THE USE OF ADVANCED INFORMATION TECHNOLOGY IN URBAN PUBLIC TRANSPORTATION SYSTEMS:

AN EVALUATION OF BUS STOP CONSOLIDATION

by

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DISSERTATION APPROVAL

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ABSTRACT

An abstract of the dissertation of Ahmed Medhat El-Geneidy for the Doctor of Philosophy in Urban Studies presented April 20, 2005.

Title: The use of advanced information technology in urban public transportation systems: An evaluation of bus stop consolidation.

This research introduces a methodology for utilizing advanced information technologies (AIT) to analyze transportation planning problems in an urban planning context. Public transit planning is the focus of this study. The study investigates bus stop consolidation as a tool for increasing transit service reliability through analysis of data collected by AIT. The Streamline project implemented by the TriCounty Metropolitan Transportation District of Oregon (TriMet), the local transit provider for the Portland metropolitan area, is used in this research.

Focusing on a single bus route where the stop consolidation program has been implemented, changes in passenger activity and operating performance in route segments where stop consolidation occurred are related to changes in adjacent route segments where stops were not consolidated. The changes are monitored through composite and disaggregate evaluation methods. The composite evaluation method includes differences in means tests to evaluate overall changes in transit system utilization. The disaggregate evaluation includes a set of four regression models to isolate the effects of bus stop consolidation from other changes that took place.

An important contribution of this research is the utilization of AIT to produce an evaluation methodology for bus stop consolidation, which contrasts with previous studies that used simulation to measure and evaluate consolidation as a tool for increasing transit service reliability. Passenger activity is found to be unaffected by stop consolidation, while bus running times showed a significant improvement. From the passengers' point of view, the results indicate that any reductions in accessibility from stop consolidation were offset by time improvements in the line haul portion of their trips. Thus, the utility of their trip-making appears to have been unaffected by stop consolidation, while the transit provider gained from efficiency improvements. TriMets' selection of bus stops for consolidation can be justified due to the savings in running time and the increase in passenger activity described through this research. Recommendations are suggested to help transit planners and operation personnel in selecting bus stops for consolidation. The research offers a methodology based on data collected by AIT that can be replicated by other transit agencies.

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GLOSSARY

AIT	Advanced information technologies
TriMet	Tri-County Metropolitan Transportation District of Oregon
NTD	National Transit Database
BDS	Bus dispatch system
APC	Automatic passenger counter
AVL	Automatic vehicle location
TSP	Transit signal priority
OTP	On-time performance
GIS	Geographic information system
TCQSM	Transit Capacity and Quality of Service Manual
VMT	Vehicle miles of travel
GPS	Global positioning system
ADA	Americans With Disabilities Act
CONS	Consolidation segments
CTRLS	Control segments
PRECONS	Consolidation segments in the pre time period
POSTCONS	Consolidation segments in the post time period
PRECTRLS	Control segments in the pre time period
POSTCTRLS	Control segments in the post time period
UID	Unique identification number
RLIS	Regional Land Information System

CHAPTER 1: STUDY OUTLINE

Introduction

The present study introduces a methodology for utilizing advanced information technologies (AIT) to analyze transportation planning problems in an urban planning context. Public transit planning is the focus of this study. The study investigates bus stop consolidation as a tool for increasing transit service reliability through analysis of data collected by AIT adopted by public transit agencies. The Streamline project implemented by the Tri–County Metropolitan Transportation District of Oregon (TriMet), the local transit provider for the Portland metropolitan area, is used in this research. Focusing on a single bus route where stop consolidation program has been implemented, changes in passenger activity and operating performance in route segments where stop consolidation occurred are related to changes in adjacent route segments where stops were not consolidated. An important contribution of this research is the utilization of AIT to produce an evaluation methodology for bus stop consolidation, which contrasts with previous studies that used simulation to measure and evaluate consolidation as a tool for increasing transit service reliability.

Problem Setting

Buses are the dominant form of public transportation in cities. They provide important means of mobility to the public. In 2002 around 9 billion unlinked trips were made using public transit in the United States. Among the various types of transit service, bus boardings comprised the majority of unlinked passenger trips (5,268 million in 2002). This represents a 15% growth in bus boardings compared to 1995 ridership (U.S. Department of Transportation, 2004).

The amount of annual delay caused by traffic congestion has increased by four hours per person per year in the last five years (Schrank & Lomax, 2004). Transit agencies are concerned with providing reliable transit service at a reasonable cost to both agency and users, despite the increase in congestion (Wirasinghe, 2003). Transit agencies are facing many challenges in both the long and short terms including increases in population, changes in land use, changes in household size, decentralization of cities, and changes in the distribution of employment. Transit agencies must develop both short and long term strategies to meet these challenges. Levinson (1991) has argued that in the short term minor improvements in service coverage, running times, and service frequencies are needed. In the long term, service modifications are needed to address decentralization by focusing on edge cities as nodes and collectors, adding more express busses or alternative service types like bus rapid transit, enhancing service coordination for transfers, improving service identity by concentrating service along major arterials and providing frequent, reliable service along those routes, and by increasing bus stop spacing. Changing the number and location of existing stops (through consolidation and/or relocation) is one tactic that can address some of the challenges mentioned above.

From a transit agency's perspective, an ideal transit service is one with few stops, and high and consistent. Passengers prefer to minimize both their out-of-vehicle time (access, waiting time, and transfer) and their in-vehicle time (Koffman, 1990; Levinson, 1983; Saka, 2003; Wirasinghe & Ghoneim, 1981). Previous research indicates that passengers are more sensitive to out-of-vehicle time, which includes walk time to and from bus stops and waiting time for arrivals (Kemp, 1973; Lago & Mayworm, 1981; Pushkarev & Zupan, 1977). Providing bus transit service often requires compromising between transit agency's and passenger's preferences. The spacing of stops should seek to maximize social benefit, which includes the effects of spacing on both passengers and agencies. In theory an increase in spacing of stops has the following consequences:

1. Bus running times will decline, reducing operating costs that can, in turn, be translated into additional miles of vehicle service for a given operating budget;

2. The variation in bus running time will decline, saving the transit provider non-revenue service time (in the form of excess recovery and layover, as well as from uneven spacing of buses) and saving passengers excess waiting time;

3. Passengers' access and egress times required to travel from and to stops increase, while their in-vehicle travel times decrease.

Commonly, only the third item is emphasized in the literature on bus stop planning. The first and second items are often mentioned in the literature as possible benefits from bus stop consolidation policies, but have not been tested or evaluated except through simulation.

Changes in Stop Spacing

In general a transit planner can propose four types of changes to bus stop locations along a route, as indicated in Figure 1.

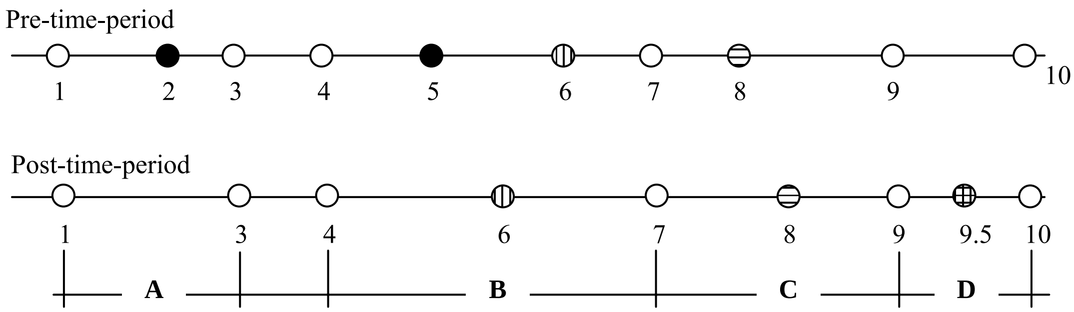

Figure 1: Types of Change in Stop Spacing

1. Stop consolidation: the elimination of a stop from service (case A);

2. Stop consolidation and relocation: the elimination of one or more stops and relocation of one or more of the adjacent stops (case B);

3. Stop relocation: the changing of a stop location (case C); and

4. Stop addition: the addition of a new stop to a route (case D).

In this research we are only concerned with cases A and B in order to measure the effect of the changes in stop spacing, which accompanies consolidation, on transit service.

Bus Stop Consolidation

Many tradeoffs are inherent in bus stop consolidation. Transit planners try to balance between bus running time, passenger access and egress time, and passengers waiting time. Optimization can be one of the tools for understanding the consequences of stop consolidation and achieving the highest benefit to passengers and agencies (Furth & Rahbee, 2000; Murray, 2003; Murray & Wu, 2003). For example, if the savings in time from stop consolidation can lead to a new trip being added to the schedule, this translates to an increase in frequency, leading to a potential increase in service reliability. Optimization solutions can be approached either through dynamic or linear programming or through simulation. The selection of bus stops for consolidation should maximize the net benefit to agencies and passengers. The problem with removing stops based on optimization concerns the output itself. Previous research used optimization to identify candidate stops for consolidation. The output of this research is tested through simulation and based on various assumptions (Furth & Rahbee, 2000; Saka, 2001). In the present research, bus stops are selected for consolidation as part of the Streamline program at TriMet. Stop selection is based on archived data collected by AIT, the agency's stop spacing service standards, and several other factors. The present research will evaluate the output of the process and not the methods of selection.

Consolidation is most often discussed in the transit literature as a means to reduce the number of stops served by transit vehicles in order to decrease average running times. Variability in running time is as important as average running time to both passengers and agencies. Variability in running time subjects passengers to unpredictable service. For an agency, running time variability will lead to an inefficient service. This research attempts to address the efficiency of bus stop consolidation as an approach for increasing transit service reliability (reducing running time variability).

Data Sources

Until recently, data sources for analyzing transit services were limited. At one point agencies used to collect data manually for National Transit Database (NTD) reporting (formerly Section 15 reporting). Agencies often had to make strategic decisions regarding the amount of spending for data collection to support internal decision making (Fielding, 1987). Many agencies used to direct their funds towards other issues, such as providing more service, rather than data collection. Recently, the deployment of AIT, has made the data collection process relatively simpler and cheaper. The TriMet Bus Dispatch System (BDS) includes a variety of AIT, such as automatic passenger counter (APC) and automatic vehicle location (AVL). Since TriMet implemented the BDS, both the quality and quantity of transit data increased.

Since implementation numerous evaluations of its accuracy, reliability, and potential benefits have been undertaken (Kimpel *et al.*, 2002; Strathman, 2002; Strathman *et al.*, 2002; Strathman *et al.*, 2000; Strathman *et al.*, 1999; Strathman *et al.*, 2001). The system has proven to be more reliable and accurate compared to manual methods of data collection. Data collected by AVL and APC technologies are used in this research to provide information on bus running time and passenger activity.

These technologies provide agencies with detailed operations data at various levels of the system. Stop level data is one of the highest resolutions for data collection. Stop level data can be aggregated to route-segment, route, and even system levels for performance reporting and operations purposes. Most agencies use AVL data excessively for real-time operations purposes, while others archive these data for offline analysis. In the past, the challenge to researchers and transit planners has been to collect data at the most appropriate level for analysis. Due to the presence of disaggregate data collected by AIT , the problem these days is determining how to utilize the data to improve internal decision making, in the areas of service planning, scheduling, and operations.

Running Time Models

Transit agencies serving metropolitan areas have grown to meet increases in population. This growth is often reflected in an increase in service coverage and service frequencies. Since buses travel with regular traffic, they are affected by the overall dynamics of the transportation system, where changes occur on both random and regular bases. Agencies modify schedules and service types on regular bases to address gradual change to the system. Operating a transit service according to schedule helps in gaining the trust of passengers and insures that the system operates efficiently. Schedule adherence is an important measure of transit service reliability. It is important to understand schedule adherence from the perspective of bus running time, since the amount of schedule delay at a given stop is simply the amount of running time delay up to that point. Most researchers agree on the basic factors affecting bus running times (Abkowitz & Engelstein, 1983; Abkowitz & Tozzi, 1987; Guenthner & Sinha, 1983; Levinson, 1983; Strathman et al., 2000). Table 1 contains a summary of factors affecting running times.

Table 1: Determinants of Bus Running Time

Variables	Description
Distance	Segment length
Intersections	Number of signalized intersections
Bus stops	Number of bus stops
Boarding	Number of passenger boardings
Alighting	Number of passenger alightings
Time	Time period
Driver	Driver experience
Period of service	How long the driver has been on service in the study period
Departure delay	Observed departure time minus scheduled
Stop delay time	Time lost in stops based on bus configuration (low floor etc.)
Headway	Scheduled headway
Headway Delay	Observed headway relative to scheduled
Nonrecurring events	Lift usage, bridge opening etc.
Direction	Inbound or outbound service
Weather	Weather related conditions

Transit agencies face a hard challenge since the amount of delay caused by the transportation system cannot be controlled for through strategic changes in service. The agency has to meet the challenges introduced by changes in traffic flow resulting from congestion, construction, and incidents. Approximately 26.8% of service hours at TriMet represents non-revenue service in the form of 1)layover or 2) recovery time which is needed to account for stochastic disturbances (Strathman et al., 2002). Adding extra running time to schedules is one possible solution used to address congestion delay. Although this strategy can lead to more consistency in service, it may necessitate holdings at stops on certain trips, resulting in delays to on-board passengers. On the other hand, transit agencies that can keep running time to a minimum realize savings in recovery time and layover time. However, the variables that agencies have direct control over are few.

One indicator in deterioration in transit service reliability is the increase in variance in running time relative to the mean. This variation represents unpredictable service from the standpoint of passengers. Since it can increases waiting time and in-vehicle time. Running time models are fairly common in the transit literature, while running time variation models tend to be rare. Abkowitz and Engelstein (1984) compared the effects of average running time on the standard deviation of running time. They used mean average running time as a proxy for route characteristics in order to understand how much variance is imposed by the route itself. Other causes of variation in running time are not addressed by the authors include driver experience and behavior, headway delay, variation in dwells, and variation in passenger activity.

Delays associated with signalized intersections are being partially addressed by transit signal priority (TSP), which is a strategy mentioned in several studies that focused on transit service reliability and running time (Levinson, 1983; Sterman & Schofer, 1976). TSP grants an extension of a green light cycle or a decline in the red light cycles at intersections for delayed buses. Recently several studies have tried to simulate the effects of TSP on running time delays and capture the savings that TSP provides to the transit system. TSP did proof to be effective in some of these studies while others contradicted with them.

Passenger activity variables, such as boarding and alighting rates, represent an additional sort of running time delay. Agencies try to minimize these delays by promoting smart-card based fare media, back door only policies for alightings, front door only policies for boardings, low floor buses, and requiring fare payment at the ends of trips. Reductions in boarding and alighting time can lead to changes in mean running time. Reductions in mean running time are equally important as reductions in the variation in running time, since average running time affects not only system attractiveness, but the overall costs of providing service as well.

Dwell time delay is the amount of time at a stop not accompanied by passenger activity. Variation in dwell time contributes to variation in running time. Since variation in dwell time, variation in passenger movement, and variation in the number of stops being served along a segment are major contributors to variation in running time, a better understanding dwell time is important. Table 2 includes a summary of findings regarding dwell time analyses (Bertini & El-Geneidy, 2004; Dueker, Kimpel, Strathman, & Callas, 2004; Guenthner & Hamat, 1988; Guenthner & Sinha, 1983; Levinson, 1983; McKnight et al., 2003; Rodriguez & Ardila, 2002; Strathman et al., 2000).

The times shown in Table 2 are presented in seconds per stop and per passenger. These studies estimated the impact of stop delays, boardings and alightings on average running time. It is clear that estimates of average stop delay time and passenger activity times vary. These differences may be due to model estimation techniques, the variables used in each model, and data related issues. It should be noted that generally stop delay time contributes more to dwell time than the per passenger time. This suggests that the presence of too many stops served along segments coupled with low passenger demand will have an additional time value to passengers in vehicles and agency. This value is equal to the number of stops served multiplied by dwell time delays.

Table 2: Summary of Passenger Movement

Study	Stop delay time	Boarding time	Alighting time
Bertini and El-Geneidy	5.8	3.6	0.85
Dueker et al.	5.17	3.82	1.56
Guenthner and Hamat	0.27-2.25	5.66	1.81
Guenthner and Sinha	10-20	3-5	3-5
Levinson	5	2.5	2.5
McKnight et al.	11.3	6	1.8
Rodriguez and Ardila	22.8	1.8-2.1	1.1-1.6
Strathman et al.	20.4	0.6	0.6

Based on the previous table, the expected savings from bus stop consolidation should range from 0.27 to 22 seconds. This wide range in values may be due to differences in model specifications and serving frequency. Acceleration and deceleration times also contribute to the mean and variability of running time. Variation in running time is the result of many factors; including variation the number of stops served and the amount of passenger activity along segment. In order to lower the amount of variation, the number of stops served can be reduced to achieve consistency in 1) passenger activity along segments and 2) the number of stops served along routes. Stop delay time at the route level is a function of the number of stops served. In theory, the number of stops served and level of service represented by the number of trips are determined by transit service planners who attempt to match service with demand subjected to budgetary constrains. In previous research, it is noticed that the amount of time increments associated with each passenger declines with the increase in passenger activity (Dueker et al., 2004). Based on this finding, increasing passenger activity through consolidation should lead to a decline in total dwell time and results in greater consistency (less variation) in the amount of time needed to serve stops along the route.

