure 19 is an approximation of how a bus would travel if it did not stop to serve passengers. Buses are large vehicles and their operations are often motivated by schedule adherence and impacted by individual driver characteristics (Strathman et al., 2001). Thus, even without stopping, their travel characteristics will be different than those of passenger cars.

As noted, the BDS system also recorded the maximum instantaneous speed achieved between pairs of stops (El-Geneidy, 2001). Also shown in Figure 19, a pseudo bus trajectory was created by stringing together segments of a trip where the pseudo bus traveled at its maximum recorded speed between each pair of stops. This was based on the hypothesis that the maximum speed could approximately reflect the

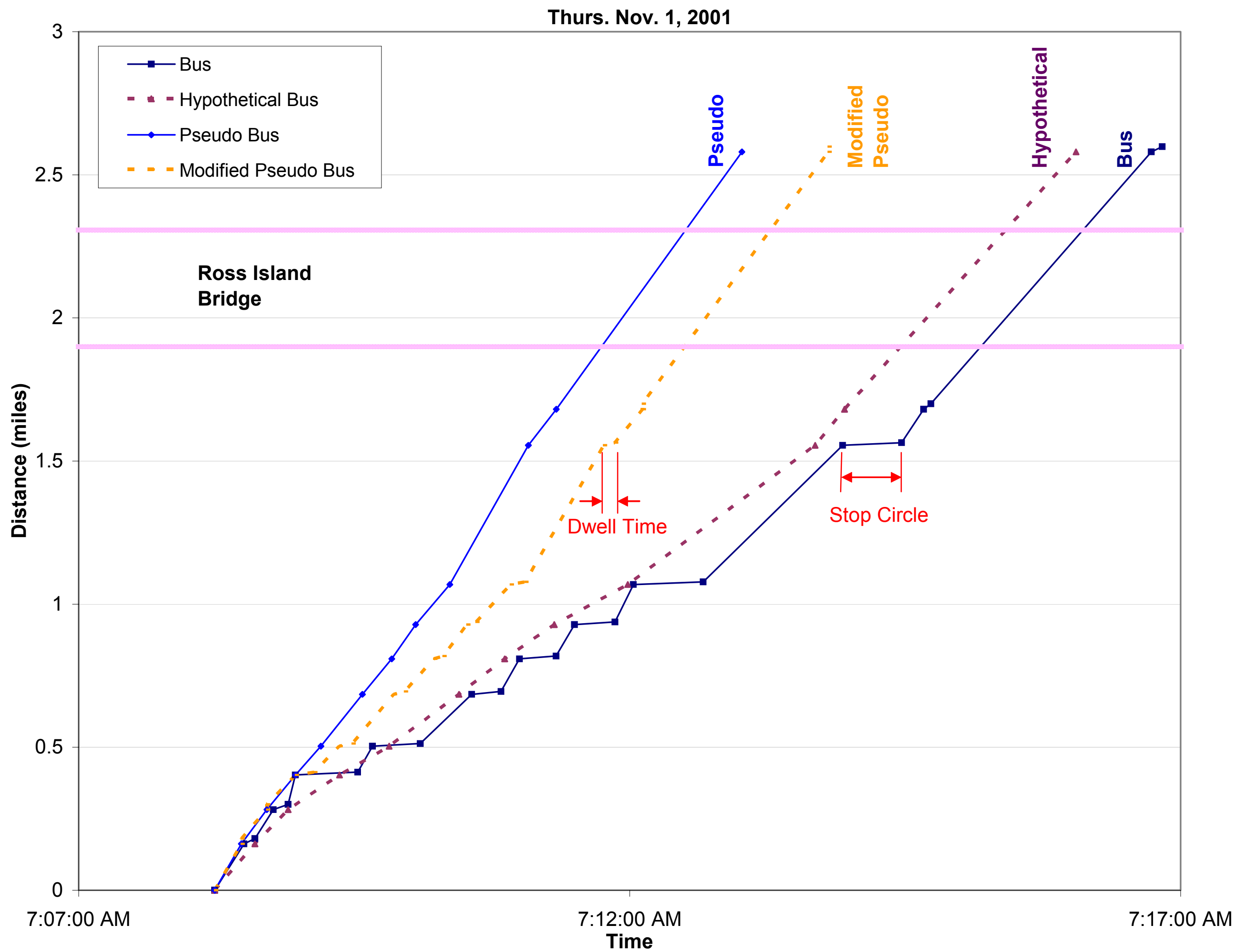
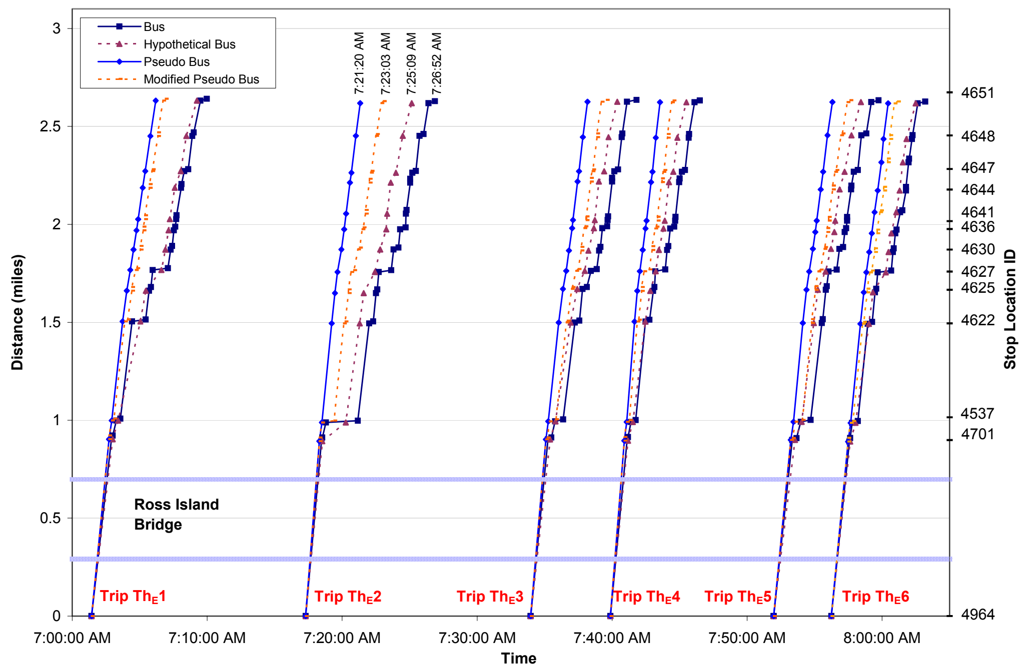


Figure 19: Actual Bus and the Three Conceptual Buses – Hypothetical, Pseudo and Modified Pseudo Bus Trajectories

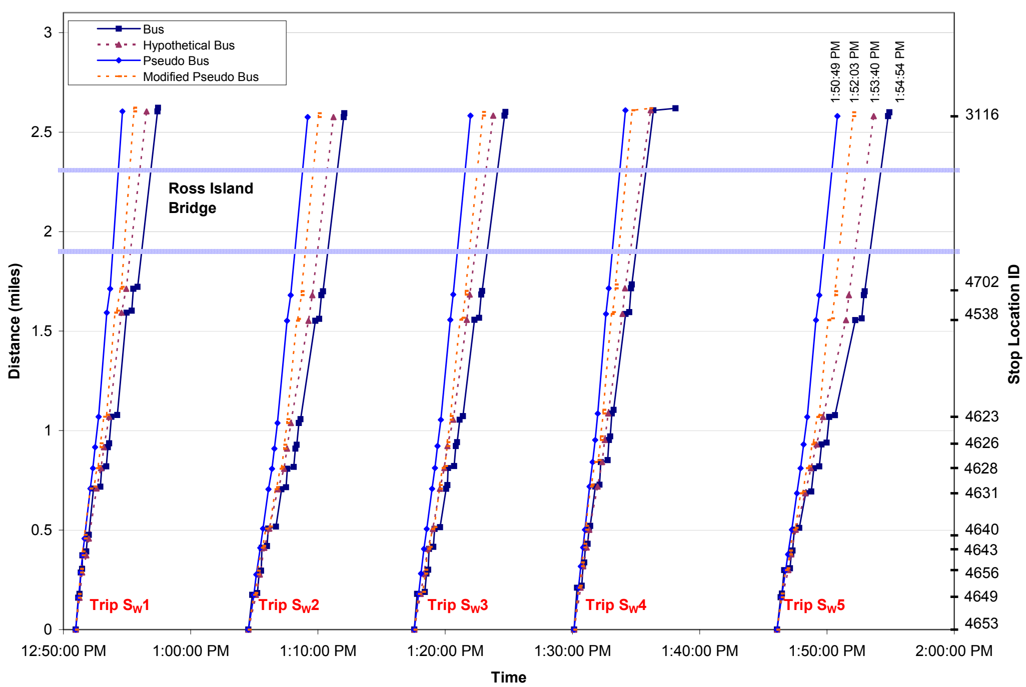
speeds of non-transit vehicles along the route. Further, a modified pseudo bus was created by including the dwell times of the actual bus while considering a bus traveling at its maximum recorded speed (pseudo bus). A modified pseudo bus would approximate the behavior of an actual bus but traverse the corridor with a faster speed. Horizontal segments shown in Figure 19 represent the time the actual bus spent in the stop circle and also the dwell time added to the modified pseudo bus trajectory.

Figures 20(a) and 20(b) show examples of the combination of actual bus trajectories with these three conceptual bus trajectories. The example from eastbound Thursday Nov. 1, 2001 shown in Figure 20(a) indicates that the four trajectories began at the same departure time. Specifically, for example, bus trip Th_E2, hypothetical bus trip Th_E2, pseudo bus trip Th_E2 and modified pseudo bus trip Th_E2 began at 7:17:18 A.M. Pseudo bus trajectories reflect the shortest travel times; for example, pseudo bus trip Th_E2 finished its trip at 7:21:20 A.M., faster than modified pseudo bus trip Th_E2, hypothetical bus trip Th_E2 and bus trip Th_E2 by 1:43, 3:49 and 5:32 min respectively. Using Nov. 1, 2001 data, the mean pseudo bus speed was 36.6 mph, 1.5 times the mean actual bus speed (21.0 mph). The mean hypothetical bus speed was 22.4 mph which is about the same as the mean actual bus speed, while the modified pseudo bus mean speed was 28.9 mph, about 1.4 times the mean actual bus speed.

Figure 20(b) is another example of a comparison between the actual bus and the three conceptual buses' westbound trajectories on Saturday Nov. 3, 2001. The



(a)



(b)

Figure 20: Examples of the Comparison of Actual Bus and Conceptual Bus Trajectories (a) Eastbound Direction on Thursday Nov. 1, 2001 and (b) Westbound Direction on Saturday Nov. 3, 2001

trajectories show that the four buses departed at the same times and that pseudo bus trajectories finished their trips with the shortest run times. For example, pseudo bus trip S_W5 reached the end of the corridor at 1:50:49 P.M., 1:14, 2:51 and 4:05 min before modified pseudo bus trip S_W5, hypothetical bus trip S_W5 and bus trip S_W5 respectively.

All three conceptual buses, the hypothetical, pseudo and modified pseudo buses were created to reflect potential non-transit travel. The pseudo buses maintain more stable speeds along the route. The comparison between the pseudo buses and the test vehicles will be most relevant and will be further described in the next section.

5.3 Test Vehicles versus Conceptual Buses

This section explains the comparison between the test vehicles and the conceptual buses. In order to use the bus data to represent actual traffic conditions, experiments comparing the "pseudo," "modified pseudo" and "hypothetical" bus scenarios to the test vehicle trajectories were conducted. As described in section 5.2, hypothetical (non-stop) travel times were calculated as the net run time minus the time the bus stopped to serve passengers. Pseudo travel times were calculated by applying the recorded maximum speed between stops to each arterial segment. Modified pseudo travel times were calculated using the same concept as the pseudo bus but including passenger activity time (dwell time).

Figure 21 shows an actual bus trajectory together with the three conceptual bus trajectories from one set of data as an example. A test vehicle trajectory was added in order to make a comparison between the test vehicle and each type of bus. As shown, the actual bus and test vehicle trajectories did not have similar shapes. It is clear that the test vehicle link speeds were substantially higher than those of the actual bus. The test vehicle's speed appeared most similar to the speed of the pseudo bus as shown in Figure 21(c). Further examples of bus trajectories, corresponding hypothetical, pseudo and modified pseudo trajectories and test vehicle trajectories for 4 study days for the eastbound and westbound directions are included in Appendix B.

This analysis has shown that the most suitable comparison will be between the test vehicle and the pseudo bus. Therefore, the next chapter will focus on conducting a preliminary analysis of the relationship between the test vehicle and the pseudo bus using their mean speeds.

