ST3 Regional High-Capacity Transit System Plan

Transit Ridership Forecasting Methodology Report

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Acronyms and Abbreviations

AA	Alternatives analysis
AAZ	Alternatives Analysis Zones
ACS	American Community Survey
APC	Automatic Passenger Count
AVL	Automatic Vehicle Locator
AWV	Alaska n Way Viaduct
CT	Community Transit
CTR	Commute Trip Reduction
DRAM	Disaggregated Residential Model
EIS	Environmental Impact Statement
EMPAL	Employment Allocation Model
ERP	Expert Review Panel
FAZ	Forecast Analysis Zone
FEIS	Final Environmental Impact Statement
FFGA	Full Funding Grant Agreement
FTA	Federal Transit Administration
HOV	high-occupancy vehicle
IIA	independence from irrelevant alternatives
JTW	journey-to-work
KCM	King County Metro
NTD	National Transit Database
PSCOG	Puget Sound Council of Governments
PSEF	Puget Sound Economic Forecaster
PSRC	Puget Sound Regional Council
PT	Pierce Transit
RTA	Regional Transit Authority
RTP	Regional Transit Project
ST	Sound Transit
TPI	time point interval
TRB	Transportation Research Board
WSDOT	Washington Department of Transportation

1 Introduction

This report summarizes the methods used to produce ridership forecasts for Sound Transit (ST) and describes the update to the ST incremental model using new data resulting from recent surveys and counts. The updated 2015 version of the ST model is used to produce ridership forecasts in support of the ST3 system planning process. The ST3 system planning process builds on the *Sound Transit 2 Regional Transit System Plan for Central Puget Sound* (ST2) adopted by the ST Board in July 2008.

The current version of the ST ridership model was developed using analytical ridership forecasting procedures refined over two decades of incremental methods applications. Over this time period, the methods have been subjected to substantial external review, including two independent Expert Review Panels, and three cycles of review by the Federal Transit Administration (FTA) over the course of New Starts grant applications for Link light rail projects. The third review cycle is still ongoing, in support of the proposed New Starts grant for the Lynnwood Link Extension.

These reviews have included comments FTA provided with respect to the ST incremental modeling procedures and assumptions described in earlier versions of this report. This report incorporates changes reflecting all of FTA's comments. The following presents a brief history of ST transit ridership forecasting.

1.1 History of transit forecasting at Sound Transit

The history of transit forecasting analysis at ST began at Seattle Metro (now King County Metro) in 1986. Work by Brand and Benham[1] led to Metro's consideration of "a quick-responsive incremental travel demand forecasting method" based on the concept of staged forecasting analysis. In 1986, Metro developed and applied "logit mode-choice equations for pivot-point analysis"[2] (as described by Ben-Akiva and Atherton[3]; Koppelman[4]; Nickesen, Meyburg and Turnquist[5]; and many others) on EMME software. In 1988, Metro staff highlighted the relationship[6] between Metro's transit forecasting methods and the Puget Sound Council of Governments (PSCOG) regional model.

The Regional Transit Project (RTP), incorporated as Sound Transit in 1993, further developed forecasting analysis procedures using incremental methods in the early 1990s, prior to the November 1996 voter approval of *Sound Move: The Ten-Year Regional Transit Plan*. An Expert Review Panel (ERP)—formed in 1990 under the auspices of the Legislative Transportation Committee, the Secretary of Transportation, and the Governor—oversaw development of the first generation of the ST incremental model. This model is described in the November 1993 *Travel Forecasting Methodology Report* published by the RTP.

The ST model was updated in the late 1990s in support of the Central Link Light Rail Transit Project EIS and the North Link Light Rail Transit Project Supplementary EIS, including respective Full Funding Grant Agreements (FFGA) with FTA. The underlying ST model procedures used to perform transit ridership forecasting analysis in support of the North Link Light Rail Projects were documented in the *Transit Ridership*

[1] Brand, D., and J.L. Benham, "Elasticity-Based Method for Forecasting Travel on Current Urban Transportation Alternatives," Transportation Research Record No. 895, 1982.
[2] Harvey, R., "Pivot-Point Analysis of Transit Demand Using EMME/2," an Internal Paper, Municipality of Metropolitan Seattle, May 1986.
[3] Ben-Akiva, M. and T. Atherton, "Methodology for Short-Range Travel Demand Predictions," Transportation Economics and Policy, v.7, 1977.
[4] Koppelman, F., "Predicting Transit Ridership in Response to Transit Service Changes," ASCE 109, 1983.
[5] Nickesen A., A. Meyburg, and M. Turnquist, "Ridership Estimation for Short-Range Transit Planning," Transportation Research B, v.17B, 1983.
[6] Harvey, R., "Comparison of Metro and PSCOG Modeling" a Memorandum to File, March 7, 1988.

Forecasting Technical Report, issued in November 2003 by ST. The ST model was further updated in the mid 2000s in support of the ST Phase 2 expansion program and subsequently in 2012 for the EIS phases of the Lynnwood Link Extension.

The ST model has now been updated again in 2015 in support of the ST3 system planning work and this report describes this latest update. Table 1-1 illustrates more clearly the historical development of the current model, showing refinements in both data sources and structure over the past two decades.

1.2 Report organization

This report contains three chapters and four appendices. Chapter 1 summarizes the methods used to produce ridership forecasts for ST and discusses important methodological considerations. Chapter 2 describes the individual methods used for each step of the ridership forecasting process. Chapter 3 describes validation of the ST model to 2014 conditions. The current model validation exercise has two purposes: (1) to highlight problems with the forecasting process that might have otherwise been overlooked and (2) to incorporate changes that could improve the forecasting results.

1.3 Sound Transit incremental transit model

The ST incremental model has been updated to a new base year (2014). Development of the base-year transit-trip tables involved a rigorous analysis of actual ridership volumes along each transit route and a realistic simulation of observed transit service characteristics for peak and off-peak periods.

For future year forecasts, external changes in demographics, highway travel time, and costs are distinctly incorporated into the process in stages, prior to estimating the impacts of incremental changes in transit service.

In the first stage of ridership forecasting analysis, only changes in Puget Sound Regional Council (PSRC) land use forecasts are considered. In the second stage, other external non-transit changes, such as highway travel time (congestion), costs (including parking costs), and household income, are taken into consideration. For forecasts of external changes, the ST model relies on the version of the PSRC regional model in current use by WSDOT on major highway projects. The first two stages of ridership forecasting analysis result in a forecast of future year zone-to-zone transit trips within the Regional Transit Authority (RTA) district boundaries, absent any changes in the transit system itself. For current year analyses, these first two stages are not necessary.

In the third and final stage, incremental changes in the transit level of service (e.g., access, wait, and ride travel times) and user costs (e.g., fares) are considered, resulting in final transit demand estimates for each transit network alternative under consideration.

Like all travel forecasting models, the ST model has some limitations. Because it uses average daily ridership, it is not particularly strong at assessing the effects of weekend special events, such as sports games or major festivals. Furthermore, the ST model is ill-suited for analyzing structural changes in regional land use beyond those already included in PSRC demographic forecasts or for forecasting in outlying areas of the three-county region where there is minimal existing transit service. Finally, the model does not explicitly take into account any differences in safety, comfort, or user friendliness among various public transportation modes.