For passengers, transit trip has three main components: 1) walking time, 2) waiting time, and 3) trip time. Passengers value their waiting time the most, at a level two to three times that off in-vehicle-time (Mohring, Schroeter, & Wiboonchutikula, 1987). Accordingly, stop consolidation should results in improved schedule adherence by concentrating passenger activity at certain bus stops, leading to greater levels of predictably when writing schedules. Stop consolidation is a matter of compromising between the needs of transit agencies to reduce the number of stops served that cause redundancy and variation in service, and additional costs to passengers. Evaluation of the changes introduced by consolidation, such as decreases in running time variation, schedule adherence, and increases in walking time, should be part in any consolidation program. This study will try to quantify the effects of bus stop consolidation on overall transit service reliability at the trip segment level.

Research Goal and Question

Goal: ***"To Increase transit service reliability through bus stop consolidation"***

This goal is achieved through answering the following research question

Question: ***"What are the effects of bus stop consolidation on bus transit service delivery?"***

Research Objectives

In order to achieve the goal of the research, the following objectives will be met:

1. Selection of study routes;
2. Estimating the effect of bus stop frequency on transit service; and
3. Estimating the consequences of bus stop consolidation on passenger activity.

The process of selecting routes involves identifying routes and time periods where consolidations took place. Selection criteria are introduced in this section to identify routes with high numbers of consolidated stops where measurement of consolidation impacts can be isolated. Analyses are conducted to measure the effect of stopping frequency on average running time and running time variation, changes in passenger demand, and changes in other operating variables.

Dissertation Organization

The study consists of six chapters. The first chapter includes the study outline and a problem statement. A summary of current literature is presented in Chapter Two, which concentrates on literature developed in the areas of transit service reliability, performance measures, bus stop spacing, bus stop consolidation, and demand for transit service. Chapter Three includes a review of TriMets' Streamline project and the research design. Chapter Four includes route selection, data preparation, and data cleaning processes. Two levels of evaluations are addressed in Chapter Five. The composite evaluation includes differences in means tests, while the disaggregate evaluation includes ordinary least square regression models. Differences in means tests are conducted for transit service utilization measures before and after consolidations. Changes in mean running time and passenger activity models are presented in the same chapter. The first model quantifies the changes in passenger activity following bus stop consolidation, while controlling for route and socio-demographic characteristics. The second model is used to quantify the amount of time savings associated with consolidated stops. In the same chapter the differences in running time variation and headway delay variation models are introduced. The difference running time variation model is used to measure effects of consolidation on service reliability. The difference in headway delay variation model is used to identify the major variables that contribute to headway variability and accordingly, contribute to passenger wait times. Finally two running time ordinary least square regression models are conducted to with different specifications and sample sizes to validate the findings of the previous models. Chapter Six concludes the study. This chapter refines the methodological approach so that transit providers can better understand bus stop consolidation and bus stop spacing. Lastly recommendations are given regarding bus stop spacing and bus stop consolidation policies.

CHAPTER 2: GENERAL BACKGROUND

Chapter Outline

This chapter includes a literature review of the major factors to consider in a bus stop consolidation study. The goal of this research is to increase transit service reliability through bus stop consolidation. Accordingly, understanding and defining transit service reliability is an essential first step. Passengers and transit agencies have their own understanding and interpretation of transit service reliability. Performance measures are indicators that can be used to measure reliability. Running time, bus stop spacing, demand for transit, and headway variation are the major factors that are related to stop consolidation. These factors will help in guiding the research in identifying gaps in existing literature that this research will try to fill.

Transit Service Reliability

Transit service reliability has been defined in a variety of ways. Turnquist and Blume (1980) define transit service reliability as “the ability of transit system to adhere to schedule or maintain regular headways and a consistent travel time.” In other words, reliability can be defined as the variability in the system performance measure over a period of time. Abkowitz (1978) provides a broader definition of transit service reliability. He defines transit service reliability as the invariability of transit service attributes that affects the decision of both the users and the operators. Strathman et al. (1999) and Kimpel (2001) relates reliability mostly to schedule adherence, keeping schedule related delays (on time performance (OTP), running time delay, running time variation, and headway delay variation) to a minimum, which agrees with Levinson (1991) and Turnquist (1981).

In theory, an increase in transit service reliability should lead to an increase in service productivity, given accurate schedules. Several researchers have outlined methods for improving transit service reliability. These methods include: 1) implementing changes in driver behavior (through training), 2) better matches of schedules to actual service, 3) implementing control actions such as bus holding at time points, 4) implementing TSP, and 5) modifying route design (route length, bus stop consolidation, and relocation). Driver behavior can be dealt with through performance monitoring by providing feedback information to training, and field supervision. In the short term, changes to schedules should be minor. Major changes to schedules can be problematic from the standpoint o f passengers due to changes in the frequency of service, which might lead to changes in waiting time and running time. As it was mentioned in Chapter One, schedulers often need to add more running and recovery time to meet the challenges that congestion imposes on the transportation system. Another solution to increase service reliability is to design shorter routes with fewer stops to decrease overall route complexity (Abkowitz & Engelstein, 1984; Strathman & Hopper, 1993). This approach might lead to an increase in total trip time for some passengers. Since passengers might need to transfer more with shorter routes. Transfers are usually accompanied by additional waiting time, which passengers value more than any other component of time.

Another strategy to improve service reliability includes control actions by field supervisors. For example, a headway-based control such as bus holding at time points is one strategy for increasing transit service reliability by decreasing passenger wait time (Abkowitz & Tozzi, 1987). The effectiveness of this policy depends on the nature of passenger activity along routes and route configurations. Headway-based control is sensitive to the tradeoff between onboard passenger delays and wait time savings to passengers downstream. Headway control should be implemented on routes with passengers boarding near the beginning and alightings anywhere from the middle to the end of routes. The savings will be minor or even will nonexistent if the passenger patterns are different from what was mentioned above (Abkowitz & Tozzi, 1986). Implementation of TSP is discussed in the literature as an effective mean to increase reliability, yet few researchers have measured its effectiveness except the periods immediately following implementation. A recent study by Kimpel et al. (2004) found that the effect of TSP on bus running time did not show a consistent pattern of improvements along the studied travel corridor. Improvements in the mean variance of running time were found for some routes, while other routes showed deterioration in running time conditions. In reality, it is still too early to tell whether TSP is a reliable method for improving service reliability. These issues suggest that modifications to service configurations may hold promises for increasing reliability and efficiency. Modifications in route design have been recommended by various researchers as means to improve reliability. Most previous researchers use simulation to demonstrate the effects of bus stop consolidation on service reliability (Furth &

Rahbee, 2000; Saka, 2001). These studies predicted improvements in service reliability and savings in running time following bus stop consolidation. None of the previous research involved an evaluation of bus stop consolidation project in order to measure actual impacts.

There are differences between reliability measured by agencies and reliability as experienced by passengers. A reliable transit service from a passenger perspective is present when accessible service is available at both origin and destination locations. Accessibility is the suitability of a system to move people from their origins to their destinations with reasonable cost such as those based on time or distance (Koenig, 1980; Murray & Wu, 2003). Accordingly, passengers value mimization and consistency in travel times. Unreliable service results in additional travel and waiting time for passengers (Bowman & Turnquist, 1981; Strathman, Kimpel, & Callas, 2003; Turnquist, 1978; Welding, 1957; Wilson et al., 1992). Excessive service unreliability can lead to loss of passengers using the service.

Conlon, Foote, O'Malley, and Stuart (2001) conducted a study to measure passenger satisfaction after implementation of major changes along a bus route in the Chicago area. The implemented changes led to a decrease in service variation along the studied route. Passengers were satisfied with the service, in the areas of running time, waiting time, route dependability, and OTP. Another recent study used a service quality index to quantify passenger satisfaction with bus service in New South Wales, Australia. This study concludes that running time and fare are the greatest source of dissatisfaction, while frequency of service and seating availability had the largest positive impact on passenger satisfaction. The study indicates that access time to bus stops when combined with the frequency of service are important aspects of reliable service from a passenger perspective (Hensher, Stopher, & Bullock, 2003). There is wide agreement in the literature regarding the definition of reliability to passengers. A reliable service for a passenger is one that has the following characteristics 1) easily accessed by passengers at both origin and destination, 2) arrives predictably resulting in short waiting time, 3) has a short running time, and 4) has low variance in running time. This means that any change in these factors will be reflected as a decline or improvement in reliability from a passenger perspective. It is clear that an overlap exists in the understanding of transit service reliability by agencies and passengers. The difference in reliability definition between passengers and agencies is running time. Running time is considered a reliability measure by passengers, while it is considered an efficiency measures by agencies. It is important to note that wait time is directly related to the size of the amount of headway variation (Hounsell & McLeod, 1998). Variation in running time and headway is considered a reliability measure for both passengers and operators. The next section discusses the different types of transit performance measures that can be used to measure reliability.

Performance Measures

Performance measures are quantitative and/or qualitative factors used to evaluate a particular aspect of transit service (Kittelson & Associates, 2003). Consumer performance measures used to measure transit service reliability are headway variations and delays, running time variation compared to mean running time, and OTP. It is known that all these measures are interrelated, and improvement in one of them will lead to improvement in the others (Strathman & Hopper, 1993).

OTP is used by transit agencies to measure schedule adherence. OTP is defined as the percentage of buses that depart a given location within a predetermined time window (Kimpel, 2001). At TriMet, a bus is considered "on-time" when it is not more than one minute early and less than five minutes late (Tri-County Metropolitan District of Oregon, 2000). OTP standards vary across agencies and, accordingly, generalization and conclusions based on OTP will be limited only to TriMets' system, which is not the aim of this study. This study tries to introduce an approach for evaluating bus stop consolidation in a manner that can be adopted by others.

Headway delay is the difference between actual headway and scheduled headway. Poor OTP and headway variation delay indicates deterioration of service. Both are caused by inexperienced drivers, demand variation, non-recurring events, and excess congestion. Headway delay at the beginning of a route tends to propagate along the resulting in bus bunching. Total dwell time increases along segments experiencing headway delays due to changes in passenger dynamics. Running time is defined as the time needed by a bus to travel between two points along a route. These points can be the beginning and ending points of the route (terminals) or any two time points along the studied route. If the running time delay is consistently present this, mean schedule revisions are needed.

The three main performance measures that can be used to adequately measure effects of stop consolidation on service reliability and efficiency are running time, running time variation, and headway delay variation. Although these measures are interrelated, each one is used to measure a certain aspect of the provided service. In addition, the implementation of AIT, such as APC and AVL, at TriMet enables the measurement of operations variables overtime at a very detailed level of aggregation. One can thus measure changes in passenger activity and compare it to other changes in service reliability that took place following bus stop consolidation. This produces the desire for a new approach to discuss and evaluate bus stop consolidation.

Running Time

An increase in average running time and/or running time variation is a primary indicator for deterioration in service reliability. This section will concentrate on understanding the characteristics of running time and factors that increase the mean and variance of running time.

Abkowitz and Engelstein (1984) found that mean running time is affected by route length, passenger activity, and number of signalized intersections. The number of stops was not included in their model. Including the number of stops in a running time model is necessary to capture the amount of dwell time delay. Strathman and Hopper (1993) include number of actual stops served along segments, but surprisingly the number of stops along the segment did not have an effect on running time. While Strathman et al. (2000) found that the number of actual stops did have an effect on running time, but the passenger activity variables did not have not have a result on running time. This is due to several factors, including but not limited to, the way their model is structured and sample size. Rodriguez and Ardila (2002) relate increases in running time to the frequency of stopping activity and not to the amount of passenger activity. Dwell time delay did not show to have an effect on running time, which contradicts with other research. While they add that the frequency of stops, which reduces travel time, and decreases system productivity, are the key factor in running time variation. Later studies that use stop level data and larger sample sizes found that the number of actual stops has a positive effect on running time (Bertini & El-Geneidy, 2004; McKnight et al., 2003; Strathman, 2002; Strathman et al., 2002). Accordingly, it is expected that variation in passenger activity will have an effect on running time variation in the present analysis.

Strathman et al. (2002) included an important variable, the square of total passenger activity (ons and offs square), in their model this variable was found to have a negative effect on mean running time, while boardings and alightings have a positive effect. The interpretation of these variables are that the time associated to each passenger activity adds to the total running time at a lower increment rate by the increase in the number of passengers. This indicates that increasing passenger activity in some of the served stops along a route and removing other stops with low passenger activity can lead to savings in the additional increments of time associated to each passenger, which can lead to savings in running time.

Recent studies with larger sample size's revealed almost the same findings as the early empirical studies done in the 1980s and the studies that used smaller sample size datasets, regarding the magnitude of stop frequency and passenger activity on running time (Abkowitz & Engelstein, 1983; Abkowitz & Tozzi, 1987; Alfa, Menzies, Purcha, & Mcpherson, 1988; Guenthner & Hamat, 1988; Guenthner & Sinha, 1983; Levinson, 1983). Even though differences exist between these studies, regarding the values associated to each variable, which is due to differences in sample sizes, unit of analysis, and model structure. It is expected that bus stop consolidation will lead to an increase in passenger activity at adjacent stops, with a net loss in total passenger activity along the studied segments. The increase in passenger activity at adjacent stops is expected to have a net negative effect on the three key performance measures.

Various researchers have analyzed bus running times from different perspectives. Variables related to the number of stops along the studied route or segment, passenger movement, and dwell time were always common factors that these studies controlled for. In the empirical literature, dwell time delays are estimated to be around 26% of the running time. Recently, Dueker et al. (2004) studied the determinations of bus dwell time. Their findings are similar to the findings by Strathman et al. (2000) study regarding the behavior of the passenger activity variables. The amount of time added to dwell time per passenger is determined by the amount of passenger activity. The time consumed per passenger increases at an almost constant level until a certain threshold is reached. The increments of time consumed per passenger activity declines beyond this threshold. There is a difference between the two studies regarding the amount of time associated with passenger activity in relation to running time, yet the similarities exists between the two studies in the behavior of the function. The difference between the studies, even though both were done using similar data source, may be due to differences in the units of analysis, sample sizes and model characteristics.

The mean and variation in running time can be reduced by using low floor buses, decreasing the number of bus stops, changing existing bus stop locations, and implementing more efficient fare payment methods. These suggestions try to address this through reducing delay time associated at individual stops (Feder, 1973; Furth, 2000; Furth, Hemily, Muller, & Strathman, 2003; Jacques & Levinson, 1997; Kraft & Domencich, 1972; McKnight et al., 2003; Zografos & Levinson, 1986).

Dueker et al. (2004), in trying to understand dwell time, included a new variable, which is the type of bus. Their study found that low floor buses reduce average dwell time by 0.21 seconds or approximately 1.6% of total dwell time. An earlier study found that the effect of low floor buses are around 0.5 seconds per dwell (Levine & Torng, 1994). Based on the unit of analysis in this research (trip-segment), the effects of bus type on running time are likely to be minor. The study by Guenthner and Hamat (1988) did not find a statistically significant difference in dwell time between fare payment methods in Detroit. Several studies recommend decreasing the number of bus stops being served along routes as means to reduce running time. These studies suggest that the fewer the stops along a transit route the faster the running time, which should lead to lower operating costs and an increase in efficiency

(Furth & Rahbee, 2000; Levinson, 1983; Saka, 2001; Wirasinghe & Ghoneim, 1981). Based on previous literature, reducing the number of stops served along routes will potentially have a positive effect on reducing the mean and variance in bus running times. Reducing both times is a win-win situation for both passengers and transit agencies. There is no evidence in the current literature regarding the presence of studies that directly evaluates the effects of bus stop consolidation policies on running time. Most of the researchers recommend consolidation in their conclusion sections, though none address it empirically. Consolidation effects are also measured in some research but through simulation. This may be due to the lack of appropriate data in the absence of the technologies needed to conduct such evaluations. Reducing the number of bus stops being served cannot be accompanied done without an understanding of bus stop spacing policies and transit demand that are introduced in the next sections.

Bus Stop Spacing

Ammons (2001) studied bus stop spacing standards for a number of agencies and found that stop spacing typically ranges from 656 – 1,968 feet (200-600 meters) in urban areas. European transit agencies have different standards for bus stop spacing. Stops are placed so that for each mile of distance there are at least 3 to 4 bus stops (2 to 3 stops per kilometer). This contrasts with practice in the United States where stops are placed so that each mile contains at least from 7 to 10 stops (4 to 6 stops per kilometer) (Reilly, 1997). Van Nes and Bovy (2000) introduced a set of formulas for optimizations when designing new bus routes. Their study found that current service standards regarding bus stop spacing in Europe and especially in Netherlands, which are much higher than the United States, are not adequate and that revision is needed to increase stop spacing. Their conclusion is based on measuring costs of various bus stop spacing policies on both passengers and agencies using a sensitivity analysis approach. They compared their estimates of optimum stop spacing to average stop spacing in two cities in the Netherlands, which range between 9,144 to 13,716 feet (300 to 450 meters) and recommended an increase in spacing from 15,240 to 24,384 feet (500 to 800 meters). Their study was done through a programming approach, where they set an objective function with a set of constraints in order to select bus stops and apply changes in stop spacing, while measuring the impacts of various weighted measures, such as travel time and waiting time.

There has not been any documentation in the literature describing the gap between stop spacing standards in the United States and Europe. In the United States, providing bus transit service to the largest number of people, in cities that were mainly designed for car use, appears to be more important compared to door-to-door travel time. In the United States the focus towards increasing access to services rather than increasing accessibility, which led to an increase in the number of stops serving a routes. This large number of stops has a direct effect on both the type and quality of service provided.

Most transit providers have developed bus stop spacing standards to support service planning activity. Benn’s (1995) survey of the transit industry found that 85% of the responding properties had adopted stop spacing standards, a substantial increase over the 62% who responded similarly in to 1984 survey. Stop spacing standards are increasingly common in the transit industry, which most likely reflects the often intense conflicts between agencies and public, surrounding the location and spacing of stops. Furth and Rahbee (2000) state that stop spacing guidelines are developed to provide transit agencies with an objective way to resist the pressure of adding or consolidating stops in the system.