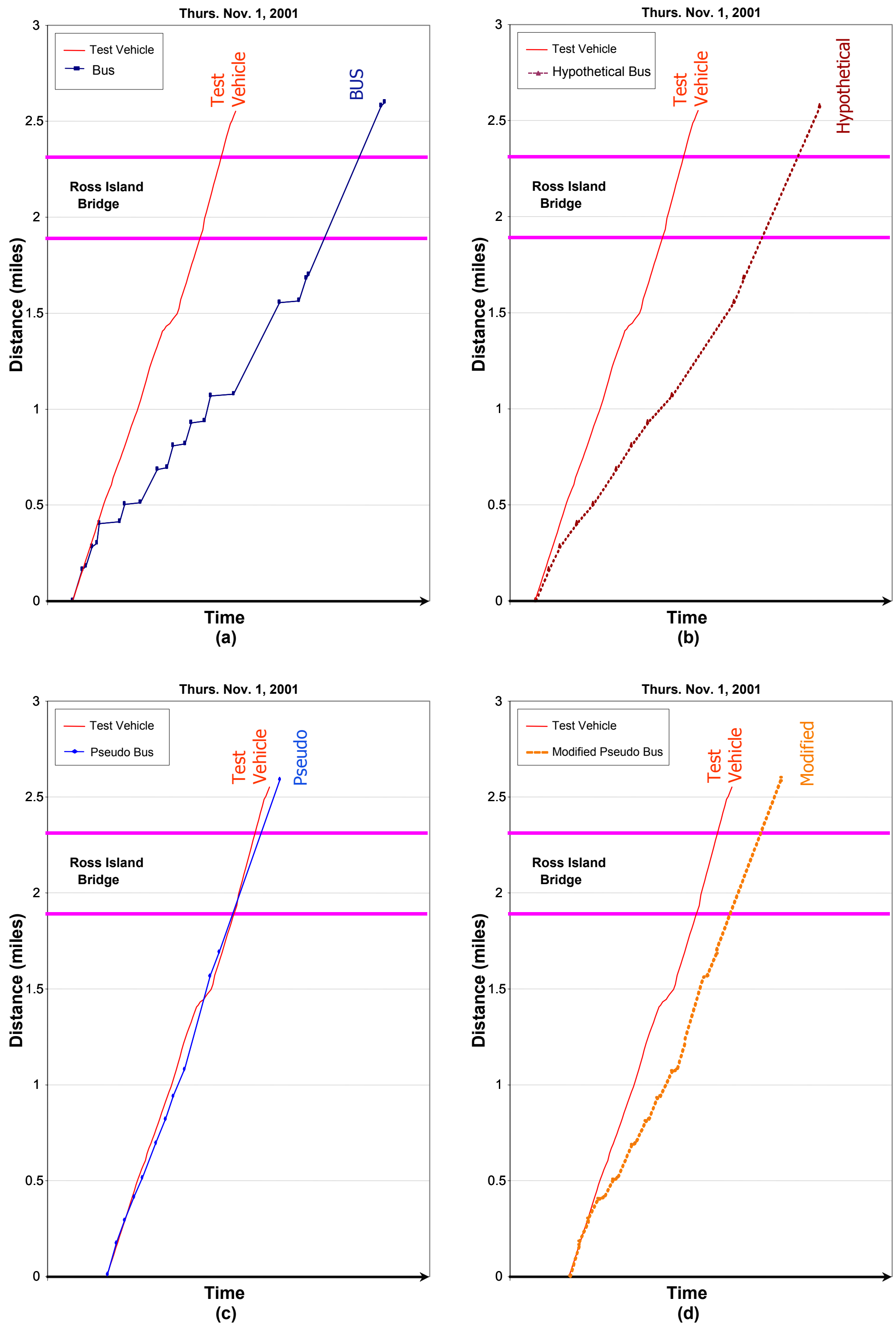


Figure 21: The Comparison Between Test Vehicle and All Bus Trajectories

6. PRELIMINARY ANALYSIS OF VEHICLE MEAN SPEED

From the previous chapter, we have shown that the relationship between the bus and test vehicle might be best explained using the pseudo bus trajectory created with the maximum achieved speed record. This preliminary analysis is designed to establish some initial relationship between the two vehicles using mean speeds as the primary variable.

Bus run times were calculated using the difference between leave time from the first stop (stop 4964 for eastbound direction and stop 4653 for westbound direction) and arrive time at the last stop (eastbound direction at stop 4651 and westbound direction at stop 3116) on the corridor. Test vehicle travel times were estimated by subtracting the time recorded at the end of the route from the time at the beginning. Both include the time when the vehicles stopped due to traffic control and congestion, e.g., at the end of the queues at signalized intersections. The next section tests the minimum statistical requirements for test vehicle and bus trip sample sizes.

6.1 Sample Size Analysis

For any travel time study, a minimum sample size is desired to verify the statistical significance of any results and to minimize the data collection cost in order to fit within budgetary constraints. Therefore, it is important to execute a number of travel time collection runs to determine a statistically permitted level of error from the sample.

In general, the statistical estimation of the sample size n is based on specifying probability statements about the level of confidence in the error that is acceptable. The permitted error E is expressed as:

$$E = Z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}$$

Where
n = minimum sample size
$Z_{\alpha/2}$ = standard normal curve area to its right equals $\alpha/2$ for a confidence level of $1 - \alpha$
σ = standard deviation of population
E = maximum error of the estimation

Often the estimation is done based on prior information or an initial sample (pre-sample) which leads to a random variable having a t-distribution with $n - 1$ degrees of freedom (Johnson, 2000). At the same level of confidence of $(1 - \alpha)100\%$, the new equation is written upon solving for n as:

$$n = \left[\frac{t_{\alpha} \cdot s}{E} \right]^2$$

Where
s = estimate standard deviation of random samples
t_{α} = t distribution statistic (used instead of $Z_{\alpha/2}$ when dealing with random samples or small sample size) (Quiroga & Bullock, 1998)
E = maximum error of the estimation

Ranges of permitted errors in the estimate of the mean travel speed are defined based on study purpose. For traffic operations, trend analysis or economic studies, a range from ± 2 mph to ± 4 mph is deemed acceptable (Institute of

Transportation Engineers, 2000). This allowable error is also confirmed in Oppenlander (1976).

For this study, both bus data and test vehicle data from initial runs were used in determining the minimum number of runs. Table 11 summarizes the key statistics used in calculating the minimum required sample size. Since the statistic t_{α} is a function of *n*, an iterative procedure is needed to solve for *n*. As a result, an example calculation found that the minimum required bus sample size is 10 runs and with the same methodology, the minimum required test vehicle sample size is 13 runs. This iterative procedure can be found documented in Appendix C.

Table 11: Minimum Sample Size Requirement

	Initial Run	
	Bus	**Test Vehicle**
Mean Speed	21.0 mph	27.1 mph
Standard Deviation	4.07 mph	5.00 mph
Number of Initial Runs	15	15
Level of Significance, α	0.05	0.05
Permitted Error, E	± 3 mph	± 3 mph
Sample Size Required, *n*	10	13

By following the methodology explained previously, Table 12 summarizes examples of minimum numbers of runs for the test vehicles at specified levels of confidence for allowable errors of ± 3 and ± 4 mph.

Recalling Table 6, bus data collected on the study days are available at a minimum of 10 runs which exceeds the minimum requirement. This ensures that the availability of bus data exceeds the minimum level of confidence of 95%. However, the test vehicle data availability as presented in Table 12, indicates that both

Table 12: Test Vehicle and Bus Minimum Sample Size Requirement Versus Existing Numbers of Runs

Eastbound

	Bus No. of Runs		Test Vehicle No. of Runs	
	Have	**Need for 95%**	**Have**	**Need for 95%**
Thursday Nov. 1, 2001	15	10	15	15
Saturday Nov. 3, 2001	12	10	3 *	15
Wednesday Nov. 7, 2001	15	10	16	15
Saturday Nov. 10, 2001	10	10	5 *	15

Westbound

	Bus No. of Runs		Test Vehicle No. of Runs	
	Have	**Need for 95%**	**Have**	**Need for 95%**
Thursday Nov. 1, 2001	19	10	15	15
Saturday Nov. 3, 2001	12	10	7 *	15
Wednesday Nov. 7, 2001	16	10	18	15
Saturday Nov. 10, 2001	11	10	5 *	15

Note: * Insufficient number of runs to meet the 95% level of significance

Saturday Nov. 3 and Saturday Nov. 10, 2001 representing the off-peak period fall below the minimum requirement for the 95% level of significance. Since the data collected on these two Saturdays represent bus travel on the corridor during the midday off-peak period as stated earlier, Saturday data were analyzed as a whole which makes the combined number of test vehicle runs in the eastbound direction 8 runs and 12 runs in the westbound direction. As shown in Table 13, the test vehicle analysis on Thursday Nov. 1 and Wednesday Nov. 7, 2001 are at the 95% level of significance and higher. In the off-peak period in the eastbound direction, results are ensured to be significant with the level of confidence of 85% and are proven to be significant at 90% level of confidence for the westbound direction.

Table 13: Weekday and Weekend Combined Scenario Test Vehicle and Bus Number of Runs and Level of Significance Met

Eastbound

	Bus No. of Runs		Test Vehicle No. of Runs	
	Have	**Need for 95%**	**Have**	**Need for 95%**
Weekday Morning Peak	30	10	31	15
Weekend Midday Off-Peak	22	10	8 *	8 (*85%*)

Westbound

	Bus No. of Runs		Test Vehicle No. of Runs	
	Have	**Need for 95%**	**Have**	**Need for 95%**
Weekday Morning Peak	35	10 @ 95%	33	15
Weekend Midday Off-Peak	23	10 @ 95%	12 *	10 (*90%*)

Note: * Insufficient number of runs to meet the 95% level of significance
(*90%*) Reduced level of significance

6.2 Speed and Travel Time Comparison

The mean travel times for all four bus scenarios together with the test vehicles during both peak and off-peak periods were analyzed for both eastbound and westbound traffic. This analysis was also separated between the entire corridor and the bridge portion. The boxplot technique was used to analyze the travel time variation during the peak and off-peak periods and was also included in Appendix D. From the boxplot analysis, pseudo bus travel times show the least variation ranging between 3:40 and 5:07 min with a median travel time of 4:12 min during the peak period. However, during the off-peak period, the test vehicle boxplot indicates less variation, ranging between 4:09 and 5:27 min with a median of 4:32 min which is slightly different from the pseudo bus boxplot.

On the other hand, the mean travel time variations for the westbound direction on both peak and off-peak periods were observed to be higher compared to the eastbound direction due to the higher traffic volumes in this direction (inbound). The pseudo bus travel times were again found to have less variation, ranging between 3:54 and 5:37 min, with a median of 4:41 min during the peak period, ranging between 3:39 and 4:53 min, with a 4:30 min median during the off-peak period. Figures illustrating the westbound travel time variation analysis can also be found in the Appendix D. The next section describes the first attempt to establish a relationship between the two vehicles.

6.3 Naive Analysis: the Relationship of Mean Speeds

To verify the relationship between the test vehicle and the pseudo bus, the two vehicle velocities and travel times were compared by departure time. The speeds of the test vehicles and pseudo buses were plotted against the departure time for peak (Thursday and Wednesday) and off-peak (Saturday) periods for both directions. Figure 22(a) shows example speed plots for the westbound peak period. The speed scatter plots show that all vehicles traveled at lower speeds during the morning peak period. Traffic conditions improved over time as the trend lines for both vehicle speed and pseudo speed sloped upward as shown in Figure 22(a). The speed scatter plots also show the improvement of traffic conditions in that the points in the scatter plots in the early morning are located lower compared to the speed plots later in the

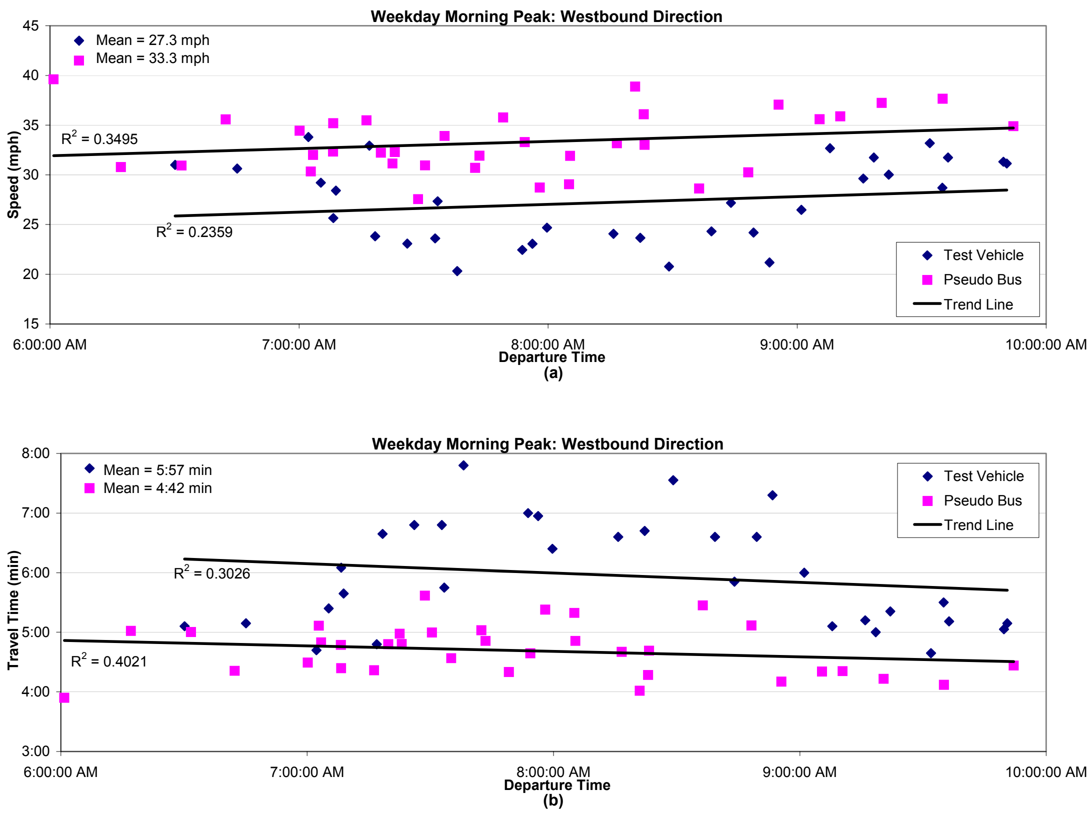


Figure 22: Examples of (a) Speed and (b) Travel Time of the Test Vehicle and Pseudo Bus Versus the Departure Time

Test vehicle and pseudo bus travel times were also plotted versus departure time. An example of test vehicle and pseudo bus travel time plots for the westbound peak period is shown in Figure 22(b). Travel time trend lines indicate that all vehicles spent more time traversing the study corridor during the morning peak period (7:00–9:00 A.M.) as well. The complete test vehicle and pseudo bus speed and travel time plots are included in Appendix E.