Table 1-1. Sound Transit incremental models history

	Survey-based model (1992 to 2004)	Counts-based model (2005 to 2011)	Counts-based model (2012 to 2014)	Counts-based model (2015 to present)
Data Sources	▪ 1992 on-board surveys, collected by bus drivers on all transit lines – Lumpy 36% one-day sample of inbound trips (mostly AM), or about 18% of daily trips – Peak and off-peak line boardings control totals for survey expansion ▪ 1990 U.S. Census Journey-to-Work (JTW) used for base transit shares ▪ No reliable data for transfer rates, checked against 1992 surveys ▪ Sparse on-board survey data used for auto-access shares ▪ After 2000: 1992 survey demand adjusted with about 100 screen-line segment 1999 ridership counts on select locations around the region	▪ 1,700 line-segment ridership counts for each time period for all lines, mostly collected by validated Automatic Passenger Count (APC) systems (2004 average weekday) ▪ 2000 U.S. Census JTW for base transit shares ▪ 2004 ST on-board surveys ▪ PSRC modeled transit trip distribution to open additional non-zero cells ▪ Little reliable data for transfer rates, checked against 1992 and 2004 surveys ▪ Sparse on-board survey data for peak auto-access shares	▪ 1,800 line-segment ridership counts for each time period for most routes, collected by most transit agencies by validated APC systems (2011 average weekday) ▪ Washington Commute Trip Reduction Surveys (CTR) 2007 to 2012 data and American Communities Survey (ACS) 2008 data used for base transit shares ▪ 2009, 2011, and 2012 ST on-board surveys added to base year matrix development ▪ 2007 to 2012 CTR Survey transit trip patterns added to base year matrix development ▪ Transfer rate estimates validated against ACS (2010), PSRC Travel Diary Survey (2006), ST on-board surveys (2004–2012) ▪ Relied on segment counts near park-and-ride lots for peak auto-access shares	▪ 1,800 line-segment ridership counts for each time period for all lines, collected by all transit agencies by validated APC systems (2014 average weekday) ▪ Washington Commute Trip Reduction Surveys (CTR) 2007 to 2014 data and American Communities Survey (ACS) 2010 data used for base transit shares ▪ 2009, 2011, and 2012 ST on-board surveys added to base year matrix development ▪ 2007 to 2014 CTR Survey transit trip patterns added to base year matrix development ▪ Transfer rate estimates validated against ACS (2012), PSRC Travel Diary Survey (2006), ST on-board surveys (2004–2012), and Smart Card Database (2012) ▪ Relied on segment counts near park-and-ride lots for peak auto-access shares

Table 1-1. Sound Transit incremental models history (continued)

	Survey-based model (1992 to 2004)	Counts-based model (2005 to 2011)	Counts-based model (2012 to 2014)	Counts-based model (2015 to present)
Structure	▪ 737 zones ▪ FAZ demographics from 2002 PSRC model DRAM/EMPAL + negotiation with locals ▪ Highway skims via blind adoption of PSRC matrices created with erroneous cost coefficient ▪ structural error ▪ Use of eight transit trip classes forced very thin demand matrices (not technically a structural error, but generally a poor practice) – PM time periods: 3-hour peak and ½ day off-peak – Trip purpose: commute and non-commute – Mode of access: walk and auto for peak and off-peak ▪ Transit Trip Tables – Base year demand derived directly from on-board surveys – Non-zero cells only 0.05% to 2% across the eight trip tables – After 2000: single-step Matrix Adjustment on non-zero cells of 0.5% to 3% for eight trip tables ▪ Fares in 2nd stage with auto-mode equation	▪ 780 zones (splits near rail stations) ▪ FAZ demographics from 2006 PSRC model DRAM/EMPAL ▪ Highway skims prepared directly by project team using a current PSRC model – Used a validated model that has been refined in major WSDOT projects – Aligned transit service levels in the PSRC model with those assumed in the ST model – Rigorous convergence criteria ▪ Use of only three transit trip classes allowed very robust demand matrices – Time periods: 6-hour peak and 18-hour off-peak with 24-hour daily counts as control totals – Mode of access: walk and auto for peak-period and walk only for off-peak ▪ Transit Trip Tables – Base year demand derived directly from detailed ridership counts by route segment, time-period, and direction – Single-step Matrix Estimation on non-zero cells of 15% for peak and 17% for off-peak ▪ Fares in 2nd stage with non-transit-mode equation	▪ 785 zones (splits for Ballard study) ▪ FAZ demographics from 2013 PSRC Land Use Targets Forecast ▪ Highway skims prepared directly by project team using a current PSRC model – Used a recent model version refined and validated for major WSDOT projects – Aligned transit service levels in the PSRC model with those assumed in the ST model – Rigorous convergence criteria ▪ Use of only three transit trip classes allowed very robust demand matrices – Time periods: 6-hour peak and 18-hour off-peak with 24-hour daily counts as control totals – Mode of access: walk and auto for peak-period and walk only for off-peak ▪ Transit Trip Tables – Base year demand derived directly from detailed ridership counts by route segment, time-period, and direction – Five-step Matrix Estimation Fares in 3rd stage with transit-mode equation	▪ 785 zones (splits for Ballard study) ▪ FAZ demographics from 2014 PSRC Land Use Targets Forecast ▪ Highway skims prepared directly by project team using a current PSRC model – Used a recent model version refined and validated for major WSDOT projects – Aligned transit service levels in the PSRC model with those assumed in the ST model – Rigorous convergence criteria ▪ Use of only three transit trip classes allowed very robust demand matrices – Time periods: 6-hour peak and 18-hour off-peak with 24-hour daily counts as control totals – Mode of access: walk and auto for peak-period and walk only for off-peak ▪ Transit Trip Tables – Base year demand derived directly from detailed ridership counts by route segment, time-period, and direction – Six-step Matrix Estimation ▪ Fares in 3rd stage with transit-mode equation ▪ In transit assignment, used logit function on connectors to improve distribution of zone access.

1.4 Important considerations and constraints

This section discusses six important considerations and constraints in travel forecasting methods. Most of these are derived from many years of FTA guidelines on transit project planning that culminated in the current policy guidance.[7] The following considerations reemphasize the use of best professional practice:

- Careful standards for validation
- Consistent application of policy assumptions across alternatives
- Use of identical land use plans and constant overall travel demand patterns across alternatives
- Generic attributes of modes
- Analysis of service levels and travel forecasts for reasonableness
- Weakness of future year forecasts relying on inputs that are themselves forecasts.

1.4.1 Careful standards for validation

Validation is a vital component of any travel forecasting effort. It demonstrates that the forecasting procedures can replicate observed travel patterns in a region to support reliable forecasts of future travel patterns. The ST model relies on surveys and detailed ridership counts to establish current transit travel patterns. In project planning, travel forecasting methods are expected to predict changes in travel patterns that are caused by general changes between the current year and a forecast year and by specific transit service changes introduced by each alternative.

1.4.2 Consistent policy assumptions across alternatives

A large number of inputs to the travel forecasting process are at least partially subject to the policy decisions of local and state agencies. To isolate the differences generated by a specific proposed project (e.g., a fixed guideway rail transit system), all conditions that are not directly attributable to the proposed project must be held constant. It is therefore required that the forecasts hold the policy setting constant across all alternatives evaluated. These policies include:

- Fare level and structure
- Levels of service provided by the background transit system
- Zoning policies
- Parking policies and prices

This constraint means that forecasts prepared for FTA evaluation and EIS documentation should only contain differences between alternatives that are primarily caused by the transit alternatives themselves. For example, service levels on feeder buses should reflect a general service policy and investment level that is applied consistently across alternatives. Assumptions on all external inputs—land use, regional income, parking costs, and other variables not specific to the transit alternatives under consideration—should also be held constant.

1.4.3 Constant travel patterns across alternatives

Forecasts of the overall travel demand for which transit competes can involve confounding factors. The FTA guideline that land use policies be consistently applied removes some sources of variability in population and employment forecasts. In basic forecasts for modes that have differing degrees of grade separation, it eliminates guessing about the extent to which a particular alternative might shift residential and commercial

[7] New and Small Starts Evaluation and Rating Process—Final Policy Guidance, August 2013.

development. Note that the forecasts provided to FTA by ST hold travel patterns constant. Supplementary analyses are used to address potential development changes related to the various transit investment proposals.

1.4.4 Generic attributes of modes

There is currently much discussion about the differences in ridership potential associated with the less tangible qualities of various transit technologies. This discussion typically focuses on the perceived differences between technologies in terms of visibility, comfort, convenience, and other characteristics that are difficult to quantify. Because there is limited data to support inclusion of these less tangible qualities in the analysis, the ST model uses a conservative assumption and treats transit modes very generically. However, current FTA guidance on methods indicates that FTA will accept forecasts that account for measureable differences in less tangible qualities, such as reliability between modes (e.g., bus and rail).

A few studies have directly addressed this question and indicated that some measurable differences can be isolated.[8] One important result is that these differences appear to be associated with real differences in facilities and services, not with unexplainable factors. For this reason, ST now includes a very small quantified reliability difference in the transit line boarding and waiting times (see Table 3-1 in Chapter 3).