Although stop spacing standards are common, the standards themselves are hardly uniform. Benn (1995), for example, concludes that each agency has its own standards and operates service based on local needs. Even within transit agencies, stop spacing standards can encompass fairly broad distance ranges, providing service planners with considerable latitude, but also exposing the agency to greater outside pressures.

Table 3: Selected Bus Stop Spacing Standards

	TriMet	TCRP Report 19	NCHRP 69
High density (80 unites/acre), CBD, shopping centers	---	300-1,000	440-528
Fully developed residential area 22 to 80 units/acre)	780	500-1,200	660-880
Low density residential (4 to 22 unites/acre)	1,000	600-2,500	2,640 -1,056
Rural (less than 4 unites/acre)	As needed	650-2,640	2,640-1,320

Distance is in feet

Table 3 summarizes stop spacing standards from two industry-level reports (Texas Transportation Institute, 1996; Transportation Research Board, 1980) and from TriMet's (1989) service planning guide. Generally, the distance between stops is inversely related to the density of development (which proxies demand), ranging from about every other intersection in central business districts to as much as one-half mile in low-density environments. Even within a given category the stop spacing range is fairly substantial. This is particularly evident in lower density settings, where the standards could yield as few as two stops per mile or as many as 12 stops per mile.

Bus stop spacing is an optimization problem that tries to balance the needs of passengers and operators. The objective of passengers is to minimize the sum of their accessibility (Murray, 2003; Wirasinghe & Ghoneim, 1981), while for agencies, the focus is on revenues, operational costs, service reliability, and passenger satisfaction (van Nes & Bovy, 2000). Spacing is defined mainly in the United States based on people’s needs and transit agencies policies, which explain the differences in Table 3 and the reason that spacing is defined in such wide ranges.

Transit agencies evaluate their regional transit service goals based on access to residences and other demand generators (Murray, Davis, Stimson, & Ferreira, 1998). Land use characteristics are often the most important factor when agencies address bus stop spacing and locations (Fitzpatrick, Perkinson, & Hall, 1997). Since transit systems have evolved over time, revisiting the distribution of bus stops along routes is important for measuring the degree of inefficiency and/or redundancy in stop placement. The locations of bus stops are based on research at some point in time, when the causalities of having these bus stops at this particular location such stop vanish or change, the presence of the bus stop may cause potential problems in the existing service (Murray, 2003).

A decline in service reliability requires revisiting all service components including bus stop spacing to understand the causalities and introduce solutions for such decline. Redundancy exists when two stops partially cover the same service area, while inefficiency exists when there are too many stops along the route that cause delays. In theory, the bus stop market is one half of the bus stop spacing when stops are equally spaced along a straight road, when land use around stops are the same, and when both stops are serving the same number of routes. Existing bus stop locations are often determined based on political concerns, as well as planning ones. It is important for an agency to have service areas that overlap to some degree. The notion of having overlapping service ensures that all parcels are being served at a low walking cost to passengers. Having too much overlap (as it is clear in Figure 2) is not adequate from a service efficiency standpoint. Transit agencies tend not to strictly follow the standards mentioned previously. Transit agencies locate bus stops around major passenger generators such as schools, hospitals, and densely populated areas. Agencies mainly base their decision by studying the aspects of providing service to the largest population.

Service areas are geographic areas around each stop where potential riders work, live, or conduct an activity. Pulugurtha and Nambisan (1999) tried to determine the location of transit service facilities that would provide the highest levels of ridership based on demographics and access. The study only concentrated on locations with high generators for ridership. It outlines a comprehensive approach regarding how to select locations with captive transit users through the utilization of a geographic information system (GIS). Their method for selecting service areas using GIS was recently debated by Upchurch, Kuby, Zoldak, & Barranda (2004). They used a raster approach to determine service areas rather than using one quarter mile network buffers in vector analysis. Modifications to Pulugurtha's and Nambisan's (1999) method for measuring service areas can be achievable through vector analysis to reach the a low level of accuracy. Figure 2 shows the effect of overlapping service areas using a quarter mile network buffer in a near urban area. A single stop, represented as the black dot, is used as the basis for the example. The black line represents the service area around the stop of interest. Service areas from other stops are overlaid to calculate how many stops serve each parcel in addition to the studied one. Only stops from the same route and direction are used. In this example 75% of the parcels are being served by two or more bus stops in addition to the studied one, while 21% of the parcels are being served by the stop of interest and an additional bus stop. Only 4% of the parcels are being served exclusively by the stop of interest.

Figure 2: Overlapping Service Areas

Utilization of GIS packages to solve problems related to access to transit service and accessibility, in a transit planning context, is common in the literature (Evans, Perincherry, & Douglas III, 1997; Furth & Rahbee, 2000; Hsiao, Lu, Sterling, & Weatherford, 1997; Kimpel, 2001; Kimpel et al., 2004; Kimpel et al., 2000; Kuby, Barranda, & Upchurch., 2004; Murray et al., 1998; O'Sullivan, Morrison, & Shearer, 2000; Polzin, Pendyala, & Navari, 2002; Pulugurtha & Nambisan, 1999). The major advantages of utilizing GIS technologies are the analytical capabilities in dealing with spatial problems and the visualization of results.

There are two general types of people who ride transit. The first are captive riders who do not have other modes to choose from except transit. The second type is people who have access to alternative modes for their activities but they choose transit because it is either convenient, cost efficient, or for other reasons. Bus stop consolidation involves trade-offs between passenger access to the stop, and those passengers already on board who are delayed each time a bus stops. Consolidation might lead to more walking for some passengers, which may lead to loss in ridership from non-captive riders. Some stops are placed according to demand potentials from local residencies even though friendly pedestrian environments may not exist. Bus stop consolidation can be politically difficult when local residents object to having the stop, they are using or intend to use, removed or relocated. It is well known in the literature that presence of transit service has an effect on nearby land value. Some people would object to bus stop consolidation due to its effect on their property value. However, the system might end with too many stops along routes. A semi-regular and consistent process for revisiting stop location should be implemented by agencies to determine stops to be eliminated or added along existing routes. This can be achieved through empirical analysis of existing demand and service supply (Kittelson & Associates, 2003).

The work of Vuchic and Newell (1968) represents a pioneering effort in the field of stop spacing and location. They define the stop spacing problem in terms of transit users' time minimization, and their analysis evaluated the trade-offs between access and in-vehicle times with respect to the distance between stops. They recommend an increase in bus stop spacing monotonically with density of demand along a route, and decrease in bus stop spacing monotonically with the number of people onboard. Optimal stop spacing is represented as the distance at which marginal changes in transit users' access and in-vehicle times were equalized. Given uniform population density, Vuchic and Newell then mathematically derived stop spacing for a hypothetical route. Their results demonstrate that service with larger vehicle capacities and passenger loads, such as commuter rail is best designed with few stops, where feeder service could be used to concentrate passenger movements.

Several scholars have proposed various bus stop spacing methodologies based on Vuchic and Newell (1968) study (Chien, Qin, & Liu, 2003; Furth & Rahbee, 2000; Kuah & Perl, 1988; Murray & Wu, 2003; Saka, 2001; Wirasinghe & Ghoneim, 1981). These studies typically use small datasets (consisting of stops along one bus route or a small segment) to demonstrate their ideas. Several assumptions were made in these studies and each one included an empirical model that was tested using a small number of data points. The studies can be grouped into two approaches. The first approach is concerned with increasing access to transit service and the second approach concerns improving average running time through changes in bus stop spacing. Most of the studies concentrate on developing criteria for bus stop spacing along new routes.

Furth and Rahbee (2000) studied an existing route to revisit the location of bus stops through an empirical approach, based on a theory that was developed by Wirasinghe and Ghoneim (1981). They use dynamic programming to achieve optimum bus stop spacing with an assumption that demand is equally distributed in service areas around the studied route. Their findings were imposed over an existing route to compare between the optimum number of stops and existing ones. Consolidation was then recommended based on this comparison. They also examine various costs to both passengers and agencies. More work is needed in this area of research to make such models easier to understand and transferable to others.

Murray and Wu (2003) use a similar approach using an objective function and a set of constraints. They tested their model on a route in Columbus, OH. Their model attempts to remove redundancy caused by overlapping service areas. Furth and Rahbee (2000) use historical passenger movement counts and do not provide information on the source, quantity and quality of the data used. Murray and Wu (2003) concentrate only on access to bus stops and do not include demand as a variable in their model even though they mention demand as theoretically relevant. Neither one of the articles provides a methodology that can be replicated. Another point is not questioned in either of these studies, which is the effectiveness of optimization as a tool for selecting bus stops for consolidation. While variability in running time and headway were not part of these studies, the solutions in these studies try to optimize between wait time, travel time, and access time. Such methods can lead to a set of candidate stops that will decrease travel time, if all other factors are kept constant, yet in reality constancy does not exist in transit service.

The determination of optimum bus stop spacing is often based on walking distance to bus stops. Most scholars agree upon one quarter mile (400 meters) of walking distance measured from bus stops along network as an acceptable method for determining service areas around stops, which is a key factor in bus stop spacing (Demetsky & Lin, 1982; Hsiao et al., 1997; Kittelson & Associates, 2003; Lam & Morrall, 1982; Murray & Wu, 2003; Neilson & Fowler, 1972; O'Neill, Ramsey, & Chou, 1992). A person would consider a transit station accessible if it is located around 5 minutes or 0.25 miles (400 meters) from either their origin or destination. This is determined under the assumption of walking speed around 262 feet/min (80 m/min). This approximation assumes at least six bus stops per mile (4/km). Determination of service areas are based on the assumption that a potential rider's activities are located within a reasonable walking distance from transit facilities.

In theory the smaller the number of stops along a route, the greater the number of passengers who will board at a given stop (Kittelson & Associates, 2003). This will reduce the average and variance of running time. As was mentioned in the previous section, Strathman et al. (2002) and Dueker et al. (2004) found that the increments of time that each passenger add to the total dwell time decreases after reaching a certain threshold. A balance is needed between providing too few stops with high dwell times (which also increases the distance riders must walk to access transit), and providing too many stops (which reduces overall travel speeds due to the time lost in acceleration, deceleration, and dwell time delays). Optimum bus stop spacing can help agencies reduce their fleet sizes, improve trip times, and increase service reliability (Kittelson & Associates, 2003; Murray & Wu, 2003; Saka, 2001, 2003). Optimization can not be considered as the best solution regarding choices for stops to consolidate unless its effectiveness is tested empirically on service reliability.

Evaluating access to public transit is discussed in the literature but not as frequently as bus stop spacing (Murray et al., 1998). This might be due to the shortage of suitable data for such studies. Currently higher quantity and quality data is available compared to previous eras. This is due to the implementation of AIT such as AVL and APC, which allows for a better understanding of passenger demand. These technologies enable measuring the direct effect of optimization methods previously.

Bus stop consolidation will lead to an increase in bus stop spacing, which should lead to improvements in service reliability. An increase in bus stop spacing is expected to decrease average running time. The other aspect of consolidation is the increase in regularity of service by introducing consistency in the number of stops served and levels of demand at these served stops. It is expected that consistency in passenger activity and the number of stops served will lead to a decrease in running time variation. The variation is measured across days in a cross-sectional manner. If average waiting and travel times do not vary much from day to day then a reliable service is present from a passenger perspective.

Stop spacing should be evaluated based on various factors such as effects on running time, access, and potential change in passenger activity. A common mistake in previous studies is the assumption that demand is evenly distributed along the transit line. The next section will discuss the literature that highlights the transit demand and the factors that affect it, taking in to consideration both the temporal and spatial dimensions of demand.

Demand for Transit

The factors affecting passengers' decision to use transit versus other modes are affected by several costs including monetary costs (fares), the cost of travel time, cost of access and egress time, effort, and finally the cost of passenger discomfort. The Transit Capacity and Quality of Service Manual (TCQSM) provide a comprehensive approach to understanding the transit trip decision making processes, which includes several transit availability factors. These factors addresses the spatial and temporal availability of service at both ends of the trip (origins and destinations) (Kittelson & Associates, 2003). The presence or absence of transit service near origin and destination is found by Murray (2001) to be a major factor in choosing transit as a mode for travel.

Transit demand is related to the number of potential users along a route (e.g. place of residence, place of work, and various transit amenities such as park and ride or transfer). Levinson (1985) developed a model to forecast ridership along bus transit routes. His model is based on the following variables: passenger activity, population; employment, travel time, and demand elasticity factors. This study provides a reasonable approach to understanding the demand for transit even with limited data availability at the time. Levinson estimates bus ridership as a function of car ownership and walking distance to bus stops. Pulugurtha and Nambisan (1999) conducted a study that looks at demand using a set of demographic variables to identify captive riders. However, their method for determining transit service areas can be debated. Understanding transit demand requires a more general approach such as adding dummy variables to capture the effects of demographics in relation to passenger activity rather than assuming that people with certain demographic characteristics are captive users, for example having variables that capture car ownership, or household size. It is also better to estimate transit demand for all users rather than targeting the study towards a smaller percentage of users. The study by Pulugurtha and Nambisan (1999) uses area ratio methods to allocate the demographic characteristics from block groups to service areas. A different approach is to assign demographic characteristics to transit service areas by using a secondary data source such as street length ratio (Hsiao et al., 1997). This approach is somewhat problematic. Since streets can exist in vacant lands or undeveloped areas in census tracts. Another approach is to assign variables to service areas around transit stops by using the ratio of the number of residential units in the census tract or block group and tie it back to stop service areas (Kimpel, 2001). This approach has the potential to smaller errors associated with it compared to the other approaches. Similarly this can be done with employment and other types of activities. The main problem with this approach is the availability of potential data sources. If area ratio approach is used with caution it can lead reasonably accurate estimates of potential transit demand. This caution requires removing non residential areas from the study area prior to calculations, while taking into consideration the effects of overlapping service areas.

Some scholars relate ridership to access, the more accessible the bus stops are the higher the usage (Hsiao et al., 1997; Polzin et al., 2002). This might not always be the case since ridership depends on additional variables such as service variability and /or socio-demographic information. The variability and frequency of service represents two basic factors that affect demand at a stop. This will be discussed in greater detail in this section.

Several studies have contradictory outputs regarding the elasticity of demand for transit. Some studies indicate that average running time increases passenger demand more than other variables (Lago, Mayworm, & McEnroe, 1981; Rodriguez & Ardila, 2002), however this is based on the understanding that most of transit users are captive riders. Other studies indicate that passengers are more sensitive to out of vehicle time (Kemp, 1973; Lago & Mayworm, 1981; Mohring et al., 1987; Pushkarev & Zupan, 1977). Passenger demand is elastic when comparing it to time, while it is inelastic when measuring it to changes in fare. Two comprehensive studies regarding the elasticity of demand with respect to fare change found that demand for transit service is inelastic when it comes to changes in price (Goodwin, 1992; Oum, Waters II, & Yong, 1992). The value associated to time is usually higher than the fare. Mohring et al. (1987) found the value associated with in vehicle time is around half the equivalent of an hourly wage, while wait time is valued at 2-3 times that of in vehicle time.

Domencich, Kraft, and Valette (1968) estimate the elasticities of demand for public transit in relation to all aspects of time and cost. They found that passenger demand will decrease by 3.9% for a 10% increase in travel time, while demand will decrease by 7% for each 10% increase in access, egress, and waiting time. These findings were reported and validated later by Kraft and Domencich (1972) and O'Sullivan (2000). Although it combines both wait time and access into one category the study is still notable as being one of the few to address this topic. The differences between these two studies may exist due to issues of sample size and units of analysis, in addition to locations where the studies were conducted. Generalization based on this research is difficult, yet the overlap in the findings can be used as indicators for expected changes in passenger demand due to bus stop consolidations. In a bus stop consolidation study there are two aspects of changes that can affect passenger activity at the stop level. First, the increase in access is expected to have a negative impact on passenger activity, if all other factors are kept constant, with a high effect on choice riders and lower one on captive riders. Second, following bus stop consolidation a decrease in running time is expected to attract more choice riders. This same effect is expected for decreases in both running time variation and headway variation.

Other studies that looked at demand for transit in relation to walking distance found that the relationship between walking distance and ridership is best explained through an exponential function (Zhao et al., 2003). They studied a sample of 722 passengers and normalized their sample using population data within one half mile network distance from bus stops. Their function can not be tracked back to its origins for replications since they normalized the passenger demand variable based on number of bedrooms in the service area. Their model is similar to functions developed by others (Hsiao et al., 1997; Levinson & Brown-West, 1984; Neilson & Fowler, 1972). All of these studies indicate that demand for transit use will diminish quickly after the walking distance reaches a threshold of 314 feet (96 meters), while the demand will vanish beyond 1,900 feet (576 meters) from a transit stop. The distance that is widely used to measure service areas around bus stops is 1,312 feet or one quarter mile (400 meters) measured along the network (Neilson & Fowler, 1972). Accordingly, using one quarter mile network distance to define service areas for potential users is appropriate

A passenger out of vehicle time is divided into two components. The first concern access and egress time and second wait time. Wait time is a key component regarding the attractiveness of the system to passengers. Accordingly understanding the factors influencing wait time is important. As mentioned earlier, wait time is directly related to the size of the headway and headway variation. Access, which is one component of out-of-vehicle time, was discussed in the previous section. While the second components of out-of-vehicle time variation in headway and headway variation will be discussed in the next section.

Headway Variation

Bus transit headway is the amount of time between the departures of two vehicles in a route measured at a given bus stop (Meyer & Miller, 2001). Passenger waiting time is derived from both mean and coefficient of variation of headway (Bowman & Turnquist, 1981; Hounsell & McLeod, 1998; Welding, 1957; Wilson et al., 1992). Therefore, it is expected that changes in headway variation will lead to changes in passenger demand, when keeping all other factors that affect demand constant. The relationship between stop consolidation and headway variation has not been addressed in the literature. This research will introduce a model looking at effects of stop consolidation on headway variation and passenger activity.