6.3.1 Corridor Relationship of Means

This section describes the naive analysis that was conducted by simply calculating the relationships between the mean travel times and mean speeds of the test vehicles and the three bus scenarios. For example, referring to Figure 22(a), the relationship between test vehicle and pseudo bus mean speeds was established as follows.

For the weekday morning peak in the westbound direction:

$$\frac{\bar{v}_{veh} = 27.3\,\text{mph}}{\bar{v}_{pseudo} = 33.3\,\text{mph}} = 0.82$$

$$\bar{v}_{veh} = b\,\bar{v}_{pseudo}$$

$$\bar{v}_{veh} = 0.82\,\bar{v}_{pseudo}$$

By following the same methodology described above, Table 14 summarizes the relationships between test vehicle and pseudo bus mean speeds and mean travel times. The analysis showed that the test vehicle speed ranged between 0.77 and 0.89 times the pseudo bus speed. Analogously, the test vehicle travel time is estimated to be between 1.05 and 1.30 times the pseudo bus travel time. As shown in Table 14, the effect from the peak period can be observed by comparing the morning peak period and the midday off-peak period in both directions. The relationships between the test vehicle and the pseudo bus during the morning peak varied between the two directions (inbound and outbound) since westbound experienced higher traffic volumes than the eastbound direction. On the other hand, the relationships on the weekend midday off-peak periods exhibited similar relationships on both directions as observed from the *b* coefficients shown in Table 14. The next section explains a similar analysis focusing on the Ross Island Bridge portion of the corridor.

Table 14: Relationship of Test Vehicle and Pseudo Bus Mean Corridor Speeds and Corridor Travel Time

Eastbound

	Mean Speed		*b* Speed	Mean Travel Time		*b* Travel Time
	Vehicle	Pseudo		Vehicle	Pseudo	
Weekday Morning Peak	28.8	37.2	0.77	5:34	4:17	1.30
Weekend Midday Off-Peak	32.0	35.8	0.89	4:36	4:23	1.05

Westbound

	Mean Speed		*b* Speed	Mean Travel Time		*b* Travel Time
	Vehicle	Pseudo		Vehicle	Pseudo	
Weekday Morning Peak	27.3	33.3	0.82	5:57	4:42	1.27
Weekend Midday Off-Peak	31.7	35.6	0.89	4:57	4:24	1.12

6.3.2 Bridge Relationship of Means

In the previous section, we described the preliminary analysis used for establishing the relationship between the test vehicle and the pseudo bus over the entire study corridor. This section will further explain the bridge analysis using the same methodology. For the bridge relationships, the test vehicle and pseudo bus travel times were found to be very similar on the bridge with a difference less than 5 sec on both directions for both peak and off-peak periods as shown in Appendix D. The bridge travel time comparisons also indicate that the test vehicle mean travel time on the bridge was lower but close to the actual bus mean travel time. The bridge naive analysis was also conducted using the same methodology as shown in the corridor relationship study in section 6.3.1. However, as we hypothesized before since the bridge has no shoulders, nor any access points, traffic conditions might prevail at free flow speed for both the test vehicle and the bus. Therefore, test vehicles were compared versus actual bus and versus pseudo bus. Figures 23(a) and 23(b) show examples of the comparisons between bridge speeds and bridge travel times. Both test vehicle and pseudo bus mean speeds and mean travel times were

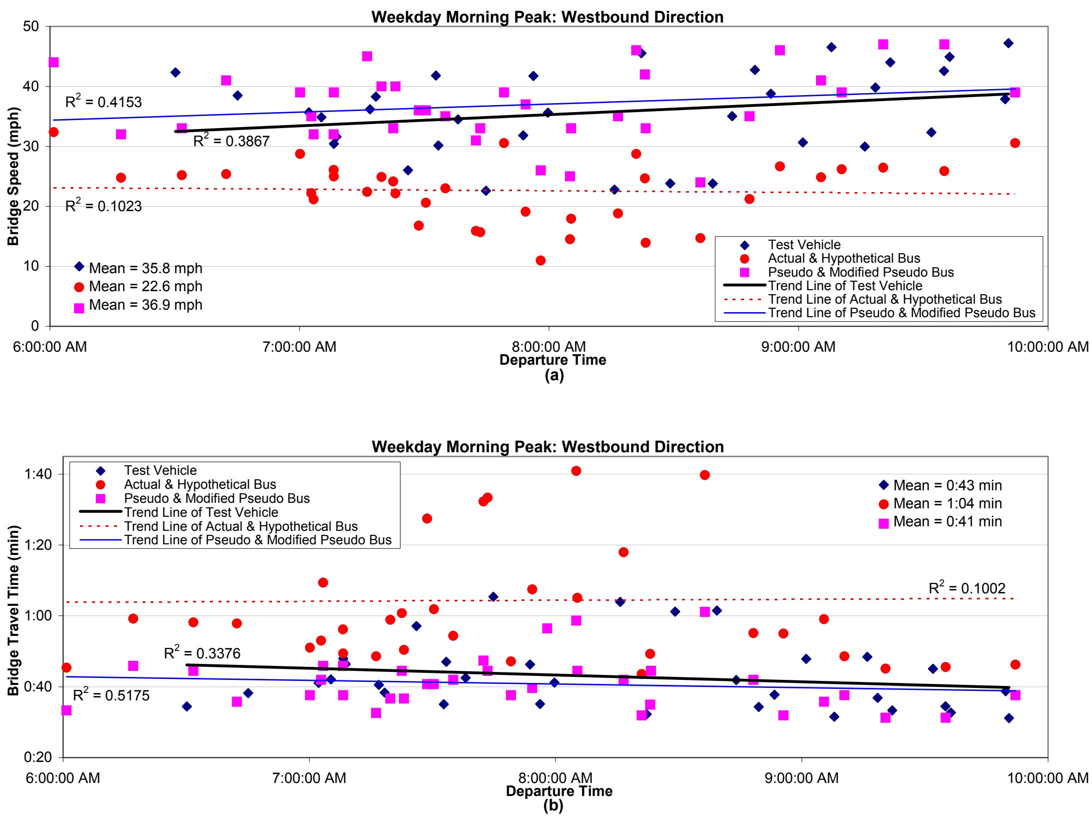


Figure 23: Test Vehicle and the Four Bus Scenarios Comparison on (a) Speed and (b) Travel Time on the Bridge

scattered close to one other and their trend lines. All of the peak and off-peak period bridge speeds and bridge travel time scatter plots for the two directions can also be found in Appendix F.

Referring to Figure 23(a) as an example, relationships between test vehicle, actual bus and pseudo bus bridge mean speeds were established as follows.

For weekday morning peak, westbound direction:

$$\frac{\overline{v}_{b-veh} = 35.8\,\text{mph}}{\overline{v}_{b-bus} = 22.6\,\text{mph}} = 1.58$$

$$\overline{v}_{b-veh} = b\,\overline{v}_{b-bus}$$

$$\overline{v}_{b-veh} = 1.58\,\overline{v}_{b-bus}$$

$$\frac{\overline{v}_{b-veh} = 35.8\,\text{mph}}{\overline{v}_{b-pseudo} = 36.9\,\text{mph}} = 0.97$$

$$\overline{v}_{b-veh} = b\,\overline{v}_{b-pseudo}$$

$$\overline{v}_{b-veh} = 0.97\,\overline{v}_{b-pseudo}$$

These outcomes, however, prove that even though the bridge characteristics are supporting free flow conditions for vehicles, it does not provide the opportunity for the bus to travel at similar speeds. Instead, the maximum speed achieved by the bus on the bridge reflects a closer relationship compared to the test vehicles.

By following this methodology, Table 15 summarizes the relationship between test vehicles and pseudo buses bridge mean speeds and mean travel times. It can be observed that the relationship on the bridge provides a similar outcome regardless of direction and peak period issues. As we can see, the *b* coefficients for the bridge speed relationship are in a very close range running between 0.97 and 1.03. Analogously, the bridge travel time relationships show a similar pattern with the *b* coefficients in a close range between 0.97 and 1.04. This emphasizes that bridge characteristics help create free flow conditions for both the test vehicles and pseudo buses.

Table 15: Relationship of Test Vehicle and Pseudo Bus Mean Bridge Speeds and Mean Bridge Travel Time

Eastbound

	Bridge Mean Speed		***b* Speed**	**Bridge Mean Travel Time**		***b* Travel Time**
	Vehicle	**Pseudo**		**Vehicle**	**Pseudo**	
Weekday Morning Peak	45.0	44.2	1.02	0:33	0:34	0.97
Weekend Midday Off-Peak	44.8	43.7	1.02	0:33	0:34	0.97

Westbound

	Bridge Mean Speed		***b* Speed**	**Bridge Mean Travel Time**		***b* Travel Time**
	Vehicle	**Pseudo**		**Vehicle**	**Pseudo**	
Weekday Morning Peak	35.8	36.9	0.97	0:43	0:41	1.04
Weekend Midday Off-Peak	41.7	40.3	1.03	0:36	0:37	0.97

In order to compare these bus travel times to national averages, corridor speeds were derived by dividing the total travel distance, approximately 2.6 mi, by the net travel time. Average U.S. bus travel times were reported as 4.2 min/mi in suburbs, 6.0 min/mi in the city, and 11.5 min/mi in the central business district (Levinson, 1983). From this study, we found that the mean travel times in the eastbound and westbound directions are 8:09 and 9:34 min respectively, or 3.13 and 3.68 min/mi, which is faster than the national study reported. A comparison of test vehicle and bus speeds also shows that test vehicle speeds were approximately 1.5 times greater than the buses. National averages indicate that vehicles usually travel 1.4 to 1.6 times faster than buses (Levinson, 1983), and the U.S. Department of

Transportation reports an average bus speed of 10 mph in the city and 14.3 mph in the suburbs (Federal Transit Administration, 1992).

From this naive analysis, we preliminarily established a relationship between the test vehicle and the pseudo bus for both speed and travel time. However, we are still lacking a robust method to generate a statistically significant relationship. The next chapter analyzes test vehicles and pseudo buses using a more rigorous statistical methodology.

7. REGRESSION ANALYSIS: RELATIONSHIP BETWEEN TEST VEHICLE AND PSEUDO BUS

Referring back to Chapter 6, what we accomplished so far is to compare the mean speed and travel time of both test vehicles and pseudo buses by direction on both peak and off-peak periods, also on the entire corridor and on the bridge. Based on this relatively naive analysis, we have proposed a linear relationship between test vehicle and pseudo bus performance parameters. In this chapter we propose a statistically rigorous methodology based on a linear relationship of the form:

$$v_{veh} = \beta \, v_{pseudo}$$

The relationship is explained as a linear equation having test vehicle speed and pseudo bus speed as the dependent and independent variables respectively. Figure 24

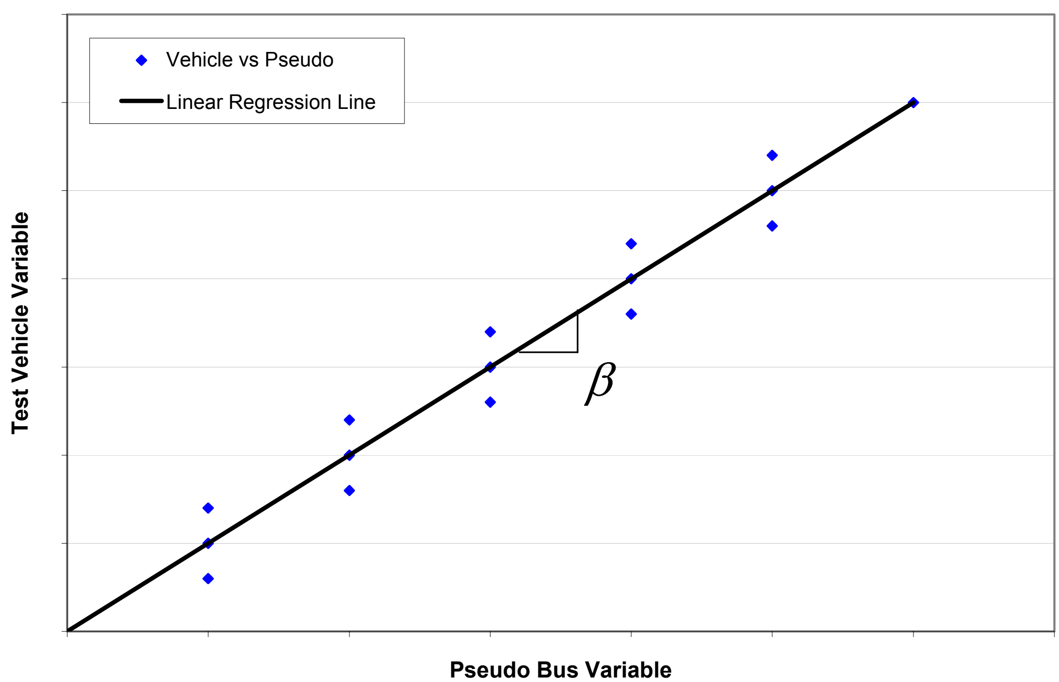


Figure 24: Linear Model Showing Relationship Between Test Vehicle and Pseudo Bus

shows an example of this linear model with the pseudo bus speeds on the *x*-axis and the test vehicle speeds on the *y*-axis.