1.4.5 Analysis of transit service levels and travel forecasts

The development of forecasts results in the production of a variety of additional types of information beyond ridership volumes. Examples include ridership changes in specific subareas, changes in roadway congestion levels, travel time savings created by new transit guideways, and transit's share of various travel markets. All of these need careful review for quality check purposes, as well as an understanding of what the forecasts reveal about potential changes between the present and the future and about the differences between the transit alternatives.

[8] The interim report TCRP H-37 provides some indications of important transit attributes not yet included in mode choice models.

2 Procedures for Travel Forecasting

This chapter describes the methods and procedures used in the ST transit forecasting model, including the input data required by the ST model and its relationship to the PSRC model.

Section 2.1 describes the methodology used to develop transit forecasts, the data requirements, and the data available. Section 2.2 describes the relationships between the ST and PSRC models. For instance, this section provides an overview of the methodology used by PSRC to produce land use forecasts that are critical to the ST model and any future year ridership forecasting analysis. The transportation analysis zone system is described in Section 2.3. The mode choice model structure, specification, and coefficients are presented in Section 2.4. Summary descriptions of the process used to develop base-year transit-trip tables are described in Section 2.5. Possible changes in population and employment, highway congestion, and cost (i.e., the application of the staged build-up forecasting analysis) are discussed in Sections 2.6 and 2.7. A discussion on changes in transit service is included in Section 2.8.

2.1 Methodology

2.1.1 Incremental vs. synthetic methods

There are two different approaches to developing transit forecasts: synthetic methods and incremental methods. Synthetic methods estimate existing transit travel patterns by using separate sequential models to

- Allocate regional population and employment projections to zones
- Estimate the total number of trips to and from these zones
- Estimate the origin/destination patterns of these estimated trips
- Estimate the travel mode share likely for each estimated origin/destination pattern
- Estimate which specific links and lines in the highway and transit systems are used by these synthesized trips

Incremental methods are simpler and more efficient for transit ridership forecasting and analysis because they

- Are directly based on observed (rather than estimated) baseline travel patterns of transit users
- Allow for concentrating efforts on transit network analysis, for studies whose primary goals are answering questions about alternative transit networks
- Are more conducive to the separate and transparent evaluation of population and employment changes, highway congestion and cost, and transit services through the three stages of the forecasting process
- Focus on direct comparisons related to specific changes rather than on complete simulations of travel behavior
- Are more usable for intermediate evaluation and error identification
- Eliminate the often laborious and time-consuming calibration of sub-choice models, since they do not require replication of base-year travel patterns for these markets.

The FTA guidelines on transit project planning have identified three strong characteristics of the incremental approach that make it attractive for many applications. According to FTA, the incremental method "is well grounded in the reality of baseline travel patterns; it deals only with marginal changes; and it focuses attention on the changes in land-use and transportation that drive the evolution of travel patterns over time."[9]

One limitation that could render incremental methods less desirable in some situations is their weakness in estimating future transit markets in locations where there is no existing transit market from which to build estimates. This is not an issue inside the ST RTA district, since both ridership and transit service coverage within the district are now highly developed. The use of incremental methods would only have limitations if applied to exurban or rural areas beyond the district boundary.

Incremental methods rely on data collection, not travel demand theory, to describe base-year travel patterns. In recent years data availability has increased dramatically, with large quantities of revealed preference data no longer requiring expensive surveys or special counts. The detailed route-level data by time-of-day from the ridership counts now widely available, coupled with recent ST surveys, American Community Survey (ACS), and the state-mandated Commute Trip Reduction (CTR) surveys, provide complete observed baseline travel patterns within the RTA district. ST now has available directional and time-of-day counts for every segment of every transit route in the entire ST service area.

In the incremental model approach, the coefficients and sensitivities are the same as in the synthetic approach. The incremental methods are mathematically derived from and parallel to the synthetic methods and are applied at the same level of network detail that would be used in a synthetic approach.

2.1.2 Data available for Sound Transit planning

The key sources of data available for ST planning include:

- PSRC land use forecasts and median income estimates
- PSRC regional travel model version adopted by WSDOT for major highway projects
- Transit operators in the three-county area—Sound Transit, King County Metro, Pierce Transit, Community Transit, and Everett Transit
- Sound Transit Surveys (2003–2012)
- Commute Trip Reduction surveys (2007–2014)
- American Community Surveys (2006–2010)
- The National Transit Database (2013)
- State and local agencies

PSRC's land use forecasts and median income estimates are key inputs to the modeling effort for future years. The ST model uses the most current land use forecasts available from PSRC at the start of a project. The estimates of household income are used in the model to capture the different sensitivities to costs that occur across households with different incomes.

The PSRC regional forecasting model, the version used by WSDOT for travel forecasting in support of major capital projects and tolling analysis, provides highway travel times for past and future years. This information includes separate travel times for vehicles that qualify for high-occupancy vehicle (HOV) lanes. This WSDOT highway model also provides changes in traffic volumes on regional highway facilities for traffic impact analysis, and local jurisdictions provide traffic counts on local arterials for station impact analysis, as required.

[9] Procedures and Technical Methods for Transit Project Planning, Federal Transit Administration, 2004.

The essential basis for incremental mode choice modeling analysis is the detailed route-level transit ridership information by time-of-day for the base year (2014). In addition to earlier on-board surveys, the 2009 and 2011–2012 on-board surveys conducted by ST provide additional detail on riders of all ST services. The ST surveys were supplemented by the 2007–2014 three-county CTR Act surveys to provide a more complete cross section of representative transit trips.

Detailed ridership count data were obtained from each transit agency. These detailed route-level count data were collected using APC technology. The data include average weekday passenger loads by route segment, direction, and time of day, which provide the necessary information to establish ridership profiles along each route by time of day. Finally, the combination of data from the 2007–2014 CTR surveys and the 2006–2010 American Community Surveys (ACS) establishes base-year transit shares for 2014.

The following sections discuss how these various databases were developed and include more detail on how they are being used.

2.2 Relationship to PSRC modeling

2.2.1 Summary comparisons of the PSRC travel demand model and the ST transit ridership model

PSRC maintains a four-step conventional synthetic travel-demand modeling system consisting of trip generation, trip distribution, mode choice, and trip assignment models.[10] Zonal trip ends are estimated using a set of trip rates classified by home-based work, home-based college, home-based shop, home-based other, home-based school, non-home-based work, non-home-based other, and three truck types. Trip distributions are estimated using a traditional "gravity" model. The PSRC mode-choice model structure is a logit-based model comprised of two transit modes, three auto modes, and two non-vehicle modes.

The ST and PSRC modeling procedures are closely inter-related and highly complementary. The ST model uses measures of regional change in travel demand and highway congestion derived from the PSRC model. Summary comparisons and interrelationships of the PSRC and ST modeling procedures are highlighted below:

- The PSRC model is a four-county synthetic modeling system comprising land use, trip generation, trip distribution, modal split, and assignment models. It also includes several feedback loops based on intra-regional accessibility.
- The ST model is a three-county, three-stage, fully incremental system purposely designed for detailed corridor-level transit planning and transit ridership forecasting.
- PSRC's regional population and employment forecasts are used to predict travel demand growth for future years.
- ST uses PSRC's time and cost coefficients for its mode choice model.
- The current PSRC model version used by WSDOT for travel and toll forecasting in support of major highway projects is adopted for interface with the ST model. This highway model has been recently refined and validated for use on several WSDOT tolling analyses. Figure 2-1 highlights the relationship between the PSRC and ST models.

[10] Puget Sound Regional Council, "Travel Model Documentation," Final Report, September 2007.