A basic model looking at the determination of headway variation was developed by Abkowitz and Engelstein (1984). The model estimates headway variation as a function of running time variation and scheduled headway. The study is used to evaluate a headway control strategy to maintain service regularity. Kimpel (2001) use's headway delay variation as a measure of service reliability at time points during peak periods. The study also highlights the importance of including route characteristics in such models. Route characteristics may include some variables such as: segment length, the number of signalized intersections, and implementation of

TSP. Reliability is expected to be affected by these variables. It is expected that bus stop consolidation will lead to decreases in headway delay variation.

Chapter Summary

This chapter introduced the concept of transit service reliability and the various aspects that affect it. Reliability was explained from passengers' and agencies' perspectives. The main performance measures that have direct effect on reliability related to bus stop consolidation are running time, running time variation, and headway variation. The effect of consolidation on these measures was introduced in the chapter with emphasis on stop spacing policies and transit demand. The chapter has shown that gaps in transit research regarding the actual measurement of bus stop consolidation outcomes. In particular there has not been any study that has tried to evaluate effects of consolidation on service reliability using AIT. Previous research and theory suggests that bus stop consolidations will have a positive effect on service reliability.

CHAPTER 3: RESEARCH DESIGN

Chapter Outline

This chapter includes an introduction to TriMet's bus stop consolidation effort, which is part of the much larger stream line project. The introduction enables understanding the current transit setting in Portland, Oregon. It also demonstrates the types of AIT that TriMet has implemented, and what the technology can offer in terms of using empirical data to better understand the consequences of bus stop consolidation. The introduction is followed by presentation of the research methodology and the study framework. The methodology includes steps that will be conducted in order to answer the main research question. Finally the research design section is presented, which includes the details of the two evaluation methods that will be used in this research.

TriMet's Bus Stop Consolidation Program

TriMet provides bus service to the Portland metropolitan region. In 2001 the TriMet operated 93 routes covering 1,460 directional miles and 8,190 designated stops. At the system level, average bus stop spacing in 2001 was approximately 940 feet. Average daily boardings in 2001 were nearly 180,000, or about 22 boardings per stop per day.

Like many urban transit providers, TriMet has faced a growing challenge in its efforts to deliver reliable bus service over a regional road system that has become increasingly congested. The Portland region experienced substantial growth during the 1990s. The region's annual population growth rate over the decade was slightly over 2%, while the annual rate of growth in vehicle miles of travel (VMT) was just less than 5%. Given that roadway capacity grew at about half the rate of VMT, the region's travel time index expanded at a 2% rate and its ranking among the metropolitan areas covered in the Texas Transportation Institute's annual mobility reports fell from 25th in 1990 to 10th in 2000 (Schrank & Lomax, 2004)

Threats to effective service delivery associated with worsening traffic conditions, however, were substantially mitigated by TriMet's adoption of AIT in the 1990s. In 1998, the agency implemented the BDS, which includes modernizing the existing computer-aided dispatch system, an AVL system based on global positioning system (GPS) technology and more widespread deployment of APCs (the latter being first introduced in the early 1980s). The BDS provides bus operators with real time information on schedule adherence, while archived operations and passenger data provides operations managers, field supervisors, service planners, schedulers, maintenance managers, and market researchers with the information they needed to adapt to changes in the service environment. Despite worsening traffic conditions in the 1990s, a number of service quality indicators (e.g., on-time performance, running times, headway maintenance, recovery/layover requirements) had either stabilized or improved over the latter part of the decade (Strathman et al., 2000). In light of these successes, TriMet is highly regarded as an industry leader for its ability to recover data with advanced technology and to effectively translate that data into higher quality and more efficient bus service (Furth et al., 2003).

The BDS has been extensively evaluated from an empirical research standpoint, since its implementation BDS in 1997. The research has focused mainly on BDS evaluation, system performance, APC accuracy, TSP implementation and many other related topics (Kimpel et al., 2002, 2003; Strathman, 2002; Strathman et al., 2002; Strathman et al., 2000; Strathman et al., 1999; Strathman et al., 2001)

Following initial efforts focusing on the use of BDS data to improve service delivery, TriMet turned its attention to the more basic question of route design, including the location and spacing of bus stops. In 1999 the agency launched its Streamline project. The stated goal of the project was to *"*improve service reliability and reduce travel time while also improving patron safety, accessibility and comfort on select routes*"* (Tri-County Metropolitan District of Oregon, 2002). A key objective related to this goal was to reduce operating costs while maintaining the same levels of services.

Bus stop consolidation and relocation was one of a number of elements included in the Streamline project. Other project components included TSP, roadway improvements (e.g., bus only/queue jump/bypass lanes, curb extensions/ramps, intersection/turning changes), enhanced stop amenities (e.g., shelters, benches, lighting, signage, trash cans), on-street parking restrictions, and changes leading to greater compliance with the Americans With Disabilities Act (ADA). The agency also considered changes in routing to provide more direct service.

With respect to stop consolidation, the approach adopted by TriMet service planners in the Streamline project consisted of segmenting selected bus routes into analysis units. A "clean slate" approach was then followed to locate and space stops in each segment. The first step was to determine the segment's "anchor" stops at transfer points, major transit trip generators, and major intersections. Once the anchor stops were located, the next step involved the placement of additional stops between the anchor points, following the agency's stop spacing standards. Site considerations included the General placement factors such as:

1) At the farside of intersections with TSP;

2) Sites well-connected to pedestrian infrastructure and with easy neighborhood access;

3) At sites that facilitate safe street crossing; and

4) Existing stops exhibiting regular lift activity.

Also, other circumstances factored into the process, including:

1) Impacts on traffic delay and traffic safety;

2) Compatibility with adjacent properties;

3) Location of opposing stops in pairs;

4) Minimize slope and adequate visibility; and

5) Input from the public and neighborhood/business associations.

The streamline project, coupled with the availability of archived AIT data from the TriMet BDS provide a unique opportunity to evaluate and measure the impacts of the stop consolidation program in relation to service reliability, particularly the mean and variation of running time, headway delay variation and passenger activity. The proposed analysis is different from previous research since it evaluates bus stop consolidation through empirical analysis rather than simulation (Furth & Rahbee, 2000; Saka, 2001). The advantage of this method is that it can be replicated by other researchers too; previous research in this area did lack the ability of replication.

Research Methodology

The proposed study tries to answer the research question mentioned in chapter one through analysis of archived AIT data based on a unique methodological approach. The overall methodology consists of four main elements. The methodology is shown in Figure 3. In the first part, the research identifies bus routes that passed through the Streamline project and had the highest number of consolidated stops. Changes in these routes are monitored in the second step, to identify the time periods when bus stop consolidation was implemented to produce a list of consolidated bus stops with time stamp adjacent to each stop to identify the date when consolidation took place. The consolidated stops list is used with a route-stop sequence table to define the consolidation segments (CONS). Adjacent to each CONS control segments (CTRLS) are defined too. The CTRLS are used to isolate effects of bus stop consolidation on transit utilization from changes that occurred at the system and route levels.

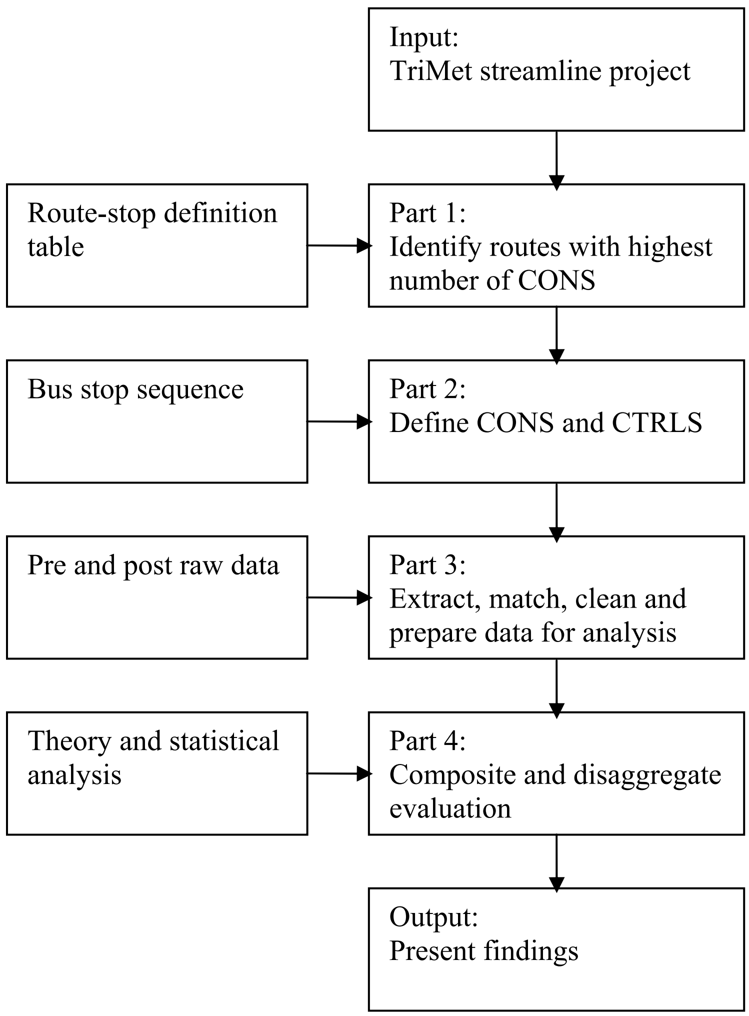

Figure 3: Research Methodology

The dates when consolidation was effective are used to define two main time periods for data requests (Pre and Post). A pre-consolidation period is defined as a three month period prior to the consolidation by at least three months. While post consolidation period is defined similarly (during the same months of the following year) but after the consolidation was effective. The reason for requesting three months worth of data is to have a sufficient number of observations to generate a robust mean and variance values for each of the study variables. Based on data availability at TriMet, some changes might occur in the time gap between the before and after time periods. The third part includes the extraction and preparation of AIT data obtained from TriMet data warehouse. Archived stop-level data for weekdays only are matched to introduce four datasets (PRECONS, POSTCONS, PRECTRLS, and POSTCTRLS).

The stop-level data is prepared through an intensive cleaning process that is described later. The data is then aggregated for both composite and disaggregate evaluations of bus stop consolidation through statistical analysis that is conducted in part four. The Composite evaluation consists of a difference in means test to compare utilization of the transit system after consolidation relative to the before consolidation time period. The disaggregate analysis includes regression models that measure changes in system performance between the two time periods, while controlling for various route characteristics. The effects are measured through difference models. After quantifying the effect of stop consolidation on system utilization, the findings are presented in a manner that addresses the effects on both passengers and the agency.

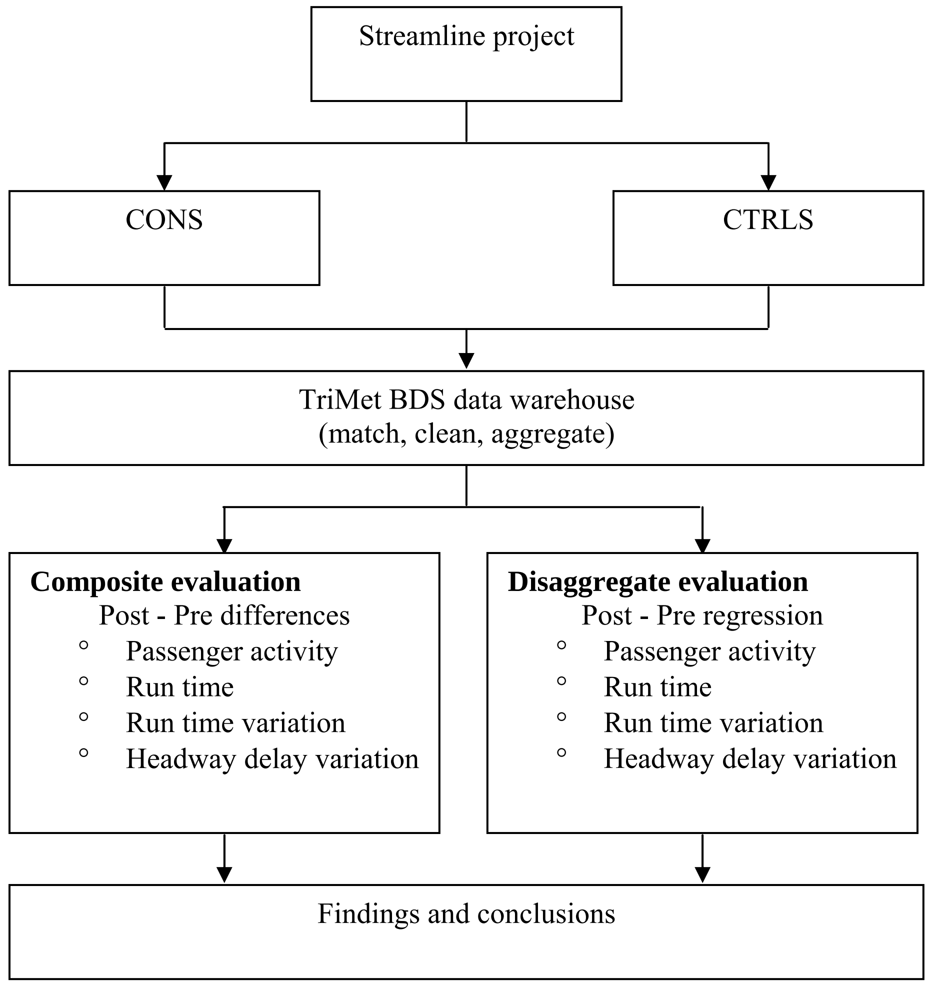

Figure 4: Research Framework

Figure 4 shows the research framework of the methodology mentioned above with more details. The composite and disaggregate evaluation methods are conducted so as to evaluate the utilization of the transit system before and after the implementation of bus stop consolidation. This is accomplished by evaluating changes in reliability and passenger activity according to several performance measures including mean running time, running time variation, and headway delay variation. Since the data cleaning process involved the removal of several trips, using a headway variation variable directly is not appropriate. Headways are calculated at bus stops based on the differences between departure times for successive trips. The presence of a missing trip at a stop will lead to an error in the evaluation of headways. This problem can be mitigated by using headway delay variation variable rather than headway variation. A headway delay variation variable was previously explained by Kimpel (2001), in an analysis of transit service reliability at time points.

The availability of archived AIT data (such as APC data) enables quantifying the direct effects of bus stop consolidation on passenger activity. Accordingly changes to passenger activity are another indication of system utilization by passenger, after consolidation. These measures of utilization (passenger activity) and reliability (run time, run time variation, and headway delay variation) will be used in composite evaluation method, which utilize before and after data, to test for differences between the two time periods. This is accomplished through use of differences in means test, while more detailed analysis is conducted at the aggregate level for each measure. The disaggregate analysis includes several ordinary least square regression models. The models include several control variables that isolate the effect of bus stop consolidation on the dependant variables from all other changes that might have occurred following bus stop consolidation.

Composite Evaluation

The objective of the composite evaluation analysis is to test for changes in passenger activity and service performance in the CONS relative to changes that occurred in the CTRLS. The approach links each scheduled bus trip prior to bus stop consolidation with its exact counterpart from the period following implementation. This trip matching produces a paired sample, or a two-period panel, which has the advantage of reduced sampling error relative to the alternative of drawing independent samples from each period (Wonnacott & Wonnacott, 1972).

The unit of analysis for the composite evaluation methods is trip-segment (e.g., passenger activity per trip per segment). Thus, for example, each paired trip will generate *n* treatment observations and *n* control observations, where *n* is the number of CONS and CTRLS. Each observation is calculated as the change in the value of a given variable following implementation, or

$$\textit{Value change} = \textit{Post-implementation value} - \textit{Pre-implementation value} \qquad (1)$$

A paired sample t-test is applied to the change to determine statistical significance. The tests will be applied to the following variables: passengers' activity, running time, running time coefficient of variation, and headway delay coefficient of variation. The coefficient of variation is the standard deviation divided by the mean. Using the coefficient of variation enables standardizing the variation in headways and runtime, allowing for comparisons across routes, time periods, and reliability indicators. These are the main variables that can be used to measure the utilization and reliability of a transit system from both passenger and agency perspectives.

Disaggregate Evaluation

In addition to the composite evaluation of changes in passenger activity and operating performance, a set of regression models are developed to measure the changes in system utilization that occurred following stop consolidation, while controlling for other factors that could influence bus operations and passenger activity. The disaggregate evaluation tries to separate the effect of changes that occurred due to bus stop consolidation from any other variable that might have had an influence on transit system utilization. The unit of analysis for the regressions is a difference-trip-segment (e.g., difference in average passenger activity per trip per segment). The data is organized and matched so as to produce a difference dataset (POST – PRE). Studying differences directly in a regression model enables the understanding of various factors influencing changes in transit service. Understanding and identifying the variables that affect changes in the dependant variables is more important than model fitting. The disaggregate evaluation is conducted through a set of four regression models. The four models directly measure the changes in passenger activity, changes in actual running time, changes in actual running time coefficient of variation, and changes in headway delay coefficient of variation, while controlling for several additional variables. Headway delay coefficient of variation is measured at the last stop in each segment. With direction from the literature, the four models are developed according to the general forms:

Model 1

$\Delta PNGRACT = f\,(CONS, \Delta POP, \Delta INC, \Delta DELSTA, \Delta SCHWS, R104, AMIN)$

Model 2

$\Delta MRT = f\,(CONS, \Delta DELSTA, \Delta SCHWS, \Delta PNGRACT, \Delta PNGRACT2, \Delta LIFT, \Delta NUMST, R104, AMIN, SEGLEN, POSTTSP, PRETSP, NUMSIG)$

Model 3

$\Delta CVRT = f\,(CONS, \Delta CVDELSTA, \Delta CVPNGRACT, \Delta CVLIFT, \Delta CVNUMST, \Delta SCHWS, R104, AMIN, SEGLEN, POSTTSP, PRETSP, NUMSIG)$

Model 4

$\Delta CVHWSDLA = f\,(CONS, \Delta CVHWSDFI, \Delta CVPNGRACT, \Delta CVLIFT, \Delta CVNUMST, \Delta SCHWS, R104, AMIN, SEGLEN, POSTTSP, PRETSP, NUMSIG)$

Detailed descriptions of each of the variables used in the models are given in Table 4. The first four variables in the table are the four dependant variables, while the rest of the table includes the independent variables. It is important to note that the change in passenger activity was also included as an independent variable in the change in running time model since passenger activity has a direct effect on running time. CONS is a dummy variable specified to capture estimated changes in passenger activity, running time, running time coefficient of variation and headway delay coefficient of variation relative to the omitted reference, which is the CTRLS. The first model measures the effect of bus stop consolidation on passenger activity, while controlling for socio-demographic characteristics, study route, and time of day. Socio-demographic characteristics are calculated using one quarter mile buffer measured along street network to define the service areas around each bus stop.