First we test the existence of a linear relationship between test vehicle and pseudo bus which will be explained in the next section.

7.1 Paired *T*-Test: the Difference of Means

This section uses the *t*-test difference of means to validate the existence of a linear coefficient β. To confirm the statistical validity of the relationship between test vehicles and pseudo buses, a hypothesis test concerning the linear regression coefficient β (slope of regression line) was conducted. The null hypothesis of $\beta = 0$ was formulated to prove the existence of a relationship between test vehicle speeds and pseudo bus speeds. A set of paired test vehicle and pseudo bus speeds was prepared by matching speeds by departure time within an acceptable window of 10 min (chosen since it reflects the mean bus headway). This analysis was performed using:

- Alternative hypothesis: $\beta \neq 0$
- Level of significance: $\alpha = 0.05$
- Number of sample pairs for eastbound direction: $n_e = 41$
- *T*-critical: $t_{0.025}$ for 40 degrees of freedom = ± 2.021
- Number of samples for westbound direction: $n_w = 40$
- *T*-critical: $t_{0.025}$ for 39 degrees of freedom = ± 2.023

From the eastbound study, the t value was equal to 9.321 which is greater than +2.021 and in the westbound direction, the t value was equal to 9.748 which is also greater than +2.023.

Since the t values for both directions were greater than their t-critical, the null hypothesis must be rejected. We conclude that the relationships between pseudo bus and test vehicle speeds are valid for both directions of traffic. The next section continues by establishing a confidence interval corresponding to the naive analysis of mean speeds.

7.2 Statistical Testing of Coefficients

In section 7.1, we proved the statistical validity of the relationship between the test vehicle and pseudo bus speeds. In this section, we continue by testing whether that relationship can be initially estimated with coefficients established earlier in section 6.3.

Referring to section 6.3, the relationships between the test vehicle and pseudo bus both on the corridor and on the bridge were tested using a naive analysis. The point estimates presented previously in Table 14 and 15 were conducted using the ratio of the two variables – test vehicle and pseudo bus – to establish uncomplicated relationships (coefficient b). However, the analysis does not necessarily yield statistically significant results. In section 7.1, we proved the statistical validity of the relationship between the test vehicle and pseudo bus speeds. A hypothesis test concerning the slope of a linear relationship (coefficient β) has proven that the relationships between pseudo bus and test vehicle speeds are valid ($\beta \neq 0$) for both directions of traffic on the corridor and the bridge.

Since point estimates cannot be expected to coincide with the quantities they are intended to estimate, it is preferable to replace them with interval estimates corresponding to the naive analysis of mean speeds. Referring to Table 14 and 15, we hypothesize that the *b* coefficients representing the relationship (slope) between test vehicle and pseudo bus speeds along the route are 0.77 and 0.82 in the eastbound and westbound directions respectively. A paired set of test vehicle and pseudo bus speeds used in the section 7.1 analysis was used again to generate a random sample set containing coefficient b_i for each speed pair. The example analysis focusing on the relationship in the westbound direction was performed using:

- Null hypothesis H_0: $\beta = 0.82$
- Alternative hypothesis H_1: $\beta \neq 0.82$
- Level of significance: $\alpha = 0.05$
- Number of samples for westbound direction: $n_w = 40$
- T-critical: $t_{0.025}$ for 39 degrees of freedom = ± 2.023

The analysis found that:

$$\bar{b} = \frac{\sum_{i=1}^{n} b_i}{n} = 0.8036$$

Standard Deviation (S) = $\sqrt{\frac{\sum_{i=1}^{n_w} (b_i - \bar{b})^2}{n_w - 1}}$ = 0.1219

Standard Error (SE) $= \frac{S}{\sqrt{n}} = 0.01927$

The 95% confidence interval of the mean relationship between test vehicle and pseudo speeds becomes:

$$\bar{b} - t_{\alpha/2} \cdot SE \quad < \beta < \quad \bar{b} + t_{\alpha/2} \cdot SE$$

$$0.7646 \quad < \beta < \quad 0.8426$$

Since $\beta = 0.82$ falls within the confidence interval, we would not reject the null hypothesis and conclude that the coefficient of the relationship between test vehicle and pseudo bus speeds in the westbound direction is 0.82 with a 95% level of confidence.

Using the same methodology, Table 16 summarizes the confidence intervals for both eastbound and westbound directions for the corridor and the bridge for the

Table 16: Confidence Intervals of Test Vehicle and Pseudo Bus Mean Corridor and Bridge Speed Relationships

Corridor

Weekday Morning Peak	***b*** **Speed**	$\bar{b}$	***SE***	**Confidence Interval**		**Level of Confidence**
				Lower	**Upper**	
Eastbound ($n = 41$)	0.77	0.7696	0.0237	0.7219	0.8172	95%
Westbound ($n = 40$)	0.82	0.8036	0.0193	0.7646	0.8426	95%

Bridge

Weekday Morning Peak	***b*** **Speed**	$\bar{b}$	***SE***	**Confidence Interval**		**Level of Confidence**
				Lower	**Upper**	
Eastbound ($n = 41$)	1.02	1.0246	0.0284	0.9672	1.0820	95%
Westbound ($n = 40$)	0.97	0.9714	0.0248	0.9212	1.0216	95%

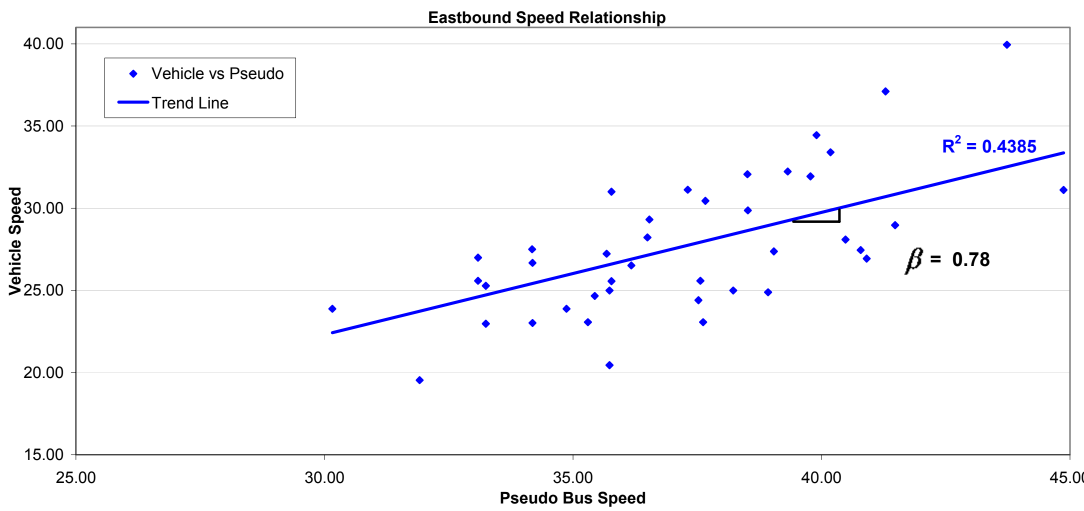
weekday peak period. The weekend off-peak relationships are not being tested due to the small sample size. The next section continues by proposing a linear model describing the test vehicle and pseudo bus speed relationship.

7.3 Linear Relationship

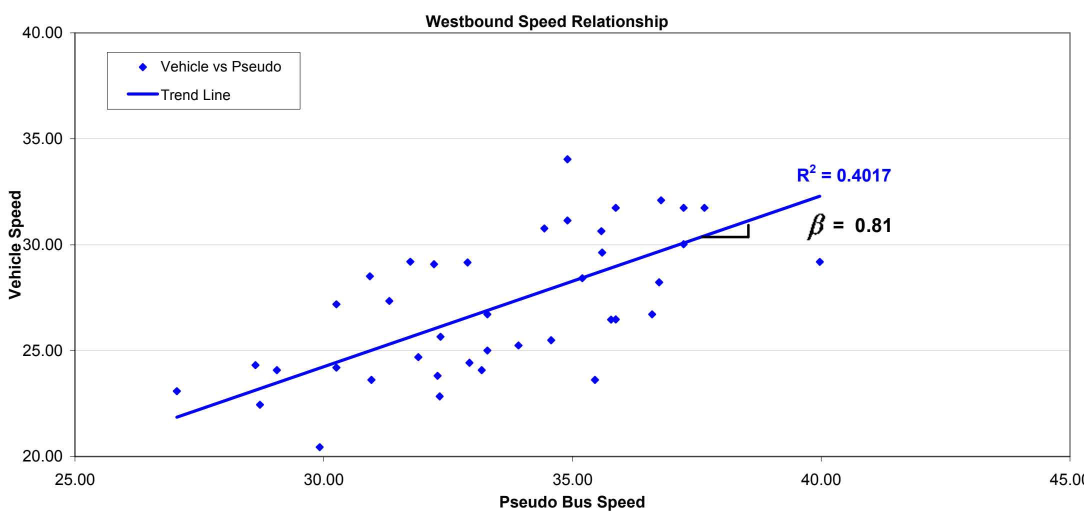
In the previous section, we have concluded that the relationship between the test vehicle and pseudo bus established using a naive analysis yields high statistical significance of 95%. This ensures the existence of a linear relationship between the two variables – test vehicle and pseudo bus. In this section, we propose a linear model describing this relationship. By plotting each key performance measure on *x* and *y*-axes against one another as shown earlier in Figure 24, a regression line with zero intercept can be generated from two variables where the slope of the regression line is the β coefficient:

$$V_{veh} = \beta V_{pseudo}$$

Sets of paired speeds from the hypothesis test were also used to test the linear relationship between the two variables – test vehicle and pseudo bus. These pairs of speeds were plotted against each other with pseudo bus speed on the *x*-axis and test vehicle speeds on the *y*-axis as shown in Figure 25(a) and 25(b). These figures show that there is the possibility of a relationship between test vehicle and pseudo bus speeds in a linear form. Since the reason for generating a relationship between pseudo bus speed and test vehicle speed is to easily estimate or predict traffic conditions on the arterial links and be able to feed such valuable messages back into the ATMS and ATIS systems, we assume that the linear relationship would be a sufficient tool for representing the overall traffic conditions. Based on this assumption, the analysis in the next section will generate a more robust tool based on the premise of a linear relationship.



(a)



(b)

Figure 25: Examples of Test Vehicle and Pseudo Bus Speeds Scatter Plot as a Proof of Linear Relationships

7.4 Linear Regression: Robust Method of Generating Relationship

In order to further confirm the relationship between test vehicle and pseudo bus speeds, reverse regression is used to test for the relative effects of measurement error and to obtain bounds on the true value of the coefficient β. Equations 1 and 2 show a switch between test vehicle speed and pseudo bus speed as the dependent and independent variables before performing reverse regression. The two variables were converted to z-scores prior running the regression, they then were estimated without constant terms (Crown, 1998).

$$Y_{pseudo} = \beta_{veh} X_{veh} + \varepsilon \tag{1}$$

$$Y_{veh} = \beta_{pseudo} X_{pseudo} + \varepsilon \tag{2}$$

where;
- Y_{pseudo} or X_{pseudo} = pseudo bus speeds
- Y_{veh} or X_{veh} = test vehicle speeds
- β_{veh} or β_{pseudo} = regression slope coefficient from (1) and (2)
- ε = unknown error associated with vehicle-pseudo bus relationship

$$\text{Bias} = \frac{\left[\left(\frac{1}{\beta_{veh}}\right) - \beta_{pseudo} \right]}{\left(\frac{1}{\beta_{veh}}\right)}$$

$$\text{Bias} = 1 - \beta_{veh} \beta_{pseudo} \tag{3}$$

Equation 3 shows a measurement of the bias attributed to the pseudo bus speed. Westbound corridor speed on the weekday morning peak was used as an example by running linear regression analysis. The linear regression analyses results in β_{veh} = 1.23 and β_{pseudo} = 0.80. From equation 3, this indicated the magnitude of the bias for the two variables of 1.6% and an average between the β_{pseudo} and the inverse of β_{veh} equal to 0.81 which will be used as a regression coefficient in equation 4.

$$V_{west-veh} = 0.81 V_{west-pseudo} + \varepsilon \qquad (4)$$

By simplifying equation 4, the relationship of the westbound vehicle speed and pseudo bus speed on the weekday morning peak is:

$$VehicleSpeed_{west} = 0.81 PseudoSpeed_{west}$$

7.3.1 Corridor Relationships Using Reverse Regression Analysis

With the method calculated in the previous section, the relationship of test vehicle corridor speed and corridor travel time with the pseudo bus corridor speed and corridor travel time were generated and summarized as shown in Table 17. The table also shows the naive relationships calculated in section 6.3.1.