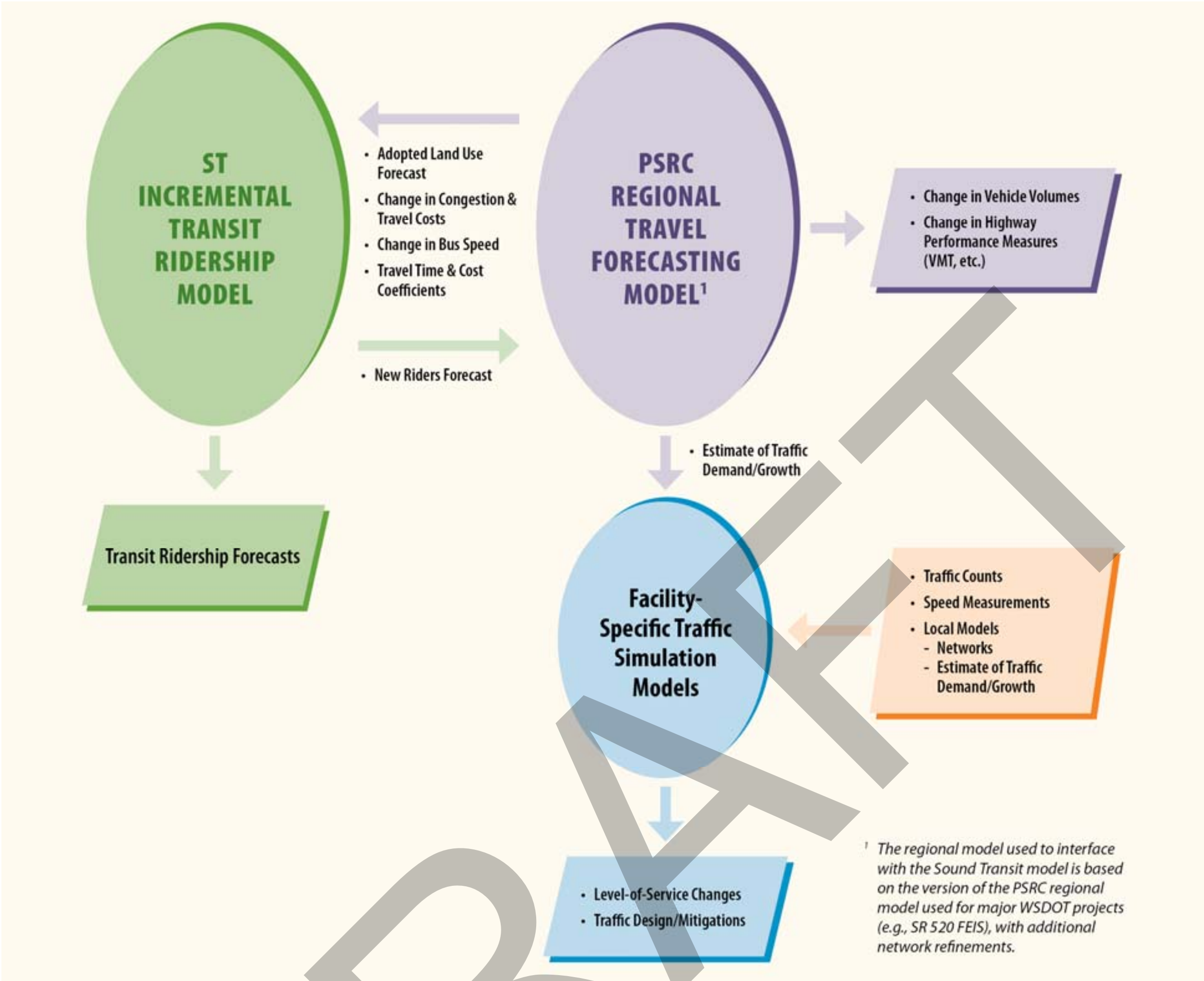

Figure 2-1. ST incremental transit ridership and PSRC regional models relationship

2.2.2 Preparation of demographic forecasts

This section summarizes the procedures used by PSRC to forecast regional population and employment.[11]

Development of regional control totals

PSRC produces population and employment forecasts for the central Puget Sound region (King, Kitsap, Pierce, and Snohomish Counties) using the Puget Sound Economic Forecaster (PSEF) model.[12]

The PSEF model is an econometric model comprising a set of simultaneous equations, reflecting economic base theory. Under this concept, growth is directly tied to the growth in sectors that export goods or services outside the region, thereby bringing income and jobs into the region. The PSEF model uses linked equations to forecast 103 variables, with the equations estimated using quarterly data dating back to 1970. Output from the PSEF model includes forecasts of population, employment, and income for the four-county area.

These forecasts establish control totals for the subsequent allocation of growth to individual subareas of the region.

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[11] Puget Sound Regional Council, "Transportation 2040, Final Environmental Impact Statement, Appendix K: Data Analysis and Forecasting at the PSRC," March 2010, www.psrc.org.
[12] Puget Sound Regional Council, Macroeconomic Model documentation, http://www.psrc.org/data/models/psef-model/.

Allocation of growth to subareas

As of May 2014, PSRC has released two alternate sets of land use allocations:

- Land Use Baseline forecasts, using a land use simulation model (UrbanSim)
- Land Use Targets forecasts, using input from local jurisdictions to modify local forecast allocations within the regional totals.

Using the regional forecasts from the PSEF model, PSRC first uses a land use forecasting model system (i.e., UrbanSim)[13] to allocate growth to local planning areas throughout the four-county region. UrbanSim is an urban simulation system developed over the past several years to be able to evaluate public policy choices by simulating long-term growth patterns. Land use forecasts resulting from application of the UrbanSim model are currently referred to by PSRC as Land Use Baseline forecasts.

The Land Use Targets Forecast[14] is a long-range land use dataset designed explicitly to represent local growth targets that are adopted under state Growth Management Act requirements.[15] It is developed using a set of allocation "decision rules" that distribute jurisdictional growth targets to sub-jurisdictional zones based on (a) available net development capacities (similar to what is used for the Land Use Baseline) and (b) a series of policy-based preferential weights for certain zones, such as designated regional growth centers and other locally-defined activity centers.

Land Use Baseline and Targets forecasts (i.e., households and employment) are summarized in 10-year increments at the FAZ level for review and consultation feedback by local jurisdictions. These forecasts are also circulated for review by a wide variety of public and private organizations. After the review process is completed, these forecasts and allocations are widely used by the state as well as by local governments, public agencies, and private organizations. Neither forecast is adopted by the PSRC.

2.3 Development of zone and district systems

The ST travel forecasts are produced for a 785-zone system of Alternatives Analysis Zones (AAZ) developed specifically for the ST model, but based directly upon PSRC's current zonal system. Summaries of inputs and forecasts are prepared using 27 summary districts or other levels of aggregation (e.g., by corridor or by county) as needed. Zone and district maps are shown in Appendix A.

2.3.1 Forecast analysis zone and traffic analysis zone systems

PSRC's FAZ structure is the basic land-use zone structure and consists of 219 FAZs that cover all the land area within the four-county region. It is usually at this level of detail that local jurisdictions, through PSRC, agree upon allocations of future population and employment throughout the region.

2.3.2 Alternatives analysis zone system

The AAZ system used to produce the ST travel forecasts is based on the zones maintained by PSRC for regional forecasts of travel demand within the four-county central Puget Sound region. The ST zone system differs from PSRC's system in two aspects.

Most importantly, the ST system does not have the same geographic boundary as the PSRC system. Whereas PSRC includes a four-county region (Snohomish, King, Kitsap and Pierce Counties), the 1993 state-established RTA excludes the largely rural areas of North and Northeast Snohomish, South and Southeast Pierce,

[13] Puget Sound Regional Council, "Analysis and Forecasting at PSRC: Land Use Forecasting," October 2009, www.psrc.org.
[14] www.psrc.org/assets/9017/Methodology Workbook.xlxs.
[15] Revised Code of Washington 36.70A.

and East King Counties, as well as all of Kitsap County, Vashon Island, and the Gig Harbor peninsula. Areas outside the RTA district are external to the ST model. The 785-zone system includes smaller zones within transit corridors of interest, especially around potential station locations, as well as 23 external zones representing 6 ferry connections and 17 areas outside the RTA boundaries.

Keeping the PSRC and ST zone structures as similar as possible reduces the level of data manipulation that would otherwise be necessary.

Summary districts were created from the AAZ system in order to

- Provide a consistent basis for aggregation of certain model inputs, when such aggregation is appropriate
- Calculate the modal shares required in the model validation and application phases
- Prepare summary reports on trip tables and travel time skims

These districts were carefully constructed to provide distinctive summary travel patterns by geographical area and corridor.