Table 4: Difference Models Description

Variable	Description	1	2	3	4	5	6
Δ*PNGRACT*	Change in average passenger activity (actual)	•	•			•	•
Δ*MRT*	Change in average bus running time (seconds)		•			•	•
Δ*CVRT*	Change in bus running time coefficient of variation (seconds)			•			
Δ*CVHWSDLA*	Change in headway delay coefficient of variation measured at the last stop (seconds)				•		
Δ*POP*	Changes in population residing within 1/4 mile of bus stops along segments (actual)	•					
Δ*INC*	Change in median income of households residing within 1/4 mile of bus stops along segments (actual)	•					
Δ*DELSTA*	Change in average delay measured at the segment origin (seconds)	•	•			•	•
Δ*CVHWSDFI*	Change in headway delay coefficient of variation per trip-segment measured at the first stop in segment (in seconds)				•		
Δ*CVDELSTA*	Change in delay coefficient of variation measured at the segment origin (seconds)			•			
Δ*SCHWS*	Change in scheduled headway (seconds)	•	•			•	•
Δ*NUMST*	Change in average number of actual stops including scheduled and unscheduled (physical)		•				
Δ*CVNUMST*	Change in number of stops coefficient of variation (physical)			•	•		
Δ*NUMDW*	Change in the average number of door openings at scheduled stops					•	
Δ*NUMUSCDW*	Change in the average number of door openings at unscheduled stops					•	
Δ*PNGRACT2*	Square of the change in mean passenger activity (actual)		•			•	•
Δ*CVPNGRACT*	Change in passenger activity coefficient of variation (actual)			•	•		
Δ*LIFT*	Change average number of lift operations (actual)		•			•	•
Δ*CVLIFT*	Change lift operation coefficient of variation (actual)			•	•		
CONS	A dummy variable equaling one if the observation occurred in a treatment segment (1=true)	•	•	•	•		
R104	A dummy variable equaling one if the trip-segment occurs on the 104-Division (1=true) relative to 4-Fessenden	•	•	•	•	•	•
AMIN	A dummy variable equaling one for morning peak inbound trip-segments (1=true) relative to evening peak	•	•	•	•	•	•
SEGLEN	Segment Length (feet)		•	•	•	•	•
PRETSP	A dummy variable equaling one if the segment has signal priority implemented before treatment (1=true)		•	•	•	•	•
POSTTSP	A dummy variable equaling one if the segment has signal priority implemented after treatment (1=true)		•	•	•	•	•
NUMSIG	Number of signalized intersections along studied segments (actual)		•	•	•	•	•

Note: delay is calculated by comparing actual to schedule, Model 6 is measured for the actual rather than the change

The second model estimates the change in running time resulting from consolidation. The effect of consolidation will be identified through the combination of coefficients of two variables, the dummy variable representing the consolidation segments (CONS) and the change in number of stops variable. The covariates in the regressions are commonly included in studies of passenger activity, running time, and service reliability (Abkowitz & Tozzi, 1987; Kimpel, 2001; Levinson & Brown-West, 1984; Strathman et al., 2002; Turnquist, 1978). For example, it is expected that passenger activity will be directly related to the change in size of the resident population within one-quarter mile distance of stops, and will not be related to the level of income in a stop area since the change in income will be minor, due to the existence of high levels of overlap in service areas. Still there is a variation in the levels of overlap, which requires including this variable in the model. The change in average running time is not included in this model for simultaneity reasons. Running time increases due to changes in passenger activity, in addition passenger activity changes with changes in running time. Accordingly including a running time variable in this model would be problematic.

Changes in running time are expected to increase with the increase in the change of: the number of stops made in a segment, lift activity, and passenger activity. Changes in mean running time are expected to be less for morning peak inbound trips relative to evening peak outbound trips. Schedule delay could be either positively or negatively related to running time. If delay is chronic and persistent, it is likely to have a positive effect on running time. Alternatively, if delay is circumstantial and operators exploit layover and recovery time opportunities, delay could be inversely related to running time. It is hypothesized that changes in running time variation will be similarly related to changes in the same set of variables that were specified in the mean running time model. The change in headway delay variation at the ending stop along segment is expected to be positively related to positive changes in headway delay at the beginning of the segment and passenger activity. A dummy variable is included for the 104-Division to capture differences in passenger activity and operations relative to the 4-Fessenden. The change in scheduled headway variable is included in all models to control for the alterations to schedules over time. Finally, since transit signal priority was implemented as part of the Streamline project, a dummy variable is added to represent segments with TSP. TSP is expected to have a reduce mean running time and running time variation.

The findings of the disaggregate evaluation and composite evaluation methods, especially the running time model, are then validated through two ordinary least square regression models with different specifications and sample sizes. The following are the specifications of the validation models:

Model 5

ΔMRT = f (CONS, ΔDELSTA, ΔSCHWS, ΔPNGRACT, ΔPNGRACT2, ΔLIFT, ΔNUMDW, ΔNUMUSCDW, R104, AMIN, SEGLEN, PRETSP, POSTTSP, NUMSIG)

Model 6

MRT = f (CONSPRE, CONSPOST, CTRLSPRE, DELSTA, SCHWS, PNGRACT, PNGRACT2, LIFT, R104, AMIN, SEGLEN, TSP, NUMSIG)

Detailed descriptions of each of the variables used in these two models are given in Table 4, except for the three dummy variables CONSPRE, CONSPOST and CTRLSPRE. CONSPRE is a dummy variable, which equals one if the observation occurred along a treatment segment in the pre time period. CONSPOST is a dummy variable, which equals one if the observation occurred along a treatment segment in the post time period. Finally CTRLSPRE is a dummy variable, which equals one if the observation occurred along a control segment in the pre time period. The coefficients of these three dummies measure the differences in running time relative to the omitted variable (CTRLSPOST). The omitted variable is the running time measured along controls in the post time period.

Model 5 captures the effects of the change in the number of stops associated with door openings on running time and directly relates these changes to the CONS coefficient, which is different from Model 2 where the CONS coefficient needs to be combined with the change in the number of stops for interpretations to measure the effects of bus stop consolidations on running time. This model uses the same four datasets used for all the other models except Model 6.

In order to ensure the robustness of Model 2 a different model (Model 6) is conducted using a disaggregate dataset to measure the effects of consolidation on running time. The sample size for this model is maximized to include all the trips that passed through the segments in the study rather than averaging (around 14,000 records). The number of stops variable is removed from this model to enable the direct interpretation of the effects of bus stop consolidation on running time. The effects of consolidation are captured through interpreting the coefficients associated with the two dummy variables CONSPRE and CONSPOST.

Chapter Summary

TriMets Streamline project, which includes bus stop consolidation, serves as the primary catalyst for this research. Coupled with the AIT data archiving system at TriMet, a unique opportunity is present for evaluating the utilization of transit system prior and after implementation of bus stop consolidation program. A research methodology and a research design for evaluating and estimating effects of bus stop consolidations using archived (not simulated) data were presented. This chapter outlines the data preparation processes that will be discussed in the next chapter. In addition to an introduction to the two evaluation methods, composite and disaggregate, that will be used in the study and will be discussed in more detail in Chapter Five.

CHAPTER 4: DATA PREPARATION

Chapter Outline

Chapter four documents the process of route selection for bus stop consolidation study and evaluation. Following route selection the process identifying consolidated bus stops is presented. The chapter contains 1) data extracting; 2) stop-level data preparation; and 3) data aggregation methods required to produce the final trip-segment-level dataset. Finally a brief discussion of efforts necessary to assign route and demographic characteristics to the study segment is presented.

Route Selection

Seven different bus routes in TriMets' bus system passed through the Streamline project. These routes were subjected to various changes including bus stop consolidation, bus stop relocation, implementation of TSP, changes in the route path, and changes in schedules. The Streamline project was started at TriMet in 1999 and it is still continuing at this point in time. Not all the recommendations of the Streamline project have been implemented. The present study is interested only in bus stop consolidations that were recommended by the Streamline project and implemented. Table 5 includes a list of the seven bus routes by direction (inbound and outbound) and the year along with the number of bus stops consolidated. The data in Table 5 was obtained through analysis of TriMets' route-stop definition table. This table includes history of all bus stops in the TriMet system. Each bus stop in TriMet system has a unique identification number (UID) that is included in the table. Along with the UID the table includes dates referring to various changes that occurred to every stop in the system. Accordingly, monitoring the history of bus stops can be achieved through a detailed analysis of TriMets' route-stop definition table.

Table 5: Summary of Consolidated Stops

Direction	Route	Year	Number of Consolidated Stops
Outbound	4-Fessenden	2000	**5**
		2001	1
	9-Broadway	2003	1
	12-Barbur Blvd	2001	**6**
		2002	1
		2004	**4**
	72-Killingsworth/82nd Ave	2000	1
		2001	1
		2002	2
	104-Division	2000	**4**
		2003	**4**
		2004	1
	109-Powell	2001	1
		2003	1
		2004	3
	112-Sandy Blvd	2001	3
		2002	1
Inbound	4-Fessenden	2000	1
		2001	**4**
		2002	1
		2003	1
	9-Broadway	2003	1
	12-Barbur Blvd	2001	2
		2002	**4**
		2004	**4**
	72-Killingsworth/82nd Ave	2000	1
		2002	2
	104-Division	2000	**9**
		2001	1
		2003	**4**
	109-Powell	2004	2
	112-Sandy Blvd	2001	3

It is clear from Table 5 that routes 12-Barbur Blvd. and 4-Fessenden/104-Division had the highest number of bus stop consolidations in both directions. A large percentage of consolidations that occurred along route 12-Barbur Blvd were in the year 2004. Accordingly, obtaining post-treatment data was not possible at the time when this study was conducted. Also route 12-Barbur Blvd is a complicated route with several patterns (regular, limited, and express service). Furthermore, several routes overlap with route-12-Barbur Blvd along various segments making analysis of route 12-Barbur Blvd. Since isolating the effects of overlapping routes and patterns is not the concern of this study and accordingly this route was discarded from being a candidate route.

The 4-Fessenden/104-Division, which provides interlined radial service to downtown Portland, was the first product of the Streamline project and is the subject of the present analysis. Service on the reconfigured routes commenced in 2000. Consolidations that occurred during other years along these routes were not concentrated in one quarter as it was in the year 2000. The 4-Fessenden/104-Division was among the most heavily patronized routes in the TriMet bus system, with approximately 7,500 weekday boarding rides and over 45 boarding rides per vehicle hour in early 2000. It was also among the lowest performers in reported excess wait time per passenger, an indication of service reliability problems (Tri-County Metropolitan District of Oregon, 2000). Figure 5 shows route 4-Fessenden/104-Division in relationship to downtown Portland and major freeways.

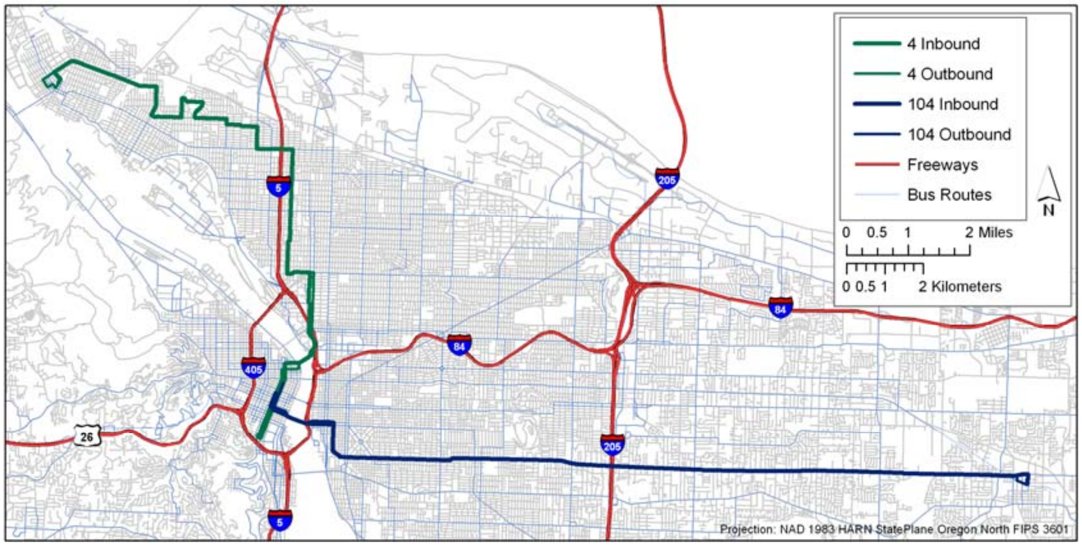

Figure 5: Study Area

Table 6 includes a list of archived AIT data available from TriMet for the study route by time periods. The analysis focuses on inbound trips during the morning peak service period (7:00 to 9:00 A.M.) and outbound trips during the evening peak (4:00 to 6:00 P.M.), since these conditions tend to derive the bus stop planning process.

Table 6: Before and After Consolidation Study Dates

Direction	Route	Before		After	
Inbound	4	Sep 15 - Dec 15	2000	Sep 15 - Dec 15	2002
	104	Jan 1- Mar 1	2000	Jan 1- Mar 1	2001
Outbound	4	Jan 1- Mar 1	2000	Jan 1- Mar 1	2002
	104	Jan 1- Mar 1	2000	Jan 1- Mar 1	2001

Three months worth of weekday, stop-level data, including passenger activity, service reliability, and operations were obtained from TriMet's BDS data archive for both the pre and post time-periods. The time periods correspond to at least six months before and six months after bus stop consolidation and relocation took place. The goal was to obtain data for the time periods that is approximately one year before and one year after treatment. Since TriMet does not archive the full set of BDS data this was not possible. A dummy variable (R104) is included in the models to address these variations in time differences. Determining the appropriate time frame for assessing change system utilization relied on judgment, given that there is little empirical evidence of the dynamic consequences of stop consolidation and relocation. Stop-level data was then extracted from TriMets' data archiving system for routes 4-Fessenden/104-Division during the specified periods of time mentioned in Table 6.

Stop Identification

After extracting the data for the selected route from TriMets' data archiving system, the pre and post-treatment data was matched to identify changes in bus stops. Table 7 summarizes changes in bus stops by direction for routes 4-Fessenden/104-Division. The 4-Fessenden had a net reduction of four inbound and six outbound stops, while the 104-Division had a net reduction of five inbound and seven outbound stops. In one instance (i.e., 104-outbound), the reduction simply reflects the elimination of stops, while in other cases new stops were added from the consolidation and relocation process that took place along this route. The net reduction in stops led to an increase in average spacing between inbound stops of more than 6% and an increase of more than 8% between outbound stops. There is a discrepancy between the numbers of consolidated stops presented in Tables 5 and 7. The discrepancy exists because in the stop-route definition table (that was used in Table 5) only removed stops from the system were monitored to obtain the number of consolidated bus stop along the Streamline routes. On the other hand, Table 8 takes into account bus stop consolidations, consolidations and relocations, and additions.

Table 7: Summary of Stop Changes

Direction	Route	Stops Before/After	Stops Removed	Stops Added	Av. Spacing Before/After
Inbound	4	67/63	8	4	933/992 ft.
	104	84/79	8	3	839/892 ft.
Outbound	4	78/72	8	2	820/890 ft.
	104	95/88	7	0	742/801 ft.

Information in Table 7 yielded to a list of consolidated and added stops. This list is used to identify CONS through a detailed analysis of TriMets' route-stop definition table. CONS represent the unit of analysis in this the study. CONS consist of a minimum of three or more bus stops in the pre time period and two or more in the post time period. As it is clear in Figure 6 there are two types of CONS.