Table 17: Linear Regression Coefficients Compared to Coefficients from the Relationship of Mean Analysis

	β_{speed}		$\beta_{travel\ time}$	
	Mean	**Regression**	**Mean**	**Regression**
Eastbound				
Weekday Morning Peak	*0.77*	**0.78** (0.439)	*1.30*	**1.29** (0.512)
Weekend Midday Off-Peak	*0.89*	**0.91** (0.481)	*1.05*	**1.06** (0.647)
Westbound				
Weekday Morning Peak	*0.82*	**0.81** (0.402)	*1.27*	**1.24** (0.410)
Weekend Midday Off-Peak	*0.89*	**0.89** (0.386)	*1.12*	**1.09** (0.201)

Note: R^2 is shown in parenthesis

The regression analysis showed that the test vehicle speeds for both morning peak and midday off-peak periods were between 0.78 and 0.81 times the pseudo bus speed. Conversely, it was shown that the test vehicle travel times ranged between 1.24 and 1.29 times the pseudo bus travel time. The analysis found that the new coefficients from the linear regression are close to the coefficients generated from the preliminary analysis of mean speed and travel time. However, the linear regression provides a more reliable and more robust estimate.

7.3.2 Bridge Relationship Using Reverse Regression Analysis

With the same methodology used in the corridor relationship analysis, the relationships between test vehicle and pseudo bus bridge speed and bridge travel time were also generated. Table 18 summarizes the coefficients resulting from the regression analysis and are compared with the previous coefficients from the naive

Table 18: Linear Regression Coefficients from the Bridge Analysis Compared to Coefficients from the Bridge Relationship of Mean Analysis

	$\beta_{bridge\ speed}$		$\beta_{bridge\ travel\ time}$	
	Mean	**Regression**	**Mean**	**Regression**
Eastbound				
Weekday Morning Peak	*1.02*	**0.99** (0.502)	*0.97*	**1.00** (0.712)
Weekend Midday Off-Peak	*1.02*	**1.00** (0.549)	*0.97*	**0.98** (0.496)
Westbound				
Weekday Morning Peak	*0.97*	**0.97** (0.415)	*1.04*	**1.03** (0.455)
Weekend Midday Off-Peak	*1.03*	**0.99** (0.203)	*0.97*	**0.97** (0.304)

Note: R^2 is shown in parenthesis

analysis of mean values. However, compared to the corridor analysis, the bridge relationships were found to be closer in both inbound and outbound directions for the peak and off-peak periods. The bridge speed model showed that the test vehicle speeds on the bridge were between 0.97 and 1.00 times pseudo bus bridge speeds. Conversely, the test vehicle travel times on the bridge were between 0.97 and 1.03 times the pseudo bus bridge travel times. As a result, this verifies the hypothesis stated earlier in section 6.3.2 that the free flow conditions on the bridge do provide the opportunity for the bus to achieve the maximum speed which reflects a close relationship compared to the test vehicles.

CONCLUSION

This study analyzed traffic conditions on one arterial during several time periods using two sets of data – test vehicle data and transit automatic vehicle location (AVL) data – in order to characterize the performance of this arterial. Existing transit AVL systems are used primarily for managing transit operations in real time. In the case of TriMet, the BDS system was generally implemented for operational and quality of service control purposes. However, the BDS provides the secondary benefit of a potentially valuable source of data for traffic monitoring and analysis on particular arterial segments. From this study, it has been shown that it is possible to explain actual arterial traffic conditions using transit vehicle AVL information.

Vehicle trajectories plotted on a time-space diagram for both test vehicles and buses were used in this study. The vehicle trajectory facilitates the observation of vehicle behavior along the corridor and contains all of the information necessary to completely describe a vehicle's movement on the roadway. Three additional scenarios using conceptual buses constructed from the bus data were proposed to uncover the best fit relationship with test vehicles. These included the hypothetical bus, pseudo bus and modified pseudo bus. The preliminary analysis using vehicle trajectories and three-dimensional speed contour plots suggested that of all transit data used herein, the pseudo bus movements generated from the maximum instantaneous speed achieved between stop pairs would most reliably depict the movement of non-transit vehicles.

It has been shown that key performance measures such as travel time and speed should also be described using the relationship established between the test vehicle and the pseudo bus. The statistical analysis confirmed the existence of a relationship between test vehicle speed and pseudo bus speed and conversely the relationship between their travel times. Speed and travel time are key performance measures which are linked to generating other performance measures such as delay. This study found that the test vehicle speeds for all four study days, during both morning peak and midday off-peak periods, were between 0.78 and 0.81 times the maximum instantaneous speed achieved by the buses (pseudo bus speed). Conversely, it was shown that the test vehicle travel times ranged between 1.24 and 1.29 times the pseudo bus travel time.

The analysis further focused on the Ross Island Bridge portion of the study corridor. We hypothesized that transit speed could appear similar to other vehicles on the Ross Island Bridge where its geometry and physical characteristics promote free-flow travel conditions. In fact, it is shown that transit speeds on the bridge were different from the test vehicle speeds on the bridge. However, the maximum speed achieved by the bus on the bridge reflects a very close relationship with the test vehicle speed. The linear regression analysis showed the statistical significance of this relationship between the pseudo bus and the test vehicle on the bridge. A bridge speed model was proposed that the test vehicle speeds on the bridge were between 0.97 and 1.00 times pseudo bus bridge speeds. Conversely, the test vehicle travel times on the bridge were between 0.97 and 1.03 times the pseudo bus bridge travel times.

Since travel time and speed are important performance measures for arterials, the heightened interest in providing such information in the context of ATMS and ATIS will require an improvement of the ITS infrastructure. Real time data communication at a satisfactory level is needed to be implemented in order to feed transit travel information into the traffic monitoring system. This study showed that an appropriate data transmission level should be within approximately on the order of 1 minute. This level is based on the mean corridor travel time and the number of bus stops in the corridor. In Portland, TriMet has its real-time communication system set up to submit poll data in the range between 60 and 90 seconds which would be sufficient in this case. However, stop level bus data is still required to feed into the communications component and be combined with the poll data in order to be able to make use of it in real time.

While this study focused on both directions of traffic during the morning peak and the midday off-peak for only four days on one arterial, the positive results provide a greater level of confidence to the study and help raise the possibility of developing a system assisting transit agencies and traffic engineers to better understand arterial performance assessment. However, this study was still limited to one section of roadway in one corridor using one transit route. Arterials are characterized by complicated traffic behavior and many more variables. Different arterial characteristics such as posted speed limits, intersection spacing, number of access points, and number of lanes; make each arterial unique. Bus routes running on arterials with different spatial and temporal components (e.g., type of route, spacing between stops, number of stops and length of the route) add another level of variability onto the travel time prediction task using bus data. In order to apply the travel time model using the relationship between test vehicle and pseudo bus data explained in this study, both arterial characteristics and bus travel behavior need to be similar to the variables in this study. Additional research on additional corridors with other bus routes should be conducted in order to create a city-wide travel time model.

From this study, it is suggested that future research should also be conducted during different peak periods on this study corridor or expanded into other corridors with different characteristics and different bus routes such as, in Portland, Division Street (Route 4), Hawthorne Boulevard (Route 14) and Burnside Street (Route 20). Incident information should also be taken into account for further analysis including a study using non-linear regression in creating a travel time model. Such results will provide a more robust relationship between test vehicles and buses in estimating arterial traffic conditions.

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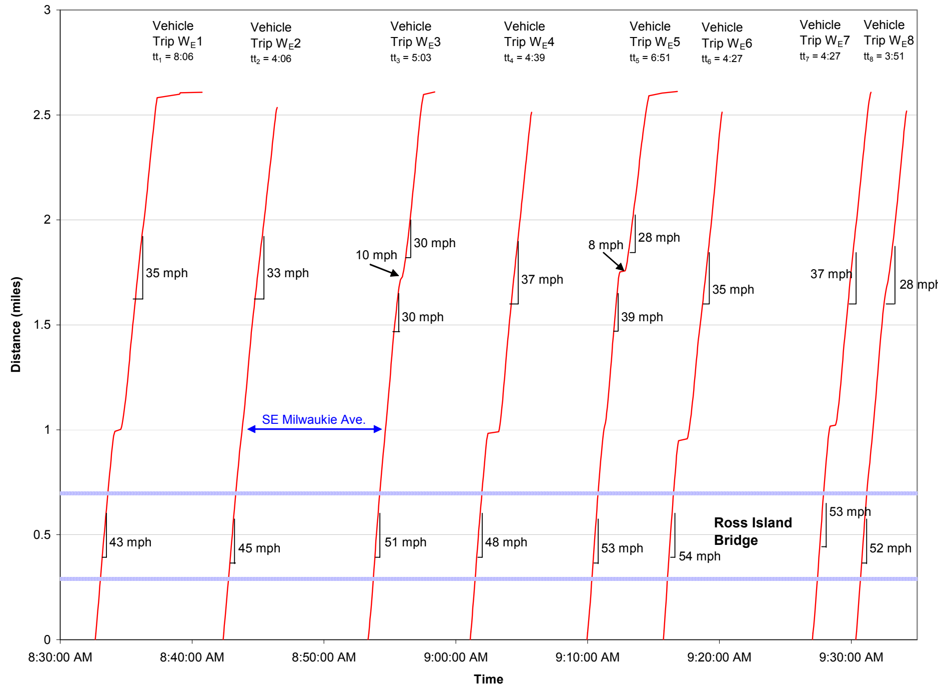
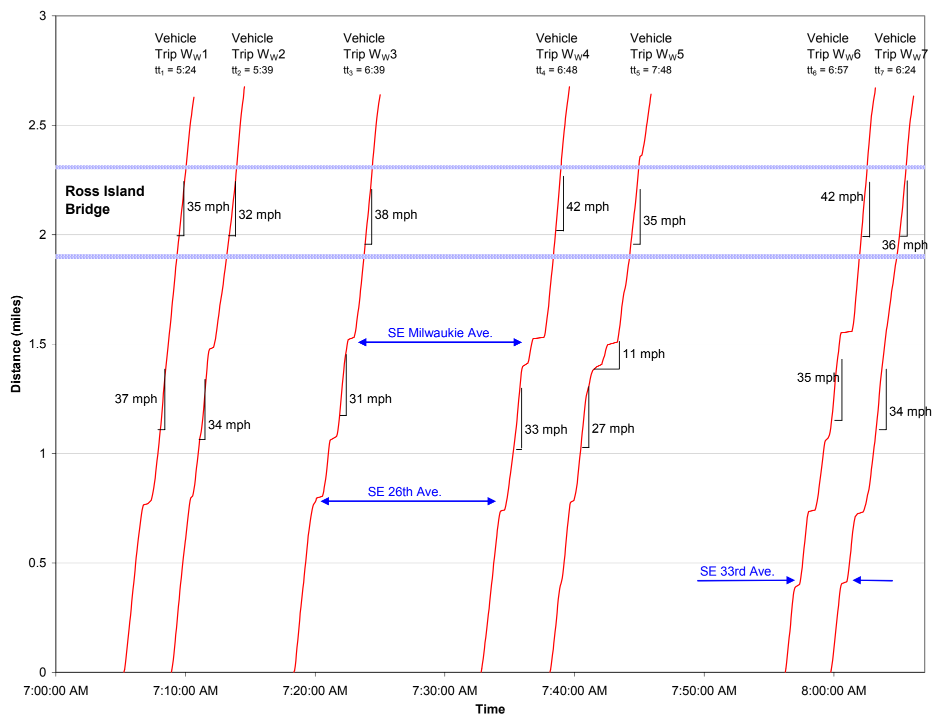
APPENDICES

APPENDIX A

Example of Test Vehicle Trajectories

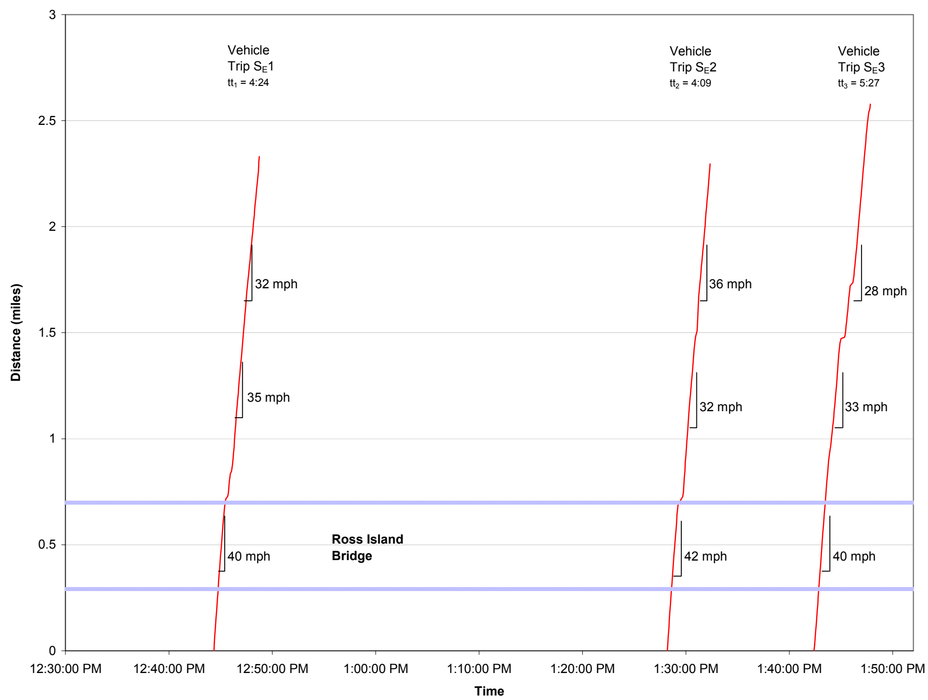


(a)