2.4 Sound Transit mode choice model methodology

2.4.1 Model structure

The ST mode-choice model structure, which is an incremental logit model, uses a pivot approach in the development of forecasts and uses the PSRC regional mode choice travel time and cost coefficients.

Incremental logit model

The incremental approach predicts changes in travel behavior based on existing travel behavior and changes in level of service. The incremental form of the logit model is derived from the standard logit formulation, which is[16]

$$(1) \qquad S_i = \frac{\exp(\mathrm{V_i})}{\mathrm{SUM_j}^{\mathrm{m}}\,[\exp(\mathrm{V_j})]}$$

Where

V_i = utility of mode i in choice set m (j=1,2,3, .., i, ..m)
Contains measurable components of transportation systems such as travel time and cost as well as socio-economic attributes of trip makers.

S_i = share of demand using mode i

[16] Domenich, T., and D. McFadden, "Urban Travel Demand—A Behavioral Analysis," North Holland, Amsterdam, 1975.

Ben-Akiva and Lerman indicate that "using elasticities is one way to predict changes due to modifications in the independent variables. For the linear-parameters multinomial logit model, there is a convenient form known as the incremental logit model which can be used to predict changes in behavior on the basis of the existing choice probabilities of the alternatives plus changes in the independent variables." The incremental form of the logit model is[17]

$$(2) \qquad S_i^f = \frac{S_i \text{ x } \exp(\text{DIFF } V_i)}{\text{SUM}_j{}^m \, [S_j \text{ x } \exp(\text{DIFF } V_j)]}$$

where

S_i = base-year observed probability of using mode i from choice set m

S_i^f = new share (i.e., forecast year) of using mode i (interzonal average)

DIFF V_i = change in utility of mode i (interzonal average)

= V_i^f—V_i = (DIFF CONST_i) + B_k x (DIFF $\text{VAR}_{i,k}$)

and

DIFF CONST_i = difference (future vs. base) in mode-specific constant for mode i,

B_k = coefficient for attribute k

DIFF $\text{VAR}_{i,k}$ = difference in numeric variable VAR k of alternative i

f = variable with superscript "f" represents value in forecast year.

All transportation models, including the PSRC synthetic model, assume that the difference between the unmeasured attributes (e.g., comfort and image) between transportation systems in the base year and future years is negligible. As a result, the term representing the difference in mode-specific constants (i.e., DIFF CONST_i) falls out of the computations. The only terms remaining in Equation 2 pertain to those attributes (e.g., travel times and costs) for which a measured change might occur, as well as Equation 3:

$$(3) \qquad \text{DIFF } V_i = B_k \text{ x DIFF VAR}_{i,k}$$

The mode-specific constants in a synthetic model theoretically represent the effects of unmeasured attributes and often account for over half of the explanatory power in synthetic mode choice models. In practice, these constants are quite large and compensate for all types of errors in synthetic models, even network coding idiosyncrasies. They are used as overall adjustment factors to move the base year model results closer to targeted base year totals.

[17] Ben-Akiva, M. and S.R. Lerman, *Discrete Choice Analysis Theory and Application to Travel Demand*, The MIT Press, Cambridge, MA, 1985.

Nested logit model

According to the Independence from Irrelevant Alternatives (IIA) assumption, logit models require that all of the modes defined in the choice set m (for travelers) be independent of one another. However, the IIA requirement is usually difficult to maintain in a simultaneous structure. In practice, a sequential (or nested) logit model that is less restrictive than the simultaneous form is often used. The nested logit model groups appropriate submodes under the primary modes (i.e., auto and transit), as shown in Figure 2-2. For peak trips, the auto mode sub-choice is usually between single and multiple occupancy, and this practice is used in the ST model. For the transit mode in the ST model, the sub-choice is between access to transit by walking or by automobile. Suggestions from FTA on the appropriateness of nesting can be found in the FTA presentation by Jim Ryan at the January 2004 Transportation Research Board (TRB) Annual Meeting.[18]

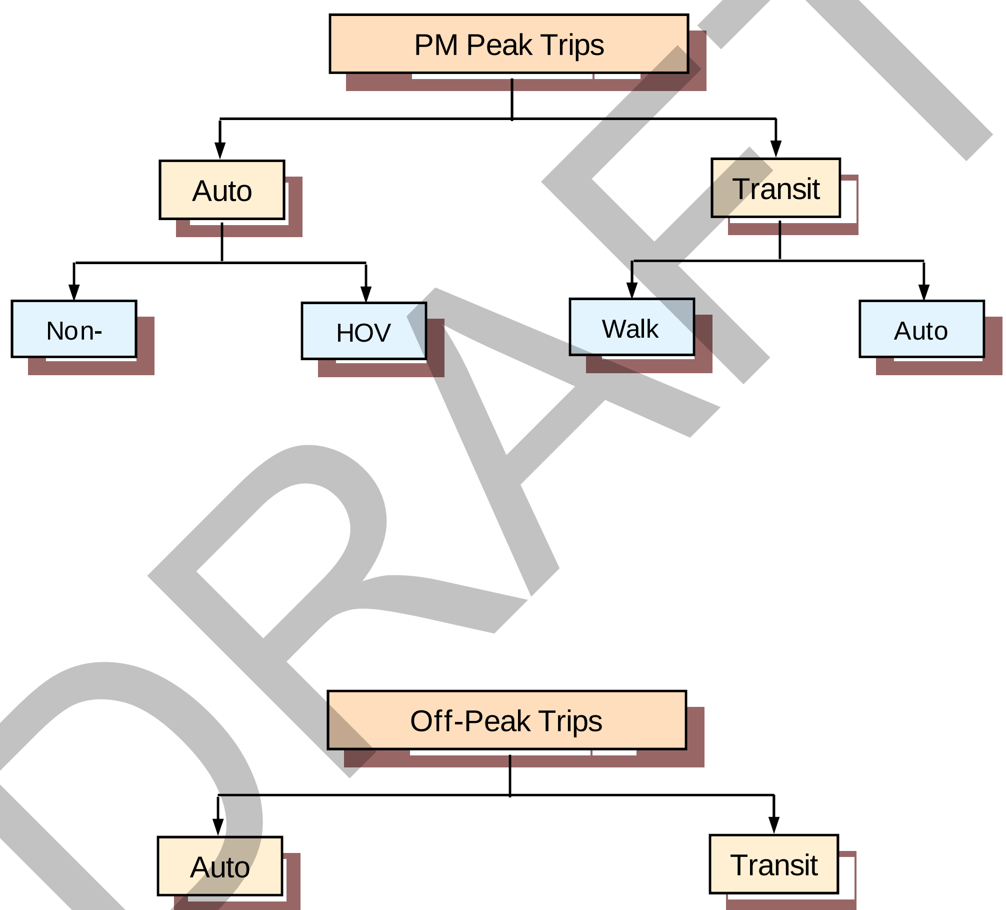

Figure 2-2. Incremental mode choice model structure

[18] Travel Forecasting for New Starts Projects, TRB 83rd Annual Meeting, Session 501, January 13, 2004.

The natural logarithm of the denominator of a logit model (Equation 1) is a single "inclusive" index I_m[19] indicating the desirability of the main mode m and taking into account the attributes of access modes. This index is often called "LogSum" and calculated from

$$(4) \qquad LogSum = Ln\ \{SUM_j^m\ [exp(V_j)]\}$$

where

V_j was defined before for Equation (1)

McFadden[20] has identified the coefficients K for the LogSum variable as indices of similarity among the sub-mode choices comprising the overall price or cost.

For the transit lower level, the composite disutility of the sub-modes (walk- and auto-access) represents transit to the upper level choice. For transit mode t, the LogSum is

$$(5) \qquad LogSum^t = Ln\ [exp(V_{walk}) + exp(V_{auto})]$$

where

V_{auto} = utility of the auto-access mode
V_{walk} = utility of the walk-access mode

The structure for PM peak period shown in Figure 2-2 is fully incremental[21] because it uses the incremental logit model at both the lower-level and upper level nests. The incremental form is highly desirable because it relies on observed data that describes current conditions, rather than using models to estimate these current conditions.

Derivation of changes in LogSum variable

In the fully-incremental ST mode choice model, the changes in ridership between future and base-year conditions are calculated based on the incremental logit formulation (Equation 2) both at the primary level of hierarchy (i.e., auto vs. transit) and at the lower levels (i.e., auto occupancy and mode of access).