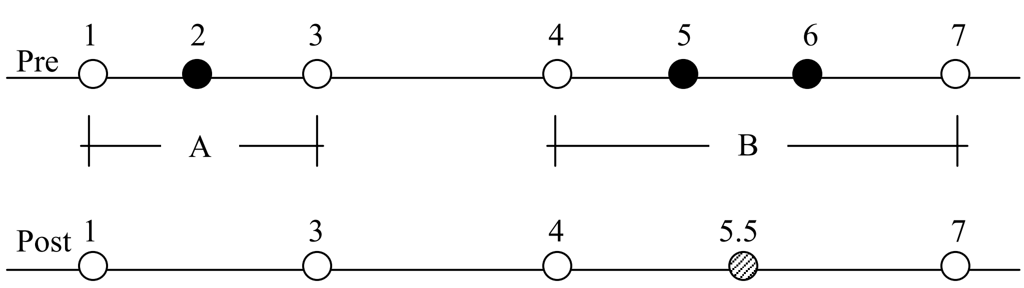

Figure 6: Types of CONS

The first type includes segments with consolidations only (Case A). Each segment in this category should include three bus stops in the pre-treatment time period and two stops in the post-treatment time period. The second type of CONS (Case B) includes segments that incorporated consolidation and relocation or addition. These segments should include a minimum of four stops in the pre-treatment time period. While in the post-treatment these CONS include a maximum of three stops. CONS are identified after organizing TriMets' route-stop definition table according to stop sequence. A unique identification number is given to all the stops contained in one CONS. Not all the consolidated stops were selected for use in the study. Some CONS were hard to define due to 1) overlapping stops or 2) errors in the route-stop definition table. For example when the last stop in a CONS overlaps with the first stop in another CONS both were removed form the study. This process ensures that effects of bus stop consolidation are isolated from changes in adjacent stops. The selection criteria yielded ten primary CONS for use in the study.

Ten additional segments were added for control purposes. These segments help isolate the effects of consolidation from the effects of overall changes occurring at the route level. The CTRLS are located adjacent to each CONS. No physical changes occurred on these segments between the two time periods. Each CTRLS contains the same number of stops as the adjacent CONS in the pre-time-period. Figure 7 shows the route segments for the 4-Fessenden/104-Division where stop consolidation and/or relocation occurred. The analysis will relate changes observed in the CONS to those observed in the CTRLS.

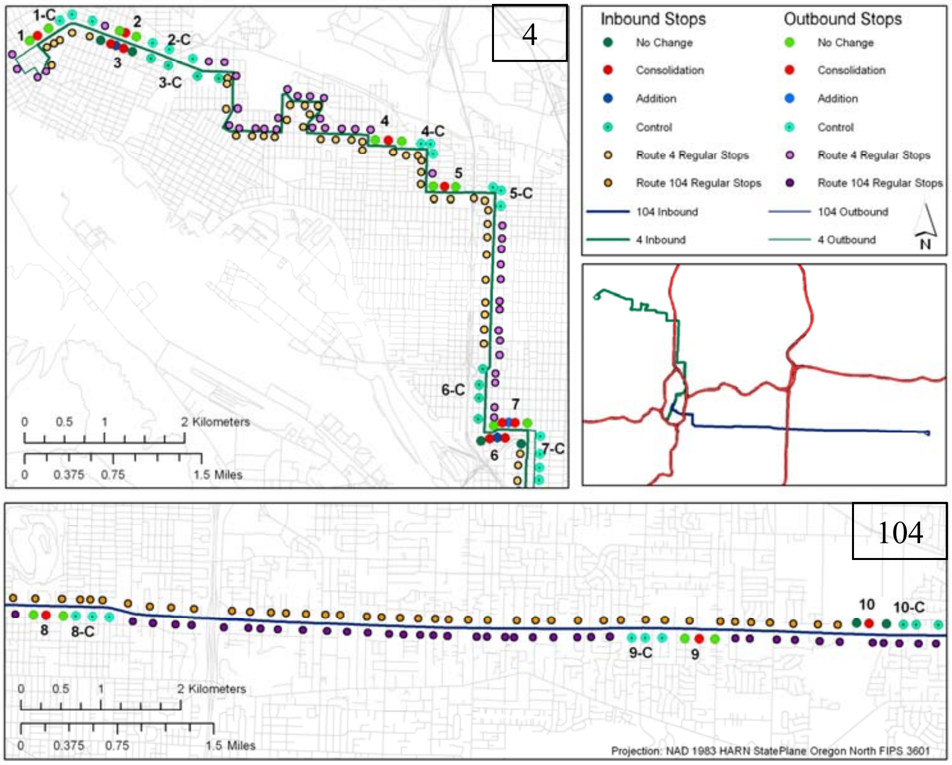

Figure 7: CONS and CTRLS Along 4-Fessenden/104-Division

Stop level data is extracted for both the before and after time periods from TriMets' data archiving system following identification of the CONS and CTRLS. PRECONS, POSTCONS, PRECTRLS, and POSTCTRLS represent the four main datasets that are extracted from TriMets' AIT data archiving system. Each record in these datasets represents information obtained at the stop-level. An identification variable is added to each record in the extracted data to define whether the data is from pre or post-time-period and if it is part of CTRLS or CONS. Additionally several calculations are performed at the stop level of in order to generate measures of running time, actual headway, headway delay (actual – scheduled) , delay (actual – scheduled) and passenger activity.

Data Preparation and Aggregation

As stated in Chapter 3, the trip-segment is the unit of analysis for this research. The assignment of trips to CONS and CTRLS leads to a new unique identifier for each segment. For example if a stop (1) was part of segment (2) and trip (1352) the unique identification number of this observation will be (121352).

Table 8: Extracted and Aggregated Variables

Variable	Description
Trip-segment	Trip segment identification number
Arrive first stop	Time bus arrived at first stop in segment
Leave last stop	Time bus departed the last stop in segment
Unscheduled stops	Number of unscheduled stops along segment
Delay at the end	Delay at end of segment
Delay at the beginning	Delay at beginning of segment
Average delay	Average delay over all stops in segment
CONS/CTRLS	Control or a consolidation segment
Pre/Post	pre or post-time-period
Estimated load	Bus load average over all stops in segment
Ons	Total number of passenger boarding along segment
Offs	Total number of passenger alightings along segment
Total Ons +Offs	Total passenger activity along segment
Lift	Total lift activity along segment
Dwell	Time associated with door opening in segment
Headway delay first	Headway delay at the first stop in segment
Headway delay last	Headway delay at the last stop in segment
Count	Total number of actual stops along segment
Check	Total number of scheduled stops along segments (for checking)

Note: delay is calculated by comparing actual to schedule

This new identification number enables summarization of stop-level data to the trip-segment level. Table 8 includes a list of extracted and aggregated variables. The data were then subjected to a process to check for errors and missing information (primarily passenger data and route patterns). Running time is calculated at this stage of the analysis. Later in the process the data are summarized over all days on a per trip basis in order to generate the final set of variables needed for the study (mean passenger activity, mean running time, running time variation, and headway delay variation). Figure 8 presents a 3D matrix that summarizes how the variables are derived along the days to generate the summary matrix that will be used in the evaluation methods.

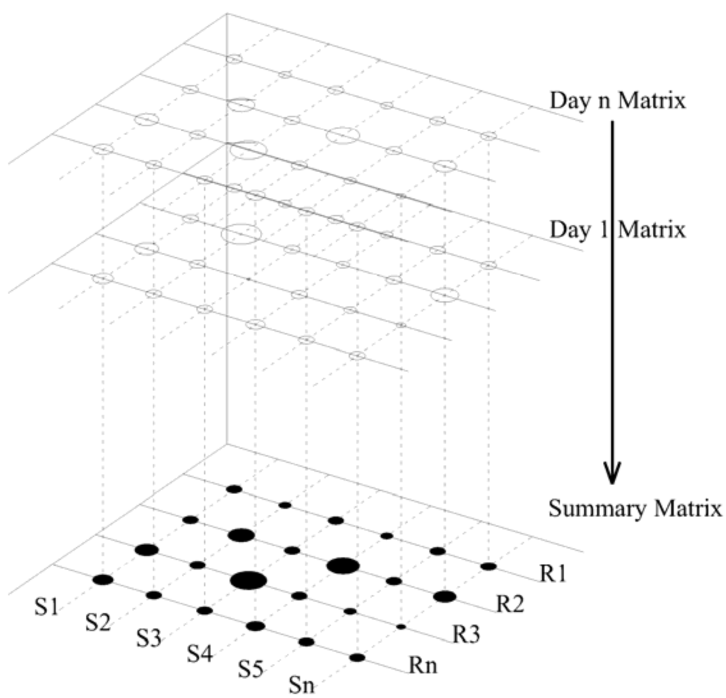

Figure 8: Data Preparation Process

The X axis (*R1 – Rn*) represents trips, while the Y axis (*S1 – Sn*) represents study segments either CONS or CTRLS, and finally the Z (*Day 1 – Day n*) axis represents days. For example, when calculating the variance in running time for segment 1 (*S1*), several trips has passed through this segment in each day, during trip 1 (*R1*), the variance is calculated from running time along this segment during this particular trip at days 1 through *n*, where *n* is the number of observed days (run time is represented as the diameter of each circle in the ay matrix).

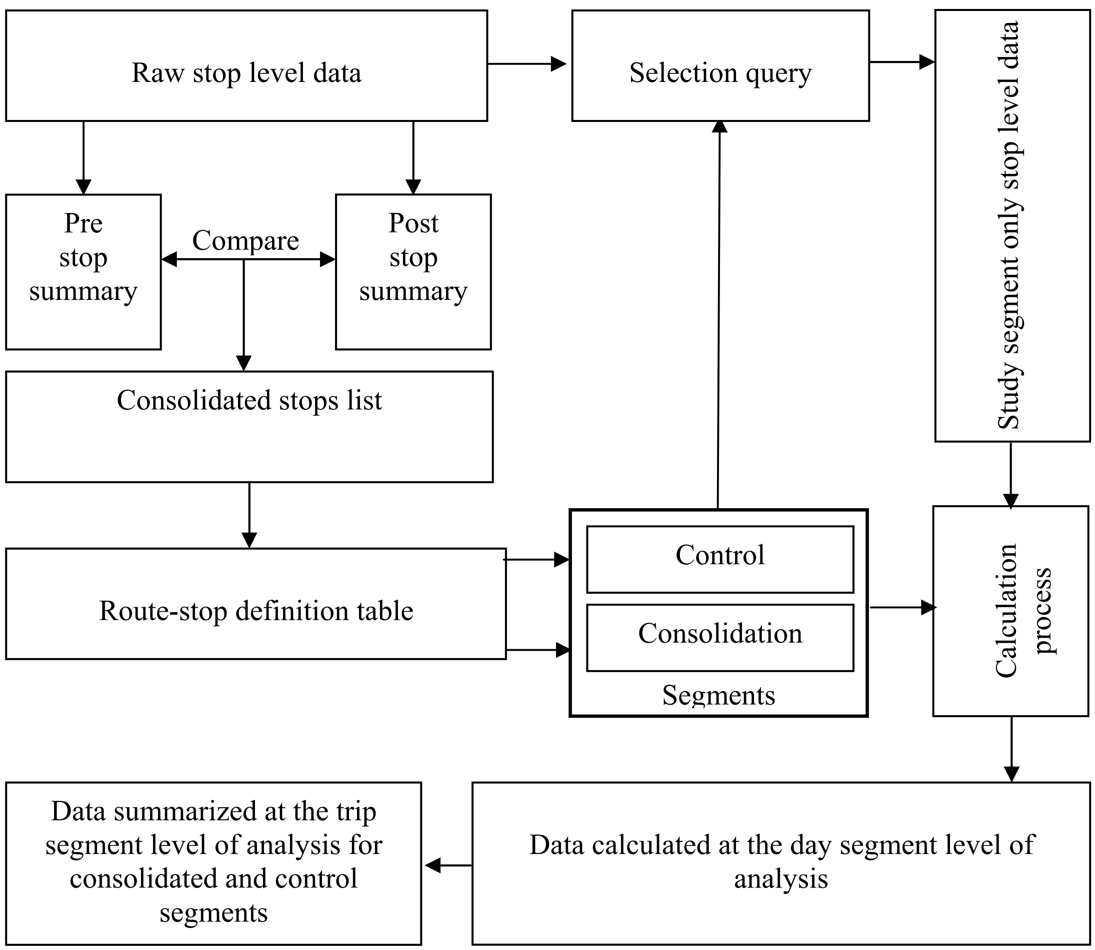

Figure 9: Summary of Data Extraction and Aggregation Process

The variance is calculated and presented as the shaded diameter in the summary matrix. All of the other variables (variances and means) are calculated in same manner. This process produced procedure produced 188 total treatment trip-segments and 188 total control trip-segments. Summary of the data extraction and aggregation process is shown in Figure 9.

Table 9: Data Reduction

Time Period	Direction	Route	Stop-Level		Segment-Trip-Level		Cleaned Segment-Trip-Level		Aggregated Segment-Trip-Level	
			CONS	CTRLS	CONS	CTRLS	CONS	CTRLS	CONS	CTRLS
Pre	In	4	7888	9131	2522	2545	1101	1584	18	18
		104	5532	4024	1793	1753	1544	705	16	16
	Out	4	6040	6100	1725	1724	1532	1629	44	44
		104	4181	3830	1607	1431	885	823	5	5
	Total		**15753**	**13954**	**5125**	**4908**	**3961**	**3157**	**83**	**83**
Post	In	4	6330	9036	2115	2115	1779	1693	18	18
		104	4575	4747	2117	2065	1814	771	16	16
	Out	4	5396	7592	2456	2465	1994	2006	44	44
		104	3182	4098	1713	1548	947	842	5	5
	Total		**19483**	**25473**	**6286**	**6078**	**4755**	**3619**	**83**	**83**
Total			**74663**		**22397**		**15492**		**332**	
Final Dataset									**166**	

The first trip in both the morning and evening time periods are eliminated since headways could not be calculated. The final datasets consist of 83 treatment trip-segments and 83 control trip-segments in both time periods. The pre dataset is matched with the post dataset to calculate the differences dataset, which is the final dataset. The differences are calculated based on the pre-time period variables subtracted from the pre-time-period (POST – PRE). This process leads to a final dataset that includes 166 observations. Table 9 shows a summary of data reduction process from the original stop-level data to the aggregated trip-segment- level. While Figure 10 shows a summary of the differences datasets developed for various evaluation methods. The composite evaluation will use the three differences data sets A, B, and C. While the disaggregate evaluation will only use A and B.

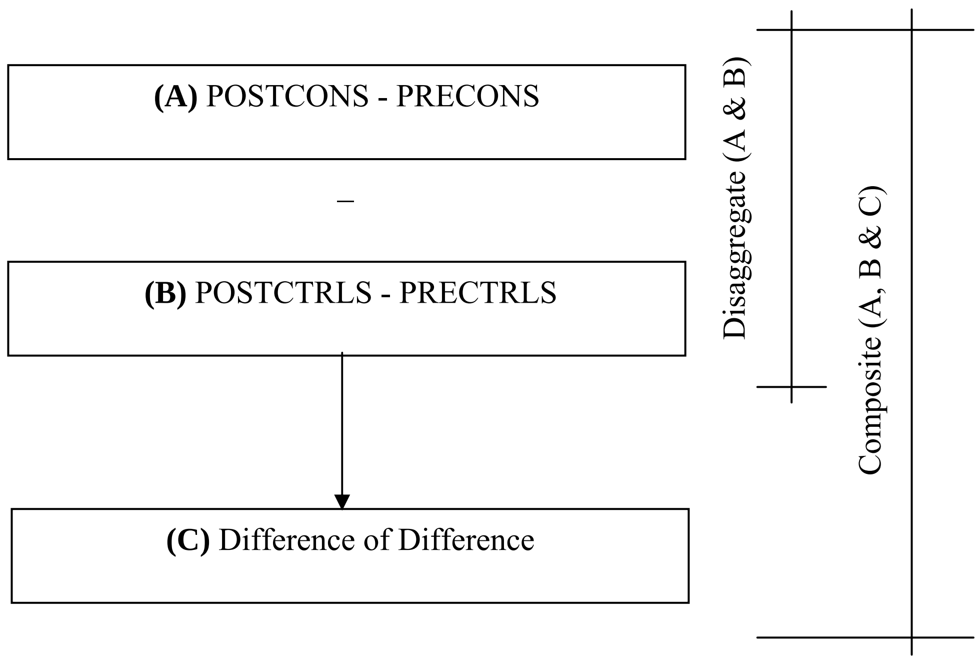

Figure 10: Differences Datasets

Route Characteristics and Demographic Data

In order to adequately isolate the effects of stop consolidation on the passenger activity and system performance measure, it is necessary to control for various route characteristics such as socio-demographic characteristics. The soci-demographic characteristics are obtained from the US Census Bureau for the year 2000. Route characteristics were derived from GIS files obtained from Metros' Regional Land Information System (RLIS). A one quarter mile service area, which is measured along the network, is calculated in a GIS to define service areas around each stop in both time periods. Then stop service areas are combined to form segment service areas. This process is conducted for CONS and CTRLS in both time periods. GIS is heavily utilized in the current study to determine population within service areas, while addressing the overlapping service areas in the calculations. Addressing the overlap in service areas for demand modeling can be done through several approaches. Peng and Dueker (1995) use an explanatory variable based on the percent of overlap to address this issue. Kimpel (2001) overlap is addressed by proportionally assigning potential demand in overlapping service areas using secondary information derived from disaggregate data as the basis of allocation. In the current study the allocation of population to each segment service area use the lowest level of aggregation (census block) to reduce the error associated with the process. Similar to Kimpel (2001) non-residential parcels, for example parks and commercials, are removed from service areas before assigning populations. The presence of overlapping service areas leads to an overstated population values, accordingly if an overlap is present in any service area in the current study, the values in the overlap are divided equally between the adjacent service areas. Median household income is calculated at the block group level of analysis in a similar manner. Linear referencing is used to calculate stop spacing and segment length. A GIS layers containing traffic signals information combined with TSP implementation table, obtained from TriMet, are used to identify segments with TSP and the dates of implementation. Also a number of traffic signals variable is calculated using the same GIS layer.

Chapter Summary

This chapter describes route selection; the identification of consolidated bus stops; data extraction; segment identification; data extraction and aggregation; and demographic and route specification data preparation. The effects of bus stop consolidation can be isolated using the dataset described in this chapter. The final dataset is ready for composite and disaggregate analyses which were described in Chapter 3 and will be the subject of the next chapter.