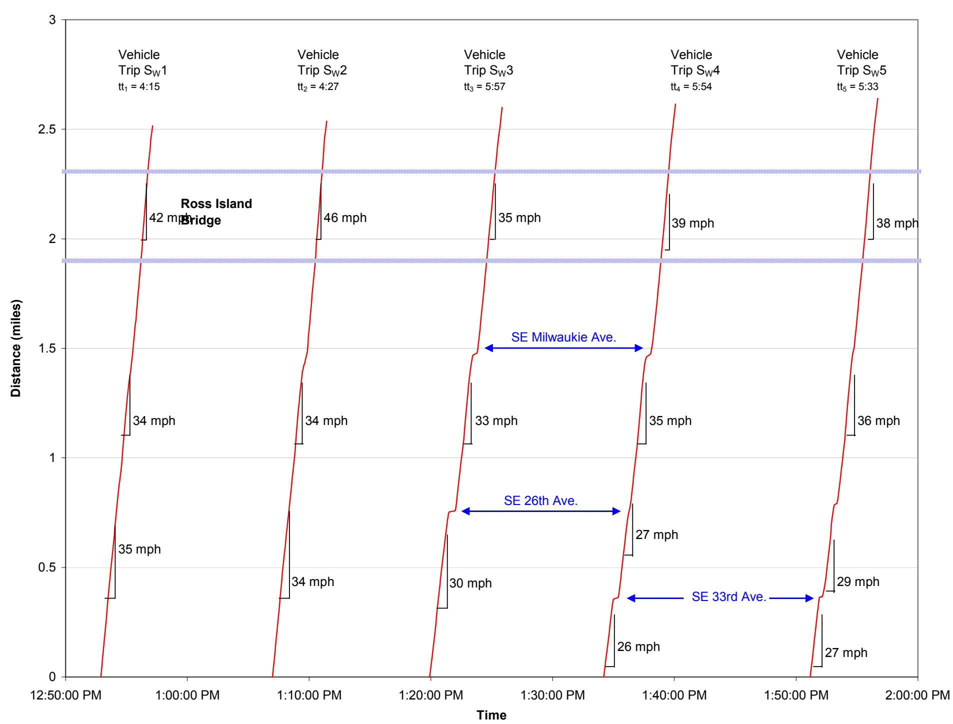


(b)

Examples of Wednesday Nov. 7, 2001 Test Vehicle Trajectories (a) Eastbound Direction and (b) Westbound Direction

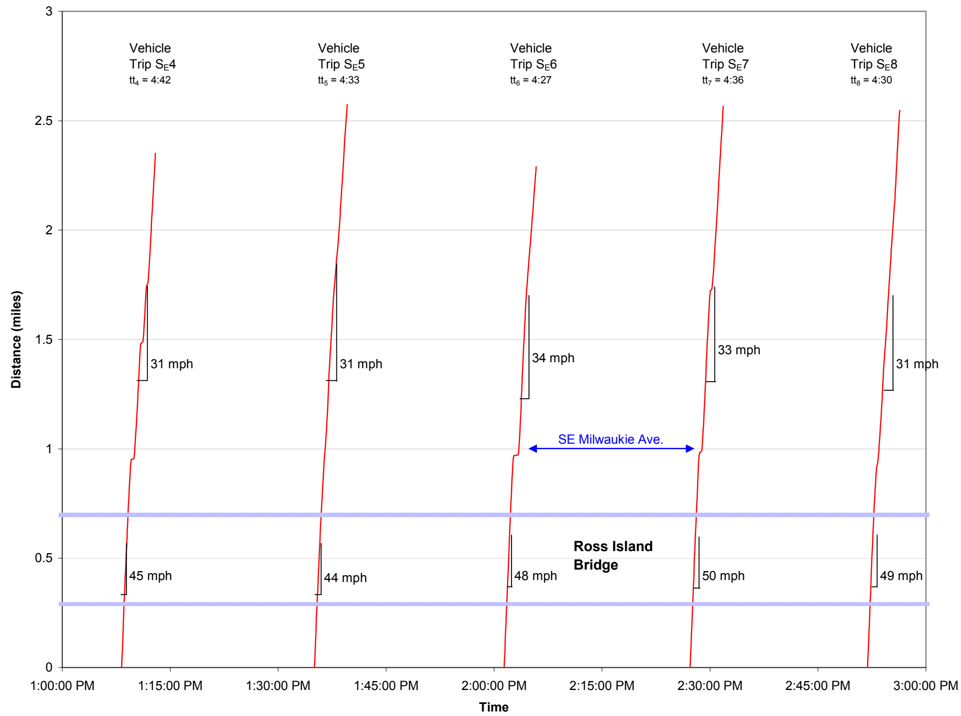


(a)

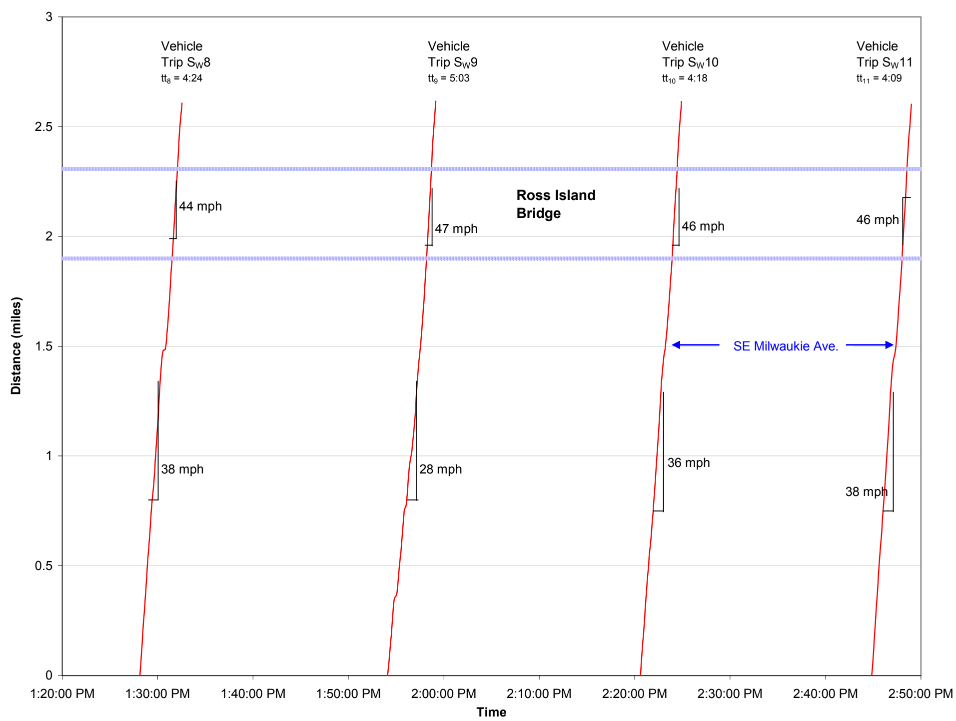


(b)

Examples of Saturday Nov. 3, 2001 Test Vehicle Trajectories (a) Eastbound Direction and (b) Westbound Direction



(a)



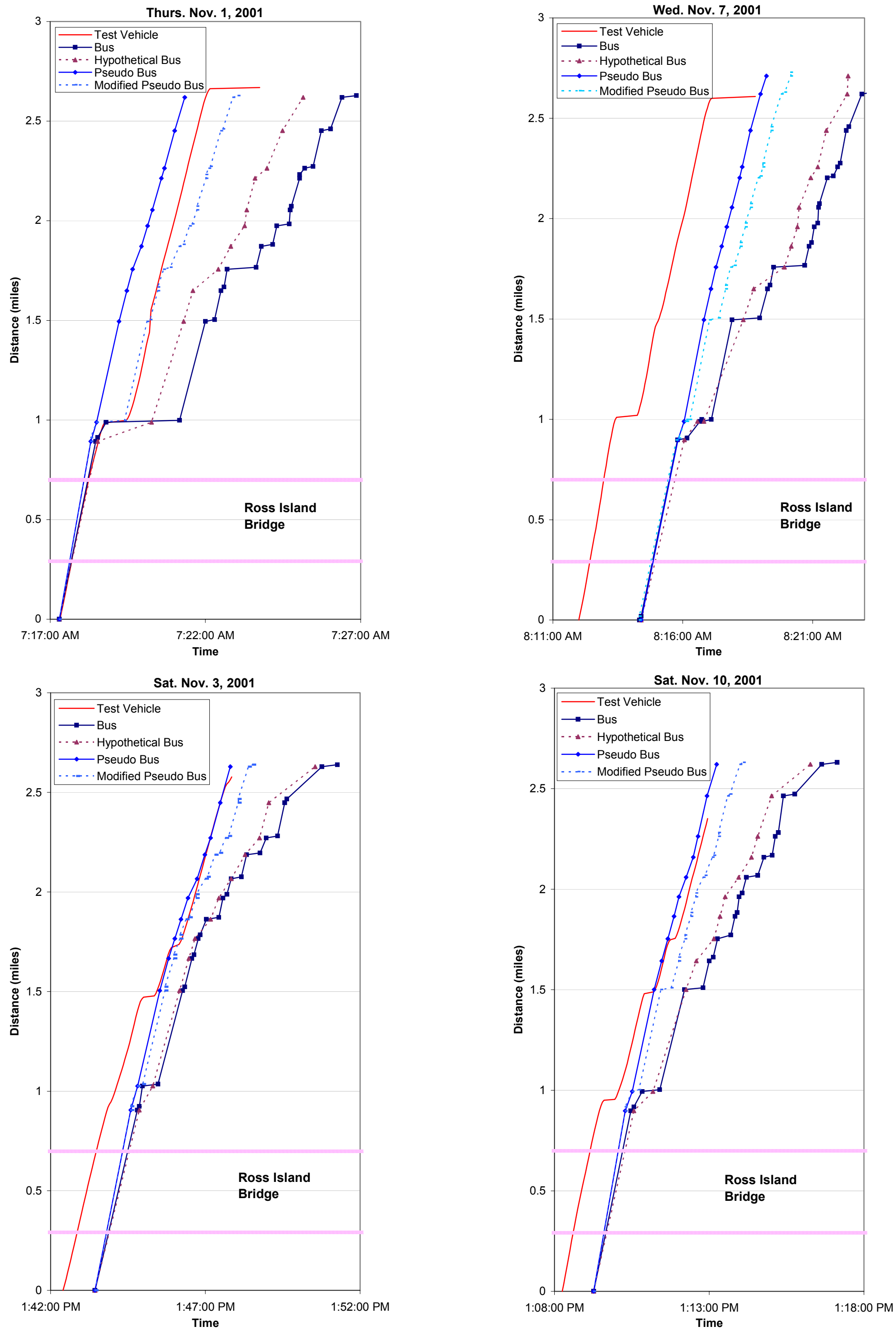
(b)

Examples of Saturday Nov. 10, 2001 Test Vehicle Trajectories (a) Eastbound Direction and (b) Westbound Direction

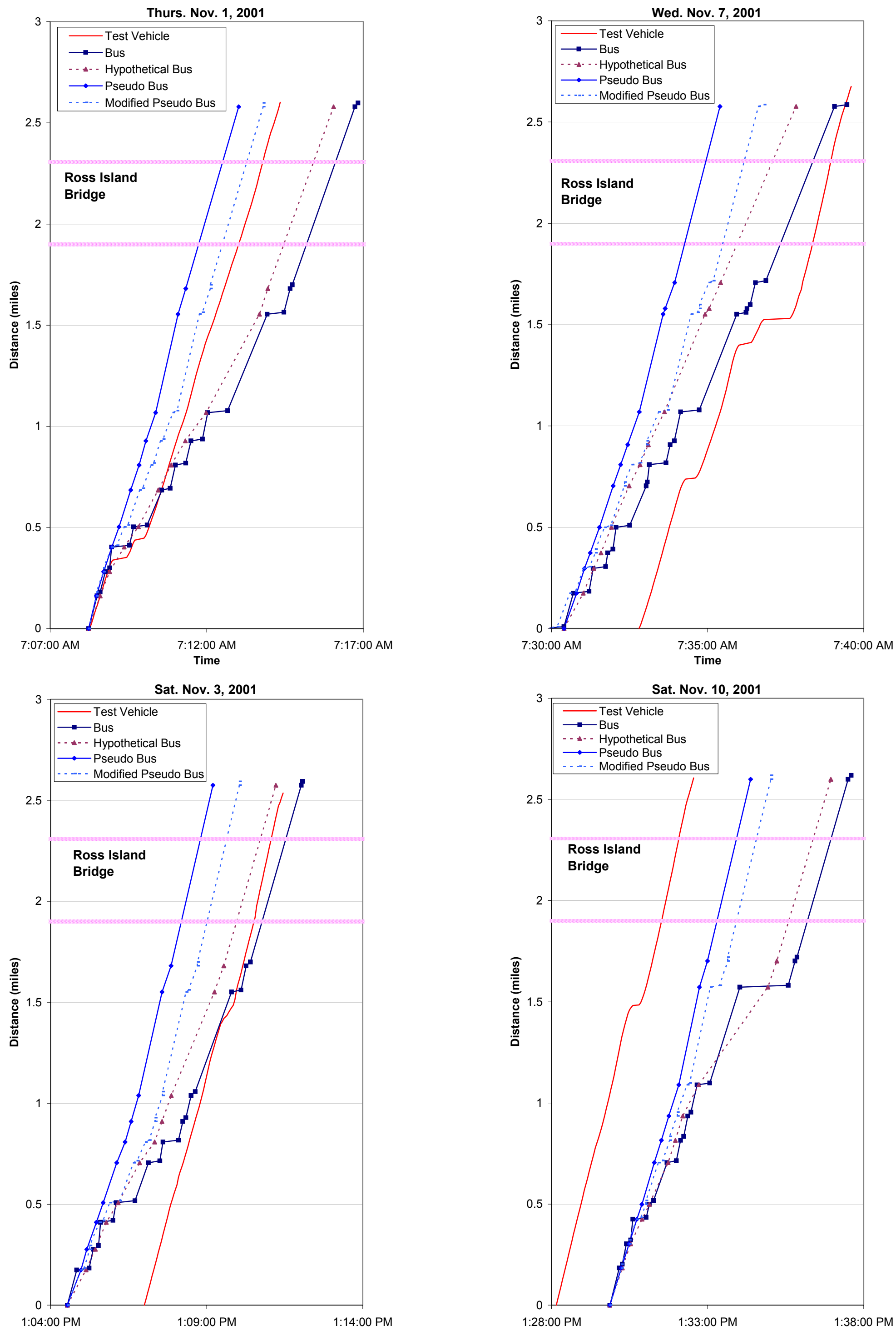
APPENDIX B

Comparison of All Trajectory:

Test Vehicle, Actual Bus and Conceptual Bus



Comparison of Eastbound Test Vehicles, Actual Bus and Conceptual Bus Trajectories



Comparison of Westbound Test Vehicles, Actual Bus and Conceptual Bus Trajectories

APPENDIX C

Minimum Sample Size Calculation

Minimum Sample Size Requirement

T-distribution with *n*-1 degree of freedom (df) is written in a form for solving sample size (*n*) as:

$$n = \left[\frac{t_\alpha \cdot s}{E} \right]^2$$

Where s = estimate standard deviation of random samples
t_α = t distribution statistic at level of confidence of $(1 - \alpha)100\%$
E = maximum error of the estimation

The estimations using the iterative procedure are shown below for both test vehicle and bus minimum sample sizes. The calculation is based on the initial run data as shown in Table 11 (page 59).