Because the incremental model requires the difference in the values of LogSum variable (i.e., DIFF $LogSum^t$ for the mode of access), the underlying components of this difference need to be spelled out first within the context of standard logit formulation (Equation 1). The derivation process starts by using the definition of difference in the LogSum values and ends up with a simple formula consisting of the logarithmic summation of the exponential difference in the utility of each mode (i.e., future minus base year), weighted by the respective base year observed share. The mathematical derivation is presented below.

[19] McFadden,E., A. Talvities and Associates, "Demand Model Estimation and Validation, Urban Travel Demand Forecasting Project (UTDFP) Final Report," Vol. V, University of California, Berkeley, CA, 1977.
[20] McFadden,E., A. Talvities and Associates, "Demand Model Estimation and Validation, Urban Travel Demand Forecasting Project (UTDFP) Final Report," Vol. V, University of California, Berkeley, CA, 1977.
[21] Dehghani, Y. and R. Harvey, "A Fully Incremental Model for Transit Forecasting: Seattle Experience," Transportation Research Board, Record # 1452, 1994.

Incremental change in $LogSum^t$ of Equation 5 can be represented by

$$\text{(6)} \qquad \text{DIFF LogSum}^t = \text{Ln}[\exp(V^f_{walk}) + \exp(V^f_{auto})] - \text{Ln}[\exp(V^b_{walk}) + \exp(V^b_{auto})]$$

Incremental change in LogSum for mode m (i.e., transit or auto), representing the upper-level of the nested logit structure, can be written as

$$\text{DIFF LogSum}^m = \text{Ln}\{\text{Sum}^n_i[\exp(V_i + \text{DIFF } V_i)]\} - \text{Ln}\{\text{Sum}^n_i[\exp(V_i)]\}$$

or

$$= \text{Ln}\left[\frac{\text{Sum}^n_i[\exp(V_i + \text{DIFF } V_i)]}{\text{Sum}^n_i[\exp(V_i)]}\right]$$

$$= \text{Ln}\left[\frac{\text{Sum}^n_i[\exp(V_i) \times \exp(\text{DIFF } V_i)]}{\text{Sum}^n_i[\exp(V_i)]}\right]$$

$$\text{(7)} \qquad = \text{Ln}[\text{Sum}^n_i(S_i \times \exp(\text{DIFF } V_i))]$$

where

DIFF LogSum^t	=	difference in LogSum term for transit mode t (future–base year)
V^f_{walk}, V^f_{auto}	=	the utility of walk and auto access modes in future
V^b_{walk}, V^b_{auto}	=	the utility of walk and auto access modes in the base year
DIFF LogSum^m	=	difference in LogSum term for mode m (e.g., auto or transit) in the upper level of the nested structure (future–base year)
V_i	=	the utility of submode i (e.g., walk or drive access attributes) under nest n (e.g., transit)
S_i	=	base-year observed share of using submode (e.g., walk or drive access) under nest n
$\text{DIFF } V_i$	=	difference in the utility (e.g., travel time) of submode i under nest n (future–base year).

The coefficients of variables (e.g., travel time) included in the utility of a sub-mode i are equal to comparable mode-choice coefficients from the upper-level nest for the same variables (e.g., travel time), scaled by the corresponding LogSum coefficient (K^i).

Values for DIFF LogSum variables resulting from Equation 7 are used in the incremental logit formulation (Equation 2) to estimate new interzonal modal shares. Nesting coefficients vary between 0.0 and 1.0 and measure the degree of similarity and dissimilarity of a group of sub-modes from other modes in the upper-level nest. For example, a nesting coefficient (K) of 1.0 on the transit nest of Figure 2-2 would indicate that auto- and walk-access sub-modes are dissimilar (independent) from each other, implying that they should have been structured simultaneously instead of within a nested form. In the absence of any information to inform the selection of a nesting coefficient, an assumption of 0.50 is neutral. This nesting coefficient of 0.50 is used in the ST model for the PM peak period.

2.4.2 Model specification and coefficients

As indicated in the previous section, since the mode-choice model structure is fully incremental, the mode-specific constants fall out of the computations. Therefore, it is not necessary to estimate values for modal constants. The model includes:

- Travel time and cost variables in the utilities of the transit sub-modes, walk and drive access (e.g., in-vehicle, out-of-vehicle times, transit fares)
- Travel time and cost variables in the utilities of the auto occupancy sub-modes

The auto travel cost is a composite variable and combines auto operating, car insurance and parking-related costs. This composite variable is normalized (divided) by the ratio of zonal median income over the base-year regional median income and used in Stage 2 of the ST ridership forecasting analysis. Transit fares are also treated similarly with respect to zonal median income and used in Stage 3 of the ST ridership forecasting analysis. This will not cause differences in forecasts between pairs of alternatives since transit fares in the ST model remain constant across alternatives.

The reason for the normalization of the cost variable is to capture change in income and its effect on transit ridership shares over time. The normalization of cost variable is primarily longitudinal rather than cross-sectional. Real personal income per capita in the Puget Sound Region has recorded an average growth rate of about one percent annually over many decades in spite of fluctuations in the local economy. The increased personal wealth has contributed to the dominance of auto travel as driving became increasingly affordable over time. Thus normalizing costs to income captures the dampening effect of increasing real income on ridership growth The ST model assumes a 1.0-percent annual growth in real income.

The ST model uses travel time and cost coefficients from the PSRC mode choice modes. The coefficients used in the ST model are:

- -0.0253 for in-vehicle travel time (which falls within the FTA's recommended range of -0.02 to -0.03)
- -0.00156 for travel cost (in 2014 dollars)
- A relative ratio of 2.0 for out-of-vehicle over in-vehicle transit travel times, which falls within FTA's recommended range of 2.0 to 3.0

These coefficients imply a value of in-vehicle time of $9.67 (in 2014 dollars), and for a typical transit trip with out-of-vehicle time approximately equal to in-vehicle time, the implied value-of-time would be about $14.50 (in 2014 dollars).

2.4.3 Base year mode shares

Equation 2 highlights the importance of having a reasonable estimate of S_i (the existing shares for transit relative to alternative modes) including existing mode of access shares. Development of these base shares, used in the ST incremental model, is described below.

Transit shares

Earlier versions of the ST incremental model relied on the U.S. Census Journey-to-Work (JTW) information to provide the base interzonal auto and transit shares. The JTW data exhibited relatively small changes in transit shares over the years 1980 to 2000, which was the final year of the JTW data.

For the 2015 ST model version, in the absence of any recent U.S. Census JTW data, a combination of data from the Washington CTR Act surveys and the ACS is used to establish base year transit shares.

The State of Washington passed the CTR Law in 1991 to encourage commuters to consider transportation alternatives, such as ridesharing or taking transit. As part of this law, employers with 100 or more employees are required to conduct a survey once every two years to record the commute options used by their employees. The ACS is conducted on an on-going basis rather than every 10 years and so it can provide up-to-date information for the planning process. Further information about the CTR surveys and the ACS is provided in Appendix B.

The CTR (2007–2014) surveys provide transit shares at the zonal level with some limitations. These limitations include an over-representation of transit users, related to employer size, in the surveyed sample which may not accurately reflect the transit share at the zonal level because it excludes small employers.

The ACS data also has some limitations as it represents a sample of residences—only about 1 in 40 households annually. The Census Bureau produces three ACS data series: *one-year, three-year, and five-year estimates*. Five-year estimates of ACS home-to-work flow by mode are currently available at the County or Census Place geographies. To address the ACS data limitations, transit shares were aggregated at the 6-district level for maintaining statistical confidence in the share values.