CHAPTER 5: EMPIRICAL ANALYSIS

Chapter Outline

An empirical analysis measuring the effects of bus stop consolidation on the utilization of bus public transit service is presented in this chapter. The chapter begins with a presentation of descriptive statistics to help the reader understand the characteristics of data used in the analysis. The second section includes the composite evaluation method using differences in means test to evaluate overall changes in system utilization. The final section includes the disaggregate evaluation, which consists of four ordinary least square regression models. These models attempt to follow the logic of the literature review presented in Chapter 2. The output of the models is followed by a discussion of the results.

Descriptive Statistics

The four main datasets used in the statistical analysis are PRECONS, POSTCONS, PRECTRLS, and POSTCTRLS. Each dataset includes 83 trip-segment observations. A summary of the descriptive statistics of these four datasets is presented in Table 10.

The mean and variance in running time (MRT and CVRT) has declined in the post-time-period compared to the pre-time-period, in both the CONS and CTRLS. Running time has declined along CONS in the post time period by eight seconds, while a decline of three seconds per trip is present along CTRLS. This indicates at least a three seconds of decline in running time along the studied route. The average passenger activity has increased slightly per-trip-segment in both CONS and CTRLS. Meanwhile the variance in passenger activity has declined with a higher rate along the CONS relative to the CTRLS. The variance in headway delay did increase over time along both CONS and CTRLS.

Table 10: Descriptive Statistics for The Four Datasets

	TRIPCONS				TRIPCTRLS			
	PRE		POST		PRE		POST	
	MEAN	STD	MEAN	STD	MEAN	STD	MEAN	STD
MRT	90	40	82	36	116	39	113	37
CVRT	0.33	0.24	0.31	0.10	0.28	0.12	0.28	0.10
PNGRACT	3.70	3.90	3.71	3.39	4.34	2.31	4.54	2.17
CVPNGRACT	0.96	0.83	1.01	0.87	0.79	0.68	0.78	0.50
AVHEADLA	7.59	155.15	-10.20	267.79	4.59	157.64	-12.87	267.30
CVHEADLA	2.45	27.11	2.87	24.83	-1.28	22.03	0.40	7.83
AVDELSTA	188	136	334	224	176	125	318	217
CVDELSTA	1.32	1.14	1.16	1.37	11.76	93.54	2.75	16.58
AVHEADF	3	155	-12	260	2	150	-12	256
CVHEADF	-1.11	14.58	1.01	15.97	-6.13	62.15	2.43	25.84
SCHEAD	736	172	740	175	741	176	747	180
AVLIFT	0.001	0.01	0.01	0.03	0.01	0.03	0.02	0.05
CVLIFT	0.58	1.70	0.99	2.18	0.66	1.76	2.04	2.73
NUMST	3.64	0.59	2.62	0.58	3.77	0.67	3.79	0.64
CVNUMST	0.14	0.07	0.16	0.06	0.15	0.06	0.14	0.05
NUMDW	1.53	0.72	1.45	0.69	2.08	0.87	2.11	0.81
CVNUMDW	0.78	0.85	0.76	0.84	0.59	0.70	0.52	0.37
NUMUNSCST	0.31	0.27	0.30	0.36	0.44	0.33	0.47	0.33
CVUNSCST	2.12	1.19	2.54	1.59	1.92	1.35	1.64	1.19
INC	34,562	7,328	34,544	7,325	34,612	5,749	34,612	5,749
POP	1,303	386	1,262	378	1,626	484	1,630	482
SEGLEN	1,290	367	1,290	367	1,741	643	1,741	643
SPAC	551	85	1,009	182	736	172	736	172
NUMSIG	0.29	0.46	0.29	0.46	0.61	0.49	0.61	0.49

The effect of bus stop consolidation along CONS is clear in both the number of stops and spacing variables (NUMST and SPAC). The average number of stops along the CONS was 3.64 in the pre-time period comparable to 2.62 in the post-time period indicating a decline of 1.02 stops per-trip-segment. Meanwhile the CTRLS exhibited a slight increase in the number of stops from 3.77 to 3.79. This represents an increase in the average number of unscheduled stops along the CTRLS and a decline in the same type of stops along the CONS. Bus stop spacing has increased in average by 458 feet (139 meters) along the CONS, while the CTRLS were not subjected to any changes in spacing mentioned earlier. The number of actual stops that were accommodated by door openings has slightly decreased along CONS and increased along CTRLS in the post time periods. The variance in actual stops has declined along both CONS and CTRLS. A decline in variation indicates an increase in the consistency of stopping. While the mean value of the number of unscheduled stops have decline, accompanied by an increase in the variance along CONS. This indicates a decline the probability of unscheduled stops along CONS in the post time period. The probability of serving unscheduled stops in the post treatment time period along CTRLS has increased relative to the pre time period

A difference is present in the number of people living in the service area in both CTRLS and CONS. The difference in population is present due to the weighting method used in GIS to allocate population to service areas. The population and income are calculated using the weighting method for both time periods. The presence of consolidated stops along CONS and overlapping service areas are the reason for such differences. The remaining variables in the table are to assist with the interpretation of the models.

Composite Evaluation Method

The composite evaluation consists of differences in two means paired samples (Wonnacott & Wonnacott, 1972). The tests are calculated using the following equation:

$$\Delta = \overline{D} \pm t_{.025} \frac{SD}{\sqrt{n}}$$

Where the $\overline{D}$ is the average of the differences, *SD* is the standard deviation of the differences, *n* is the number of observations (83), and $t_{0.25}$ is the percentage points of the *t* distribution at the 95% confidence interval. After matching the pre and post datasets together for both the CONS and CTRLS, two differences datasets are calculated. The differences are calculated based on pre-time period observations subtracted from post-time period observations (POST-PRE). The means and standard deviations of the differences are calculated for the variables of interest in both the CONS and CTRLS differences datasets. This helps in identifying the range of the difference mentioned in the previous equation. The range is tested to determine if it is statistically different from zero in order to derive conclusions regarding the statistical significance of the change between the post and pre-time periods.

The second section of the analysis utilizes a different dataset representing the differences between the CONS and CTRLS differences datasets. This new dataset of differences measures whether the changes in the CONS and CTRLS were different from each other or not. It is calculated based on the CTRLS differences subtracted from the CONS differences (CONS-CTRLS). Similarly the mean and standard deviation for this new dataset are calculated to apply a difference in means test similar to the test used to measure the changes in CONS and CTRLS.

Table 11 presents the midpoints of the range for the post and pre differences in means for the treatment and control trip-segments. It includes the output of the differences test measuring the changes in passenger activity and three operations variables. The passenger activity variable is found to change by 0.01 person per trip segment for the treatment segments. Among the CTRLS, passenger activity per trip segment increased by approximately 0.2 persons. No statistical significant difference was founding when comparing the changes in passenger activity along CTRLS relative to CONS. This contradicts the theory regarding the increase in access time to bus stops. The theory suggests that an increase in access time, represented by bus stop consolidation, will lead to a decrease in passenger activity, if all other variables were kept constant. Accordingly the ability to measure other changes that occurred in the system is important for understanding the reasoning of such increase in passenger activity that followed the bus stop consolidation. The changes in the mean and variance of the number of actual stops that are accompanied by door openings are added to the table. The change in the means and variances of the number of unscheduled stops is also included in the table. These variables are added to confirm the findings that are noticed in the descriptive statistics regarding the decline and increase in the number of unscheduled stops along CONS and CTRLS. Also they can be used to confirm the presence of consistency in the number of stops accompanied by dwells (door openings).

Table 11: Paired Sample Means Differences Output

	CONS-DIFF	CTRLS-DIFF	DIFF-(CONS-DIFF-CTRL-DIFF)
ΔPNGRACT	0.01	0.20	-0.19
ΔMRT	-8.12*	-3.82*	-4.31**
ΔCVRT	-0.02	0.00	-0.03
ΔCVHWSDLA	0.42	1.67	-1.25
ΔNUMDW	-0.08*	0.03	-0.11**
ΔCVNUMDW	-0.02	-0.07	0.06
ΔNUMUNSCST	-0.02	0.03	-0.04
ΔCVUNSCST	0.42**	-0.28	0.70**

* Indicates statistical significance at the 90% level.
** Indicates statistical significance at the 95% level.

The most notable change in Table 11 is the reduction in running time that occurred after bus stop consolidation. Bus running time on the treatment segments declined by slightly more than eight seconds (8.8%), and it also declined by more than three and a half seconds (3.2%) on the control segments. The change in running time along CTRLS may be attributed to several factors, including the implementation of TSP, changes in schedules, and differences in segments lengths. The disaggregate model will include several variables that will help in understanding the causes of this decline. The difference between the reductions in CONS and CTRLS (4.31 seconds) represents a net 5.6% reduction in running time along CONS, which might be attributable to bus stop consolidation. The results of the research presented in the next section helps explain this finding.

The variability in running time shows a decline for the CONS when compared to CTRLS. Headway delay variability increased in both the CTRLS and the CONS. The increase was higher among CTRLS compared to the CONS. Neither of the variables addressing running time and headway variability exhibited statistically significant changes on the study segments over time. The net benefit of bus stop consolidation on service reliability did not show a statistically significant improvement. Taken together, the passenger activity and running time results indicate that stop consolidation achieved an intended objective of concentrating passenger movements among fewer stops, thus eliminating acceleration and deceleration delay at consolidated bus stops.

The total number of stops that are accompanied by a door opening has declined along CONS by 0.08 stops, while it has increased along CTRLS by 0.03 stops. A statistically significant difference is present when relating the decrease along CONS to the increase in the number of stops along CTRLS. The CONS have 0.11 stops less than CTRLS in the post time period. The variation in the number of stops has declined among both CONS and CTRLS. The number of unscheduled stops has declined along CONS and increased among CTRLS in the post time period. The variation in the number of unscheduled stops along CONS has increased and this increase is statistically significant. In addition, a statistically significant difference is present between this increase and the decrease in the variation of unscheduled stops along CTRLS. These two findings regarding unscheduled stops can be interpreted as a decline in the number of unscheduled stops after treatment along CONS, accordingly the probability of having an unscheduled stop along a CONS after treatment has declined.

Reliability has improved in terms of running time along consolidated segments, yet improvements in reliability are not confirmed. More research is needed to isolate the effects of bus stop consolidations from the other variables that also changed over time. This will provide a greater insight into the reasons behind the positive changes in passenger activity.

Disaggregate Evaluation Method

Since this research is interested in the net effects of bus stop consolidation processes on the utilization of bus transit service, the disaggregate models are calculated using a net change dataset. This dataset is calculated based on subtracting the pre trip-segments attributes from post trip-segments attributes (POST-PRE). The final dataset consists of 166 observation including both CONS and CTRLS. Ordinary least square regression models are calculated for passenger activity and transit service reliability performance measures. Since variances and means variables are derived from different sample sizes, diagnostic tests for hetroskedasticity are conducted for each model. The tests indicate the presence of statistically significant hetroskedasticity in the models. White's (1980) correction procedure is thus employed in the models for corrections. The results of the corrected regression models are presented in Table 12 with mean values reported in parenthesis.

Table 12: Regression Models Output

Variables	Models 1	2	3	4
Dependant Var.	*ΔPNGRACT*	*ΔMRT*	*ΔCVRT*	*ΔCVHWSDLA*
Intercept	-0.305	-4.932	-0.052	5.227
CONS	0.498* *(0.5)*	22.197*** *(0.5)*	-0.031 *(0.5)*	-3.996 *(0.5)*
ΔPOP	0.012** *(-18.3)*	-----	-----	-----
ΔINC	0.007** *(-8.9)*	-----	-----	-----
ΔDELSTA	0.002*** *(143.7)*	-.007 *(5.27)*	-----	-----
ΔSCHWS	-0.003* *(5.27)*	-0.019 *(5.27)*	-0.0001 *(5.27)*	-0.032 *(5.27)*
ΔPNGRACT	-----	3.165*** *(0.11)*	-----	-----
ΔPNGRACT2	-----	0.930*** *(1.69)*	-----	-----
ΔLIFT	-----	48.250*** (0.011)	-----	-----
ΔNUMST	-----	29.733*** *(-0.5)*	-----	-----
ΔCVDELSTA	-----	-----	0.0001*** *(-4.58)*	-----
ΔCVPNGRACT	-----	-----	0.071* *(0.02)*	17.757*** *(0.02)*
ΔCVLIFT	-----	-----	0.009*** *(0.01)*	-0.930 *(0.01)*
ΔCVNUMST	-----	-----	0.723** *(0.01)*	-42.636 *(0.01)*
ΔCVHWSDFI	-----	-----	-----	0.246*** *(5.33)*
R104	0.385* *(0.24)*	11.707*** *(0.24)*	0.022 *(0.24)*	1.701 *(0.24)*
AMIN	0.552** *(0.27)*	2.555 *(0.27)*	-0.078* *(0.27)*	6.434 *(0.27)*
SEGLEN	-----	0.0003 *(1,515.6)*	0.00004* *(1,515.6)*	-----
PRETSP	-----	-3.468 *(0.09)*	0.0102 *(0.09)*	-14.004 *(0.09)*
POSTTSP	-----	-13.01*** *(0.31)*	-0.037 *(0.31)*	-5.511 *(0.31)*
NUMSIG	-----	-1.200 *(0.27)*	-0.018 *(0.27)*	-3.878 *(0.27)*
R^2	0.133	0.558	0.132	0.357

* Indicates statistical significance at the 90% level of confidence.
** Indicates statistical significance at the 95% level of confidence.
*** Indicates statistical significance at the 99% level of confidence.

Regarding the changes in passenger activity model (Model 1), a statistically significant difference is present when comparing changes in passenger activity along CONS relative to changes in passenger activity along CTRLS. Although an increase in access time along CONS was found, CONS have a higher change rate in passenger activity (0.49 passengers per trip-segment) relative to CTRLS. The increase in access time should lead to a loss in passenger activity if all other aspects of service are kept constant, even though passenger activity increased along CONS. This change can be related to changes in other aspects of service that accompanied bus stop consolidation and the minor changes in access time that exist due to the large overlap in service areas. Accordingly, more detailed analyses regarding changes in service are introduced in this section. The change in passenger activity may also be attributable to changes in the size and income of the population residing within one-quarter mile of stops on route segments following stop consolidation.

The income variable did show a positive and statistically significant relationship in relation to changes in passenger activity. This contradicts the theory that considers public transit as an inferior good. The average change in mean income is about eight US dollars per service area around each segment, which is a small number compared to the mean income (34,582 US dollars). Accordingly, this finding cannot be generalized and more research is needed to identify the type of effects.

For each minute of positive change in delay at the starting stop in a segment, the change is calculated as the difference between the post and pre-time periods, it is estimated that a statistically significant positive change in passenger activity will be present (0.12 passengers per trip-segment). In other words, passenger activity will increase along segments experiencing delays at their origins. On the other hand, changes in passenger activity are sensitive to changes in scheduled headway with a statistically significant negative coefficient. For example, for a five-minute change in scheduled headway along segments, the loss in passenger activity is expected to be around one passenger per trip-segment.

Both the route and period/direction coefficients are statistically significant in relation to the changes in passenger activity between the pre and post-time-periods. Passenger activity along 104-Division is estimated to increase around 0.38 passengers per trip-segment more than the 4-Fessenden. This can be related to the differences in land use and socio-demographic characteristics around the two routes and/or the differences in time of the data collection. The data used in the 104-Division are collected during the year 2002, when a recession effect could be present. The morning peak inbound service is estimated to serve 0.55 passengers more than evening peak outbound service. This is due to passenger behavior and types of activities. In the morning peak, passenger movement is concentrated around the three-hour peak periods, while during the evening peak, passengers tend to spread their commute time to avoid delays and traffic congestion.

In the change in running time regression model (Model 2), the CONS coefficient is estimated to be statistically significant relative to CTRLS. The interpretation of this variable should be combined with the interpretation of the change in the number of stops variable ($\Delta NUMST$), which also has a statistically significant effect on change in running time. CONS exhibited a decrease in running time due to change in the number of stops being served; meanwhile CONS may experience an increase in mean running time compared to CTRLS due to other factors that are not controlled for in this model, for example: street configuration, stop location (far side or near side), and variability in the number of the stops served. The net effect of bus stop consolidation along CONS is approximately 7.5 seconds along each trip-segment. This change represents an 8% savings when compared to mean running time in CONS during the pre-time period reported earlier in Table 10. Thus, the previously documented reduction in running time represents the net effect of reductions in deceleration, dwell, and acceleration times from the elimination of stops.

Looking at Table 10, it is important to note that the number of unscheduled stops has declined along CONS, while it increased along CTRLS, which means more savings in running time along CONS. If consolidation were not effective in the post-time-period, travel time along CONS would have increased by 22 seconds relative to CTRLS, which represents a 24% deterioration in running time. This confirms that TriMet planners were correct in that consolidation would lead to improvements in running time.

The change in running time between the two time periods is expected to increase with an increase in the change in the number of passengers being served along each trip-segment. The change per passenger is positive and statistically significant in terms of its effect on change in running time. Each positive change in passenger activity is expected to add around 3.16 seconds of running time per trip-segment. This finding is within the same range of change in passenger activity that was reported earlier in Table 2. The square term of change in passenger activity is used to account for the marginal effects of additional changes in passenger activity on changes in running time. Each additional positive change in passenger activity in the post time period is estimated to take 0.9 seconds more (Δ*PNGRACT2*). Each positive change in lift activity during the post period adds 48 seconds to trip time. In other words, lift activity has a statistically significant positive effect on trip time. Route 104-Division is estimated to be slower than the 4-Fessenden by 11.7 seconds per trip-segment with a statistically significant relationship.