Bus Minimum Numbers of Runs

Iteration	**Input** n_0	**df** $(n_0 - 1)$	$t_{0.95,\,df}$	s **(mph)**	E **(mph)**	**Output** n_1
1st	5 (random picked)	4	2.7765	4.07	± 3	14.2
2nd	14 (n_1 from 1st iteration)	13	2.1604	4.07	± 3	8.6
3rd	9 (n_1 from 2nd iteration)	8	2.3060	4.07	± 3	9.8
4th	10 (n_1 from 3rd iteration)	9	2.2622	4.07	± 3	9.4
5th	9 (n_1 from 4th iteration)	8	2.3060	4.07	± 3	9.8
6th	10 (n_1 from 5th iteration)*	9	2.2622	4.07	± 3	9.4

* minimum sample size requirement at 95% level of confidence

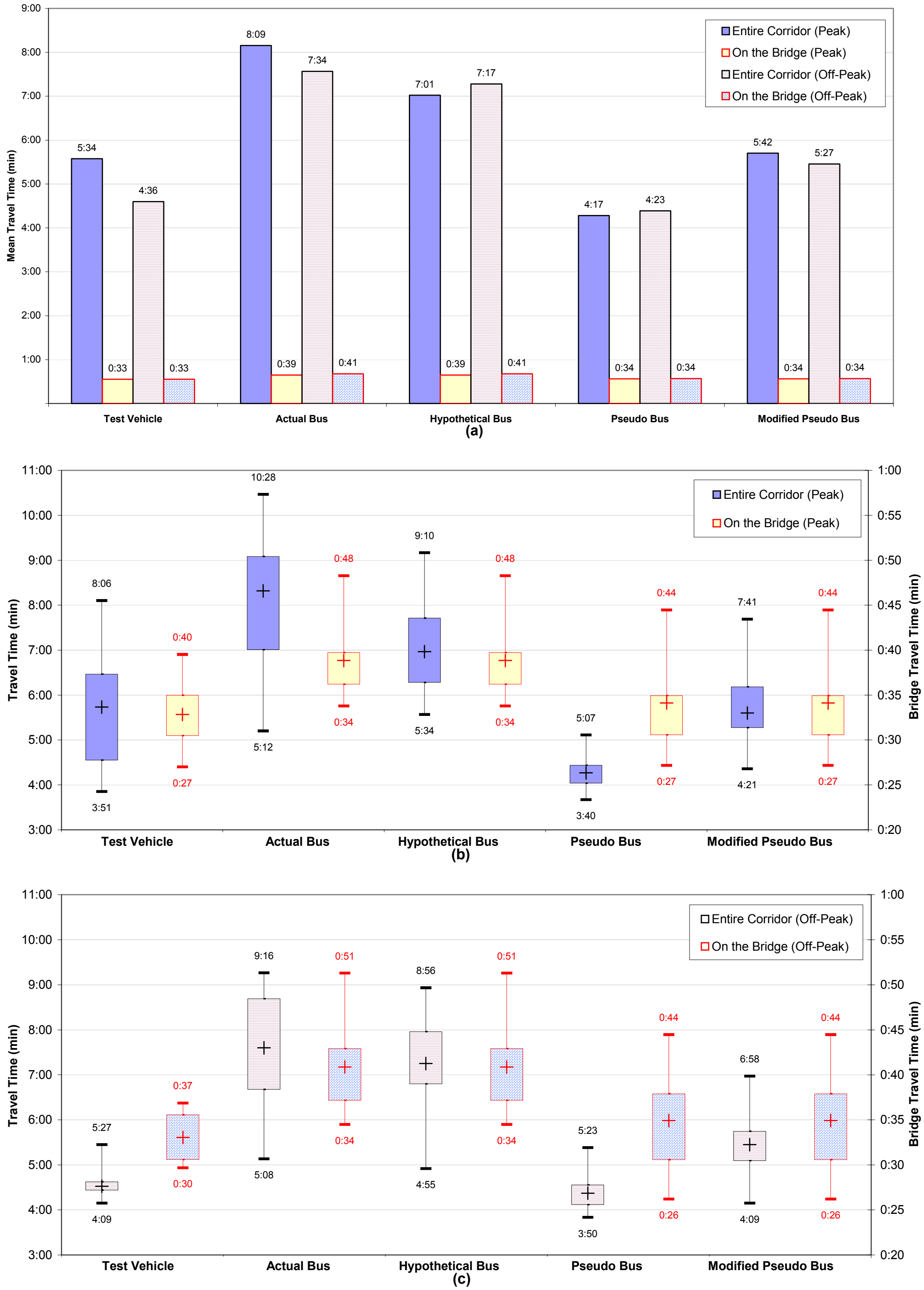
Test Vehicle Minimum Numbers of Runs

Iteration	**Input** n_0	**df** $(n_0 - 1)$	$t_{0.95,\,df}$	s **(mph)**	E **(mph)**	**Output** n_1
1st	10 (random picked)	9	2.2622	5.00	± 3	14.2
2nd	14 (n_1 from 1st iteration)	13	2.1604	5.00	± 3	12.9
3rd	13 (n_1 from 2nd iteration)	12	2.1788	5.00	± 3	13.2
4th	13 (n_1 from 3rd iteration)*	12	2.1788	5.00	± 3	13.2

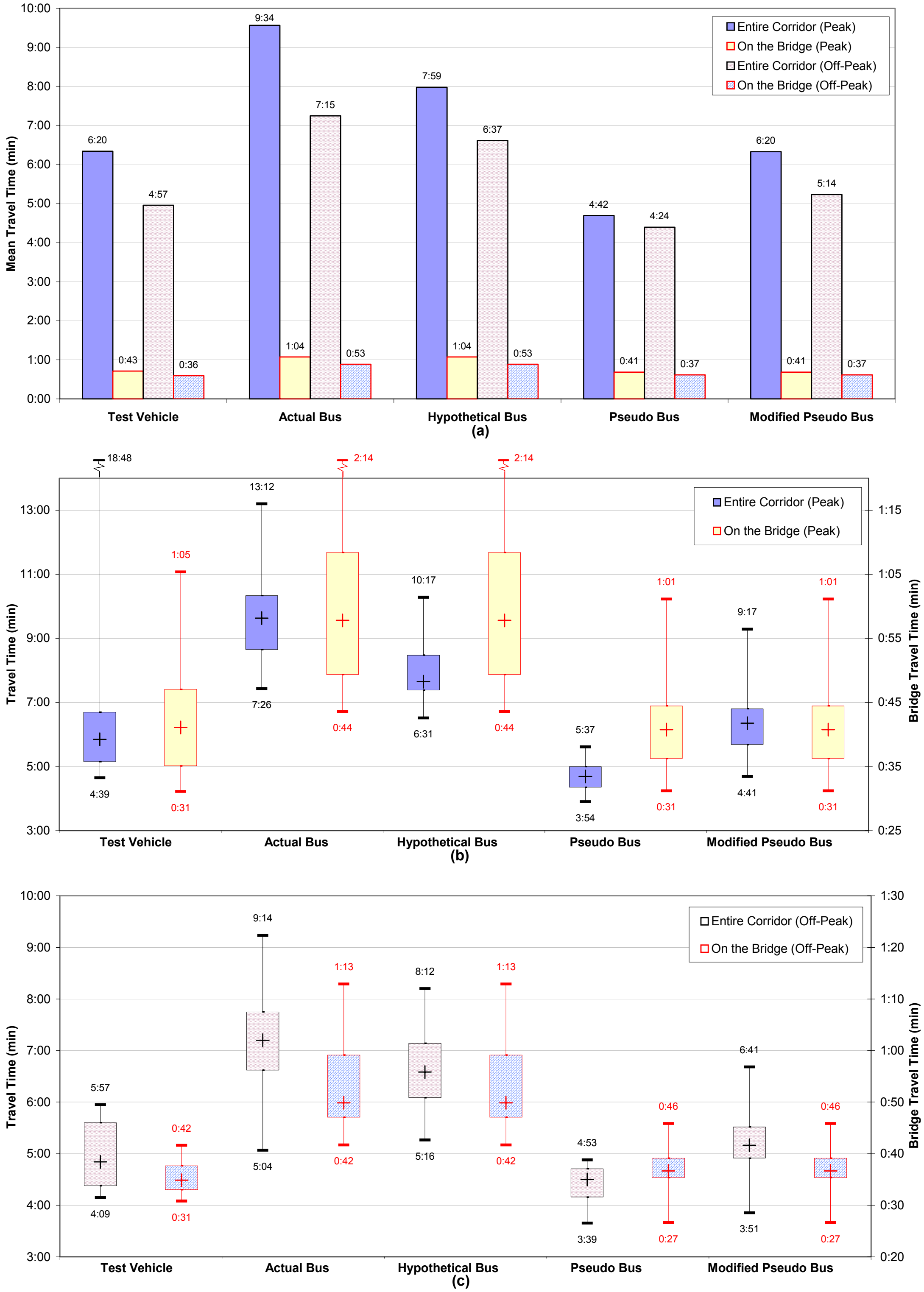
* minimum sample size requirement at 95% level of confidence

APPENDIX D

Mean Travel Time Comparison



Eastbound Mean Travel Time of all Scenarios for Entire Corridor and on the Bridge on both Peak and Off-Peak Periods

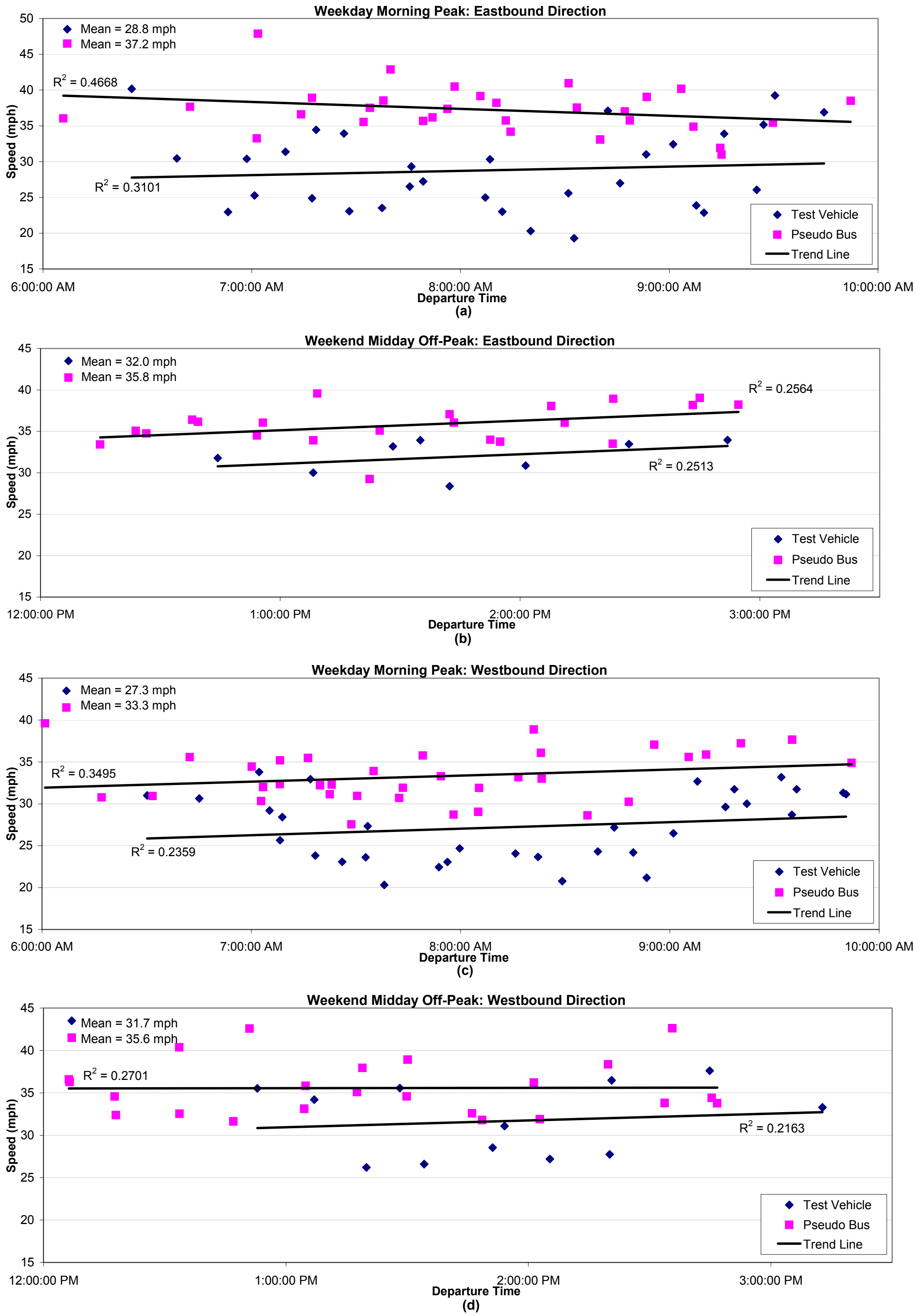


Westbound Mean Travel Time of all Scenarios for Entire Corridor and on the Bridge on both Peak and Off-Peak Periods