A 6-district level summary comparison of transit shares in the ST service area indicated that

- CTR shares are higher than those obtained from the ACS
- ACS shares for 2006–2010 are somewhat higher than those obtained from the 2000 U.S. JTW data

Based on the findings from the above analysis, it is reasonable to adjust CTR transit shares relative to ACS shares in the following manner in order to retain the CTR geographic detail:

- Aggregate CTR 2007–2014 surveys to the 27 districts at the work ends and 27 districts at the home end and calculate transit shares accordingly. Calculating the shares at this level (i.e., 27-district to 27-district) preserves the variation in current mode-choice behavior for PM peak and, therefore, the elasticities in the incremental logit model.
- Adjust 27-district-to-district base transit shares based on using the 6-district-to-6-district transit shares calculated from the ACS (2006–2010) five-year estimates) as follows:
- Since the aggregated CTR shares are higher than the ACS shares at the 6 by 6 district level, reduce the CTR shares proportionately using the ratio of the ACS share to the aggregated CTR share.

For calculating off-peak base shares, a procedure similar to the one described above was used with the following exceptions:

- Aggregate CTR surveys at 27-district to 27-district level and calculate shares accordingly
- Adjust CTR shares based on using 6-district level ACS shares similar to the method for peak shares.
- Balance the resulting 27-district-to-27-district share matrix by adding its transpose and dividing by 2
- Apply a factor of 0.5 to reflect the difference in base off-peak transit share relative to peak—this factor was calculated based on using past survey data and more recent ST 2011 and 2012 transit on-board survey data.

Note that a procedure similar to the above was used to update base auto occupancy related shares with the ACS data. The base auto occupancy level shares were originally derived from the 2000 U.S. JTW data.

Access shares

In the past, on-board survey data alone were used to develop transit mode-of-access shares. The resulting shares included a considerable number of zero-value cells. To alleviate this shortcoming, access shares are now obtained as a by-product of the matrix estimation process rather than from a very sparse set of on-board survey data.

The 2015 ST model version relies on a matrix estimation process for the development of base-year trip tables that is based on using a seed matrix with a high number of non-zero cells. The process includes seeding of counts on appropriate segments to capture potential demand at each park-and-ride facility. These considerations, together with the fact that existing park-and-ride facilities are adequately represented throughout the region provide a good database from which to calculate access shares. Steps used to calculate access shares are summarized below:

- Perform a select segment analysis on segments representing potential peak demand to park-and-ride facilities
- Aggregate the resulting demand matrix for PM peak auto-access trips and the total PM peak transit trip table at 27 districts (work ends) and 165 FAZs (home ends)
- Divide the aggregated trip tables to provide existing auto-access shares at a 27-district-to-165 FAZ aggregation level.

2.4.4 Discussion of staged build-up analysis application

For future year forecasts, the procedures described in the previous sections are applied in three distinct stages as highlighted in Figure 2-3. This application method explicitly recognizes a build-up approach to the ridership forecasts and encourages the analysis of intermediate results in the process as well as the checking of intermediate results for reasonableness. Specific contributions to changes in ridership at each stage are calculated and analyzed separately as they build on each other. The three stages are:

- Overall growth in travel related to population and employment growth
- Changes in ridership related to changes in highway congestion and costs
- Changes in ridership related to transit service changes, including transit fare changes, if any

By applying forecasting analysis in stages, the method also ensures that only those changes that are important to the study transit alternatives will be considered. For example, it is common in ridership forecasting (and preferred by the FTA) that only the changes in transit service be considered in the future year comparisons of transit ridership. Therefore, all demographics, such as land use, trip distributions, and gas and parking prices, are effectively held constant when comparing ridership on transit alternatives.

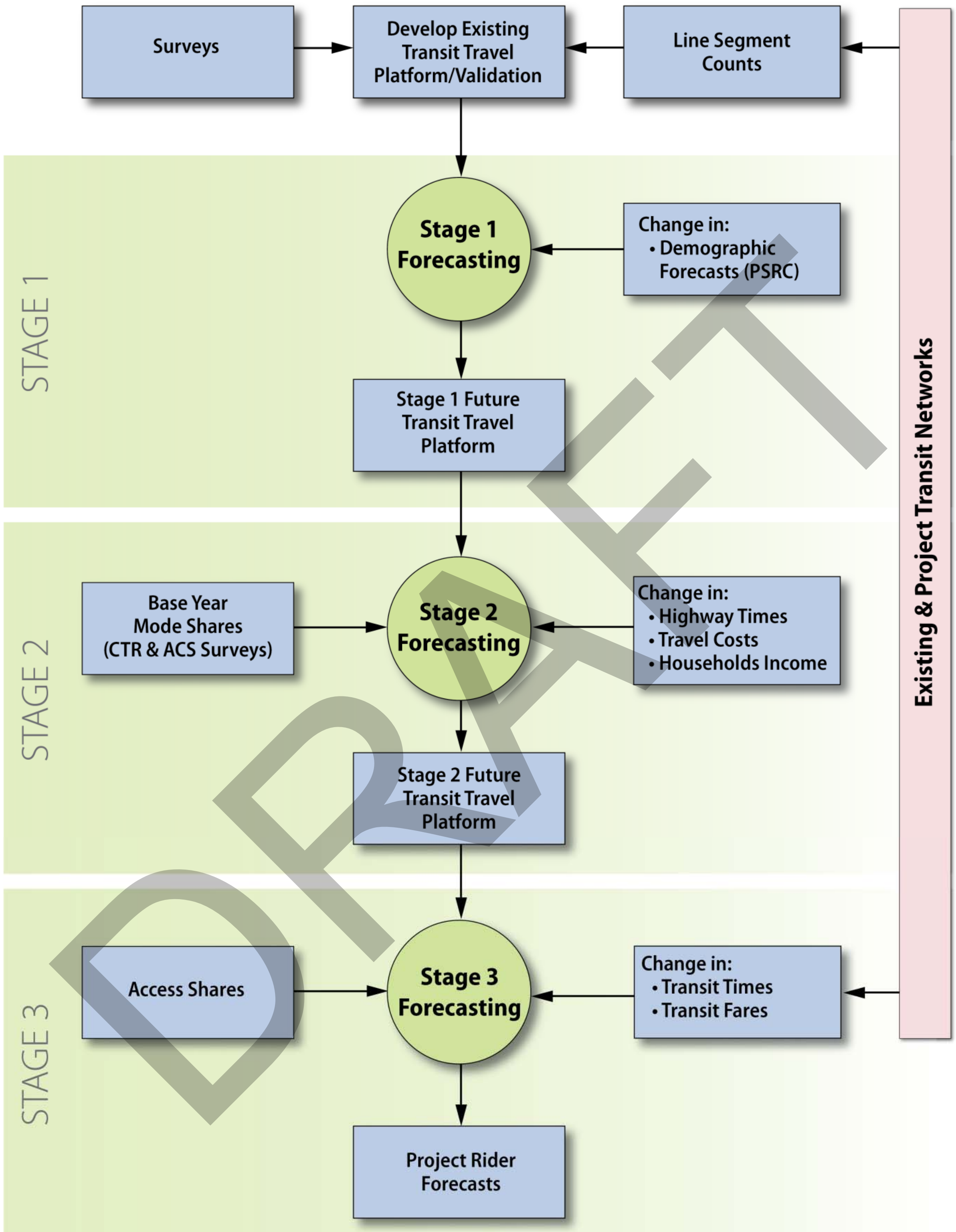

Figure 2-3. Staged ridership forecasting Process

FTA now considers transit benefits measures related to economic development effects and to land use entirely separately from the ridership estimating process. Furthermore, by requiring Current Year ridership estimates, with future years optional, FTA is de-emphasizing future year forecasts in favor of simple network-based comparisons. As the FTA Policy Guidance points out, "Use of current year data increases the reliability of the projected future performance of the proposed project by avoiding reliance on future population, employment, and transit service levels that are themselves forecasts."[22]

Staging the forecasts in an incremental model explicitly isolates sources of error, makes consistencies in the non-transit assumptions transparent, and reduces superfluous calculations. When only variations in the transit service are under consideration, Stage 3 of the incremental model is the only step needed to evaluate each proposed variation in transit service. This method does not preclude varying inputs other than the transit service (i.e., for sensitivity testing) but allows such variation to be addressed simply and specifically, rather than as a hidden piece of a very large and complex model.

2.5 Base-trip table development

The essential basis for incremental mode choice modeling analysis is the reliance on actual transit travel patterns. Capturing existing travel patterns is achieved in the ST model by using available, pertinent data that provide a complementary balance between survey data and detailed route-level transit ridership information by direction and time-of-day for the base year. Chapter 3 includes a detailed discussion of the process used to develop base year (2014) peak and off-peak transit-trip tables.