TSP did show a statistically significant effect on changes in running time along segments in which TSP was implemented between the two data collection periods. TSP is estimated to reduce running time change by 13 seconds for each trip segment. Meanwhile, segments with TSP implemented prior to the pre time period did not show a statistically significant effect on changes in running time. This finding can be related to the short term effect of TSP observed by previous research. It also agrees with other research looking at the long term effect of TSP. The remaining control variables did not show a statistically significant effect on changes in running time.

Regarding the reliability models (Model 3 and Model 4), CONS did not have a statistically significant effect on either the changes in running time variation or the changes in headway delay variation model relative to CTRLS. This finding confirms the findings of the composite evaluation method. TriMet did not include service variability as a factor when choosing stops for consolidation. Still it is important to presents the results of these models for future research, so as to contribute to the understanding of the main factors resulting from changes in service variability.

Concerning the change in running time variability model (Model 3), a statistically significant and positive increase in running time variation is associated with positive changes in the following variables: variability of passenger activity, variability of lift activity, and variability of the number of actual stops being served. Change in the variability of the number of stops being served ($\Delta CVNUMST$) has the greatest impact on the change in running time variability. Accordingly consolidating stops with high variability should lead to substantial improvements in running time variation and accordingly in reliability. Changes in running time coefficient of variation are also statistically significant and positively related to segment length, in other words, the longer the segment the higher the variation in running time. Morning peak time period trips have a statistically significant negative effect on changes in running time coefficient of variation, indicating that morning peak period trips were subjected to smaller changes in running time coefficient of variation relative to evening peak period trips. Finally, the positive changes in the coefficient of variation of delay at the segment origin are shown to have a statistically significant effect on the changes in running time coefficient of variation, which means the greater the variation of delay at the segment origin, the more the variation in running time. Surprisingly, TSP did not have a statistically significant effect on the changes in running time coefficient of variation. Segments with TSP implemented prior to the consolidation did have a positive effect on running time coefficient of variation. While segments with TSP implemented after consolidation did have a negative effect on running time coefficient of variation.

The changes in the coefficient of variation of headway delay at the ending stop along the studied segment (Model 2) did not show a statistically significant relationship with any of the studied variables except for two variables. The two variables are: 1) the change in the coefficient of variation of the number of people being served along each trip-segment; and 2) the change in headway delay coefficient of variation measured at the segment origin. This indicates the importance of decreasing the variance in passenger activity at bus stops, which is one of the outputs of a bus stop consolidation policy. The headway delay coefficient of variation measured at the segment origin is found to be the main contributor to variability in headway delay at the ending stop of a segment. In other words, variability in headway delay at the segment origin has a statistically significant effect on variability at the segment destination.

Model Validation

Two models (Model 5 and Model 6) are used to validate the findings in Model 2. The output of Model 5 is presented in Table 13. Change in running time is the dependant variable used in Model 5. The savings in running time due to bus stop consolidation along CONS are directly interpreted from the coefficient associated with the CONS variable. Running time has declined in the post time period by 7 seconds along CONS relative CTRLS with a statistically significant change. This finding is relatively consistent with the savings mentioned earlier (7.5 seconds).

Table 13: Model 5 Output

NAME	Coefficient	Mean
Intercept	-4.277	
CONS	-6.939***	0.500
ΔDELSTA	0.007	143.740
ΔPNGRACT	0.753	0.107
ΔPNGRACT2	0.511	1.693
ΔLIFT	40.916**	0.011
ΔNUMDW	12.787***	-0.031
ΔNUMUNSCST	37.743***	0.006
ΔSCHWS	-0.021	5.271
R104	9.647***	0.241
AMIN	0.659	0.277
SEGLEN	0.002	1515.600
PRPOTSP	-3.298	0.096
POSTTSP	-14.570***	0.313
NUMSIG	-1.063	0.452
R^2	0.58	
N	166	

* Indicates statistical significance at the 90% level of confidence.
** Indicates statistical significance at the 95% level of confidence.
*** Indicates statistical significance at the 99% level of confidence.

Passenger activity and the square term of passenger activity have the same positive sign as in Model 2. Since passenger activity is associated to door openings it is not surprising that statistical significance is not present along these variables. The effect of changes in lift activity shows a statistically significant effect on change in running time similar to Model 2. The positive change in the number of stops associated with the door openings (ΔNUMDW) has a statistically significant positive effect on the change in running time. In other words, each dwell adds around 12.7 seconds to the running time. The change in the number of unscheduled stops has a statistically significant effect on changes in running time. The time associated to unscheduled stops is around 37 seconds. TSP did show a statistically significant effect on the change in running time along segments in which TSP was implemented between the two data collection periods. TSP is estimated to reduce running time by 14.5 seconds for each trip segment relative to 13 seconds reported in Model 2. Route 104-Division is estimated to be slower than the 4-Fessenden by 9.6 seconds per trip-segment with a statistically significant relationship relative to 11 seconds reported in Model 2 for the same variable. Model 5 has indicated similar findings as Model 2, the effects of bus stop consolidations and other variables on running time are consistent (within an acceptable range) even with the changes in the model specifications.

A different approach for validating the findings in Model 2 is through increasing the sample size and using the disaggregate dataset mentioned in Table 9 (15,492 observations). The data set is subjected to in depth screening and cleaning process to remove outliers and segments with different patterns. The final sample used in Model 6 consists of 14,280 observations. The running time along CONS and CTRLS is the dependant variable in this model. The output of Model 6 is presented in Table 14.

Three dummy variables are added to the model CTRLSPOST, CONSPRE, and CONSPOST to measures the effects of bus stop consolidation relative to the omitted variable CTRLSPRE. The number of stops variable is removed from this model to enable the direct interpretation of the CONSPRE and CONSPOST variables.

Table 14: Model 6 Output

	Coefficient	Mean
Intercept	27.656***	
CTRLSPOST	1.181	0.28
CONSPRE	4.265***	0.22
CONSPOST	-4.452***	0.27
PNGRACT	7.449***	4.34
PNGRACT 2	-0.107***	36.6
DELSTA	-0.003***	244.1
LIFT	62.439***	0.01
AMIN	-4.418***	0.34
TSP	-12.288***	0.29
NUMSIG	26.066***	0.5
R104	-22.856***	0.21
SEGLEN	29.728***	1.602
R^2	0.67	
N	14,280	

*** Indicates statistical significance at the 99% level of confidence.
Note: Segment length reported in 1000 feet

The coefficient associated with CONSPRE variable shows a statistically significant positive effect on running time relative to the omitted variable (CTRLSPRE). This indicates that running time along CONS is slower than CTRLS in the pre time by 4.2 seconds. While, the coefficient associated with CONSPOST variable shows a statistically significant negative effect on running time relative to the omitted variable (CTRLSPRE). This finding indicates that running time along CONS in the post time period has declined relative to the running time along CTRLS in the pre time period by 4.4 seconds. Combining the two relationships mentioned above, CONSPRE and CONSPOST can be related directly to each other.

In other words, running time has declined along consolidated sections relative to control sections that did show a slight increase in running time (1.18 seconds). The net effect of CONSPRE (4.265), CONSPOST (-4.452), and CTRLPOST (1.181) is a 7.536 second saving in running time. However, since the CTRLPOST coefficient is not significant the actual saving is likely to exceed eight seconds in running time per trip, which also indicates an improvement in running time along CONS relative to CTRLS. The coefficients on passenger activity confirm the above findings. Low volume stops like those eliminated likely serve a single passenger. Passenger activity and passenger activity square have a statistically significant effect on running time. Each passenger adds around 7 seconds to the running time, while the increments of each passenger decline by 0.1 seconds. The remaining variables did show a statistically significant effect on running time, which are added for control purposes to the model. Comparing the 8.6 seconds noticed in this model to the 7.5 and 6.9 seconds, noticed in Model 2 and Model 6 respectively, indicates a consistency in the savings in running time that is associated to bus stop consolidation. The changes in model specifications and sample size did not have an effect on the value associated to the savings in running time that are present due to bus stop consolidation.

Chapter Summary

Descriptive statistics and empirical analysis and evaluation of bus stop consolidation were presented in this chapter. The empirical analysis consisted of two main sections: 1) composite evaluation, which is based on differences in means tests; and 2) disaggregate evaluation models based on ordinary least square regression models. Bus stop consolidation was shown to have an influence on mean running time and perhaps more surprisingly, a positive effect on changes in passenger activity along trip-segments. Model 2 was validated in this chapter through two ordinary least square regression models with different specifications and samples sizes to increase the confidence levels of the finings of the models used in the study. Additional discussion is included in Chapter 6 regarding the finding of the models presented in this chapter.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

Chapter Outline

The results of the present research are discussed in this chapter. The chapter consists of four sections. The first section includes a discussion of the main findings in this research, while the second section discusses the recommendations of the research. The third section discusses the contribution that this research offers to the transit industry. It also highlights the contributions of this research to the body of knowledge in the field of bus stop spacing and consolidation. Finally, the last section includes the future research that can be developed based on the findings from this study.

Conclusions

The effects of bus stop consolidation on passenger activity and bus operating performance has been empirically analyzed. The study made extensive use of AIT by utilizing archived AVL and APC data recorded at the bus stop level. Passenger activity was found to be unaffected by stop consolidation, while bus running times showed a significant improvement. From the passengers' point of view, the results indicate that any reductions in accessibility from stop consolidation were offset by time improvements in the line haul portion of their trips. Thus, the utility of their trip-making appears to have been unaffected by stop consolidation, while the transit provider gained from efficiency improvements. This reflects a reliability improvement from a passenger perspective. Although reliability improvements are a commonly expected consequence of bus stop consolidation, from an agencies perspective, we found no evidence of a change in running time or headway variation in the route segments studied that can be related to bus stop consolidation. This can be related back to the method used by TriMet planners in selecting bus stops for consolidation, in which service reliability was not part of their selection criteria.

TriMets' selection of bus stops for consolidation is justified based on the savings in running time and increase in passenger activity. As it was mentioned in the interpretation section in Chapter 5, if consolidation did not take place along CONS, trips along CONS would have faced a 24% increase in running time. At the same time, consolidation was shown to lead to savings in running time of approximately 32% along each trip-segment. Combining both the expected negative effect and positive one together an overall decrease in running time is realized. The net savings due to consolidation is calculated to be around 8%. Other models were tested at lower levels of aggregation (166, 332, and 15,000 observations) and the same savings were noticed, which adds more confidence to the findings of this model.

The benefits of running time reductions resulting from bus stop consolidation to an agency could be translated into reductions in the number of vehicles needed to serve a route or by perhaps increasing the amount of time before new vehicles need to be added. From a passenger standpoint, the direct benefit is the decrease in travel time. An indirect benefit of the reductions in running time to passengers is the possibility of increasing service frequency. By keeping the fleet size constant an agency can increase the frequency of service along bus routes following bus stop consolidation. An increase in frequency would lead to a decrease in waiting time for passengers, which might attract more passengers to the existing bus service. Model 1 did show a negative relationship between the positive changes in scheduled headway and the changes in passenger activity. Increasing the frequency of service means decreasing the scheduled headway, and accordingly it is expected that the service will attract more passengers.

The relationship between changes in running time and changes in passenger activity is found to be statistically significant, yet Model 2 reflects a different relationship compared to previous research conducted by Strathman et al. (2002) and Dueker et al. (2004). Their research indicates that the time associated to each passenger activity adds to the total running time at a lower rate by the increase in the number of passengers being served at a bus stop.

Using the four datasets (CONSPRE, CONSPOST, CTRLSPRE, and CTRLSPOST), discussed in the data preparation section, a linear regression model is employed to explain running time as a function of the same variables used in the change in running time model, including passenger activity. Three dummy variables are added to this model to separate the effects of consolidation and time differences. This model is found to be similar to previous research in terms of the relationship between running time and passenger activity. In addition, Model 6, which used a larger sample size, indicate a relationship similar to previous research too. The differences between Model 2 and previous research might be due to factors that were not included in the model, which may affect passenger activity and running time, for example changes in congestion levels, bus operators, and signal timing and/or it might be related to the minor change in passenger activity that is noticed along CONS combined with the error term in the model. Accordingly more research is recommended in this area.

The expected change in passenger activity due to bus stop consolidation or increases in stop spacing is a loss of passenger activity. The findings of Model 1 contradict this theory. Passenger activity did increase along CONS with a statistically significant difference relative to CTRLS. This finding is directly relevant for policy, especially the policy makers who endorse the idea of bus transit service as a public good that all citizens should have equal access too. This policy has resulted in a transit system with too many stops with overlapping service areas, as mentioned earlier in Chapter 2. Passengers did value the changes that occurred in CONS and more passenger activity is observed, even though an increase in access time was present.

The implementation of TSP did show a negative effect on changes in running time and running time variation. If this finding is combined with findings of Kimpel et al. (2004) a new understanding of the effects of TSP on running time can be introduced. TSP did show to be effective in reducing running time and running time variation in the short term when studied at a disaggregate level in this research. While Kimpel et al. (2004) in their research did not find a consistent statistically significant effect of TSP on bus performance, which was related to drivers' behavior and other factors in the system not included in the present study. Drivers' behavior can be speculated to be the main contributor for this difference. The difference is speculated to be similar to risk homoeostasis theory. This theory predicts that, as safety features are added to vehicles and roads, drivers tend to increase their exposure to collision risk because they feel better protected (Wilde, 2002). Similarly as TSP is implemented at intersections, drivers might have changed their behavior regarding adhering to scheduled running time.

Recommendations

This research has evaluated a bus stop consolidation policy implemented by TriMet. The criteria that TriMet's researchers used to select stops for consolidation is based mainly on passenger activity and measuring effects on running time. Their stop selection criteria led to an increase in efficiency from an agency's perspective and an increase in reliability from a passengers' one in terms of running time. In order to select stops that can lead to an increase in transit service reliability, variability in passenger activity should be a component in such selection. Variability in the number of stops being served and the variability in passenger activity were found in the models to be the major contributors in the variability of service. A stop that is rarely served along a route is not the adequate choice for consolidation with respect to increasing transit service reliability. Stops with high variability are the ones that need to be considered for consolidation studies.

Similar to previous research, it is noticed in this study that the existing stop spacing, along studied routes, is too low compared to the national and international standards. In order to achieve a substantial increase in system performance, an aggressive implementation of bus stop consolidation is recommended. The expected loss in passenger activity is expected to diminish compared to the gains in passenger activity that reflects the improvements in running time and other changes that might accompany bus stop consolidation.

Contributions

This study utilizes a large amount of operations data collected from TriMet's BDS. The study provides a comprehensive analysis of changes in bus performance from the perspective of operators and passengers by analyzing data collected before and after consolidation. The main contribution of this work is in its empirical orientation. While there has been extensive research on the subject of stop location and spacing, it has relied heavily on analytical and simulation methods. The availability of archived stop level data provided a unique opportunity to analyze and evaluate bus stop consolidation. This research was unable to find evidence in the literature regarding studies that were based on actual experience in the field. Generally, the results of this research lend empirical support to the claims from prior analytical and simulation studies that stops are likely to be too closely spaced and that related service planning standards ought to be relaxed. Other findings of this research are also consistent with the expected consequences of increasing traffic congestion, which degrades travelers' line haul times, but does not affect their access or egress times. The findings of this research are validated through various linear regression models with different specifications and sample sizes to add confidence to the results and findings.

Future Research

Travel time for a passenger includes access time, egress time, waiting time and running time. The waiting time is expected to be one-half the scheduled headway in the case of short headways. After the implementation of AIT such as AVL several transit agencies have recently implemented next-bus-arrival capabilities to their websites and bus stops. Expected arrival time at bus stops is calculated based on the current bus location identified through AVL technology and the published time table. The presence of such technologies affects perceived as well as actual waiting time. IN the later case passengers consult the website and calculate their access time to decrease the waiting time. More research is recommended in this area to understand the effects of these technologies on passengers waiting time. Since the presence of these technologies can change passengers understanding of service variability.

This research used a one-quarter-mile buffer measured along the network from each bus stop to determine service areas around segments. As it was mentioned in Chapter 2, passenger demand is expected to diminish quickly after the walking distance reaches a threshold of 314 feet (96 meters), while the demand will largely vanish beyond 1900 feet (576 meters) from a transit stop. None of the previous research that studied effects of walking distances on passenger demand can be tracked back to its origin for replication. Also none of the previous research provide a comprehensive approach for understanding the relationship between passenger demand and walking distance. The relationship between passenger demand and walking distance can be hypothesized as an exponential function. More research is needed in the area of studying the diminishing effect of walking distance on passenger demand in order to introduce a methodology that can be generalized and used by other researchers.

The relationship between bus stop spacing and transit system utilization is fairly complex. This research introduced it by utilizing some of the available AIT. In order to conduct a simulation analysis to measure the consequences of stop consolidation more research is needed in the areas of bus stop spacing and bus stop consolidation. A better understanding of passenger access and egress time and how the former can interrelates with waiting time can improve analysis using simulation techniques. The changes that accompanied bus stop consolidation in Portland, OR, on Routes 4-Fessenden/104-Division, contradicted the theory, which suggests that a loss in passenger activity is a likely outcome of bus stop consolidation. Since additional passenger activity was associated with CONS, a new area of research is introduced to explore the reasons behind such change.

As part of a bus stop consolidation study, the variation in running time and headway delays is recommended. This research did not find a relationship between changes in service variability and bus stop consolidation. More research is needed in this area to study the relationship between bus stop spacing and variability in transit service.

The findings in this research regarding the relationship between TSP implementation and running time need to be studied more carefully. The findings of this research contradict with previous research that is conducted at a higher spatial scale (longer segments). Changes in drivers' behavior are speculated to be the reason for such differences, yet no evidence is present to support such speculation. Accordingly more research is recommended in this area of transit research.

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