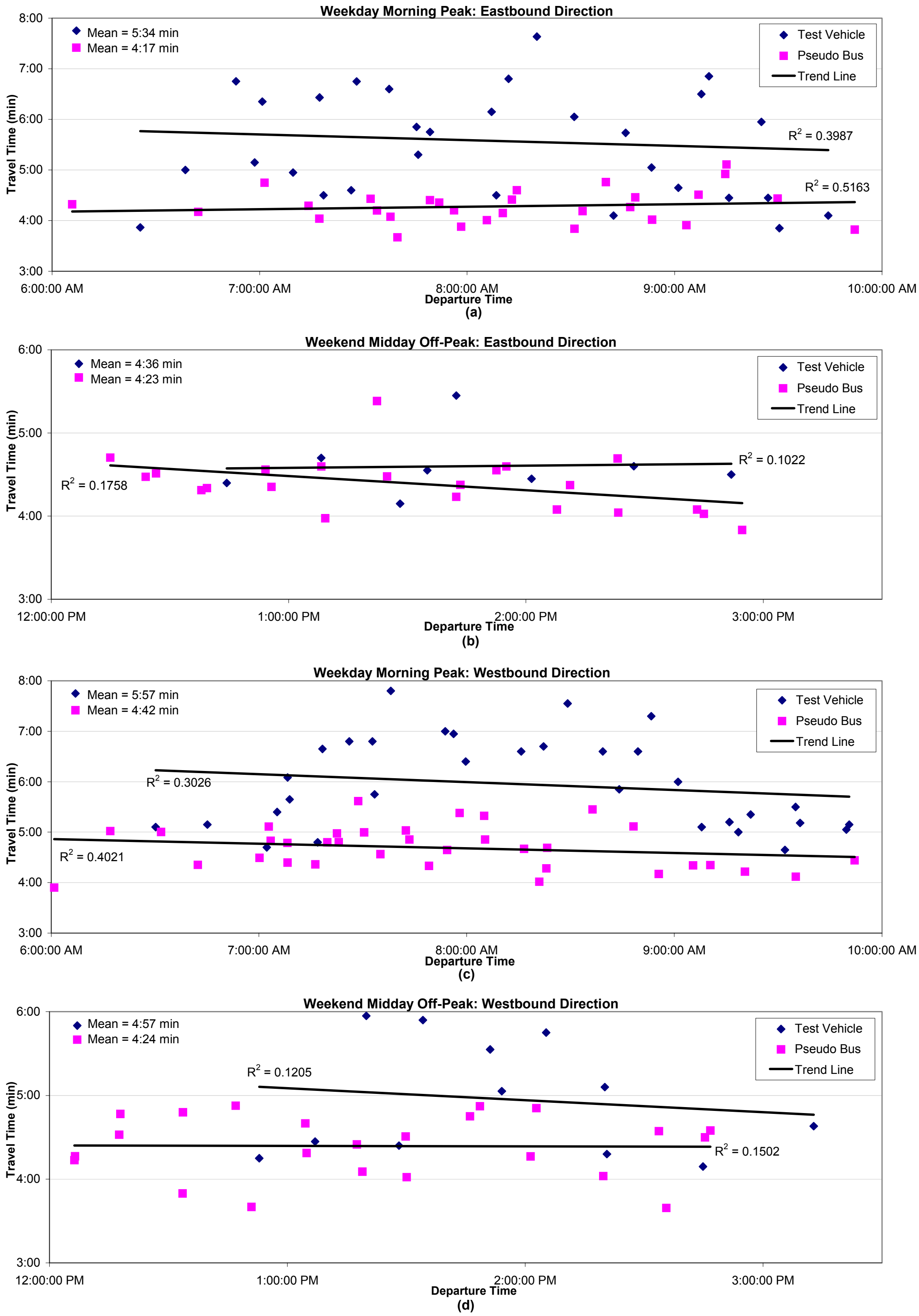
APPENDIX E

Test Vehicle Versus Pseudo Bus:

Speed and Travel Time



Speed of the Test Vehicle and Pseudo Bus versus the Departure Times

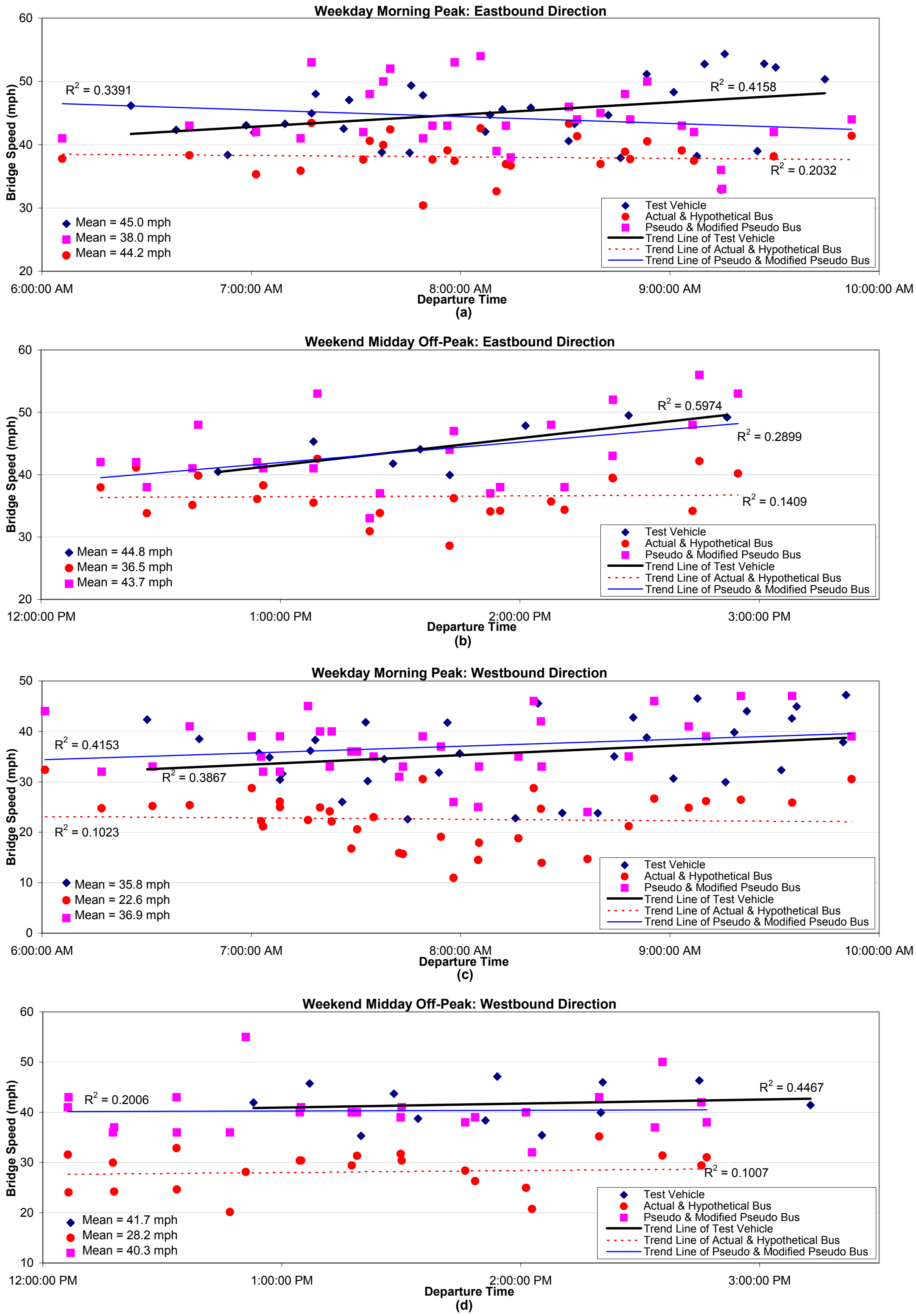


Travel Time of the Test Vehicle and Pseudo Bus versus the Departure Times

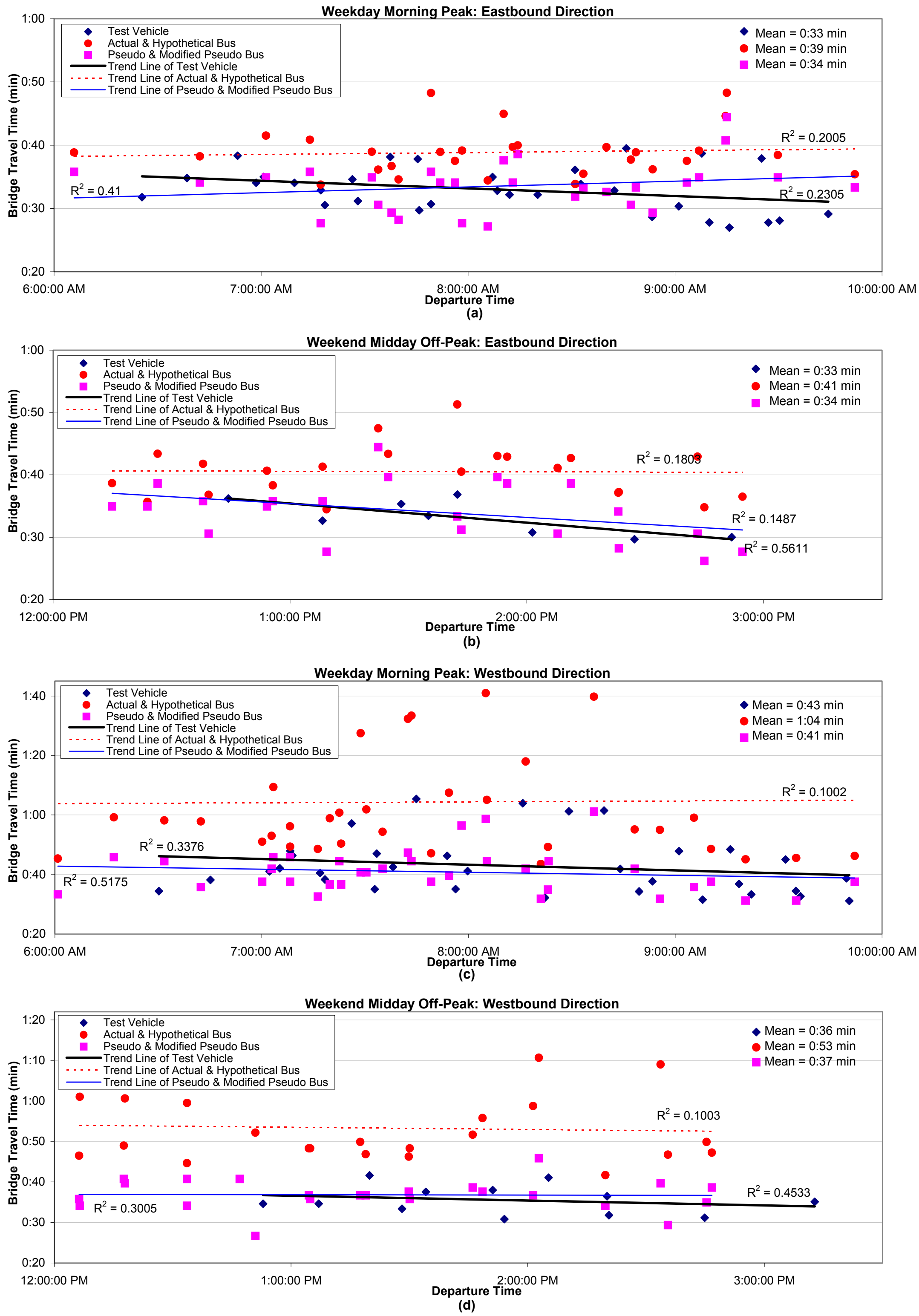
APPENDIX F

Test Vehicle and Bus Scenarios on the Bridge:

Speed and Travel Time



Test Vehicle and the Four Bus Scenarios Comparison on Speed on the Bridge



Test Vehicle and the Four Bus Scenarios Comparison on Travel Time on the Bridge