2.6 Stage 1—Changes in demographics

2.6.1 Formulation of Stage 1 forecasting analysis

The ST ridership forecasting analysis depends on PSRC model databases for the overall growth in travel demand. Growth estimates could either be derived from PSRC model trip distribution results or directly based on forecasts of demographics. PSRC is currently hoping to develop a new generation of models, and until reasonable and stable trip distribution results become available and validated, travel growth factors for the ST model will be derived from published PSRC forecasts of households and employment.

Growth in total households and employment between 2014 and a future year is calculated at a FAZ level and applied to the base year (2014) transit-trip tables using a two-dimensional matrix balancing method (i.e., similar to a Fratar calculation). The results of the Stage 1 analysis are the estimated transit trips for a future year. The secondary impacts of growth on transit demand (e.g., increased highway congestion or costs) are not yet accounted for at the end of Stage 1.

A combination of households and employment is used in establishing the zonal growth factors applied at the origin and destination end of the base year (2014) trip tables.

- For the PM peak period, a combination of 20 percent households and 80 percent of employment is used to calculate the growth in PM peak transit origins, and the reverse is used to calculate growth in p.m. peak transit destinations.
- For the off-peak period, a combination of 50 percent households and 50 percent employment is used to calculate growth for both origins and destinations.
- These factors are derived from ST on-board surveys conducted over the years 2009 through 2012.

[22] New and Small Starts Evaluation and Rating Process—Final Policy Guidance, August 2013.

Because of earlier concerns about a supposed tendency of two-dimensional balancing to artificially increase trip lengths, an examination is performed to examine any alteration in average trip length in every application of the Stage 1 process. As highlighted in Figure 2-4, the balancing method has only slightly changed the underlying average trip length frequency distribution exhibited in the base year (2014) transit trip table. In fact, the average trip length and the standard deviation of the trip lengths actually decrease slightly upon application of the two-dimensional balancing. While this check on trip lengths is performed for each new application of the Stage 1 balancing, the results of the checks have consistently shown the process to be neutral for trip lengths.

Note that if activity-based generation and distribution procedures are developed, tested, and documented by PSRC and subsequently adopted by WSDOT for travel forecasting in support of major highway projects, ST will be able to make a shift in the Stage 1 forecasting analysis.

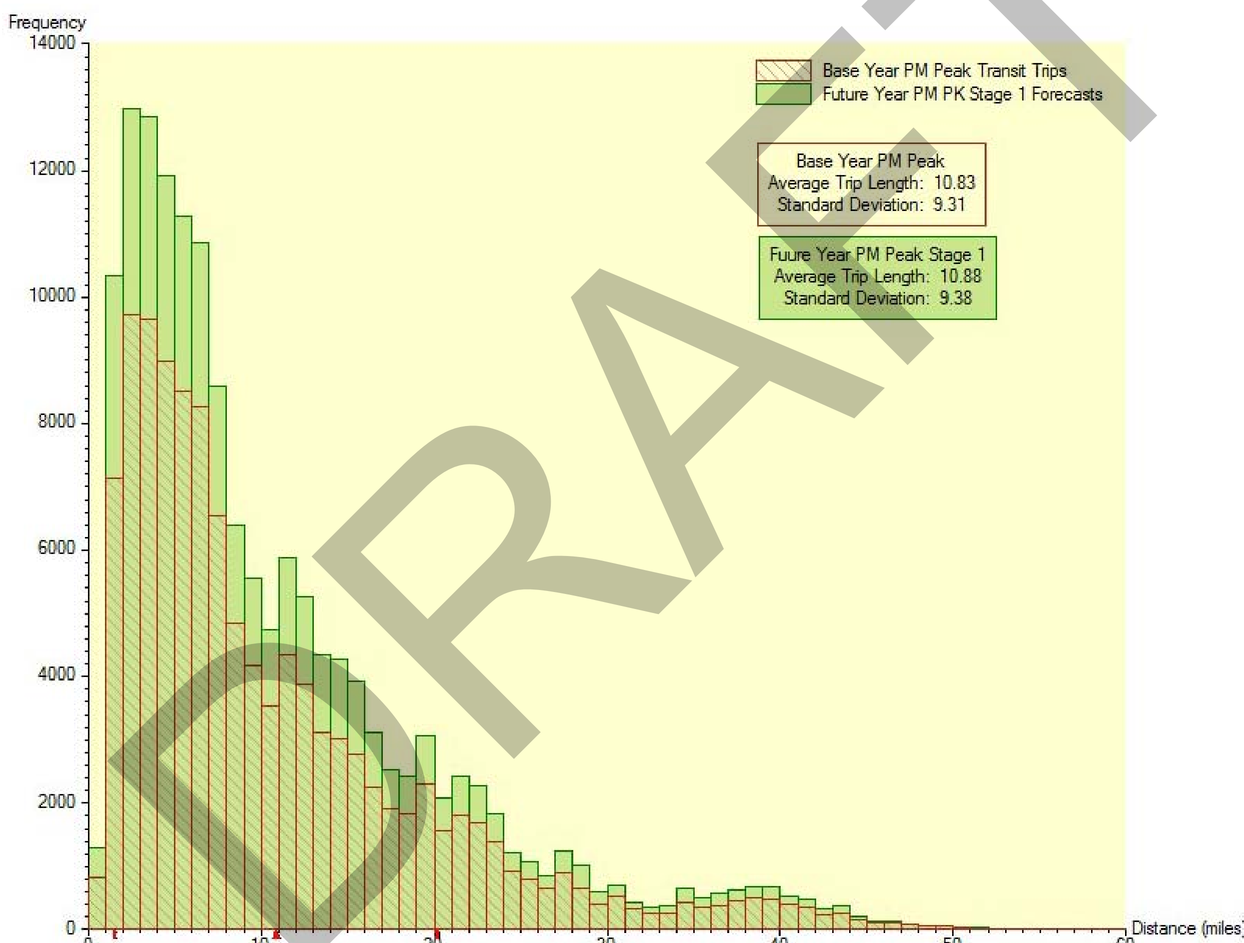

Figure 2-4. Average trip length frequency distribution comparison

2.7 Stage 2—Changes in highway congestion and cost

2.7.1 Formulation of Stage 2 forecasting analysis

Stage 2 considers how changes in highway congestion, auto costs (including parking, operating, and insurance), and income will influence mode choice.

The ST ridership forecasts use the PSRC model version, as adopted by WSDOT for travel forecasting in support of major highway projects, to estimate highway travel times. This highway model has been refined and validated in recent years for use on the SR 99 Alaskan Way Viaduct (AWV) & Seawall Replacement project, the I-90 tolling analysis, and the Lynnwood Link Extension (see Appendix C). These times are tabulated in the form of 219 x 219 FAZ-to-FAZ times for each highway network. A weighted averaging process is used to convert the more detailed TAZ-based travel times to FAZ-level highway travel times.

When a transit alternative significantly affects the highway system (e.g., taking freeway lanes for transit facilities), additional analysis of future highway networks and congestion using the PSRC highway model is required. Likewise, when a Build alternative has significantly higher ridership in a corridor than the No Build alternative, an additional highway model application may be necessary to account for slightly higher highway volumes in a No Build alternative.

In the Puget Sound region, transit fares and auto costs (except parking costs) are usually assumed to increase only at the rate of overall inflation; therefore, they are usually immaterial to the ST model. The ST model, however, includes these variables for the effects of income growth as these costs are normalized to income and for use in sensitivity tests that are not directly part of project planning ridership forecasts.

Stage 2 transit trip forecasts are calculated using the following incremental logit equation:

$$(8) \qquad \mathrm{Stg2Trn} = \frac{\mathrm{Stg1Trn}}{\mathrm{S_t} + (1 - \mathrm{S_t})\mathrm{X}[\exp(\mathrm{K} \times \mathrm{DIFF\ LogSum_h})]}$$

where

Stg2Trn	=	Stage 2 transit trip forecasts
Stg1Trn	=	Stage 1 transit trip forecasts
S_t	=	the base year observed transit shares
K	=	nesting coefficient on the auto nest
DIFF $LogSum_h$	=	Difference in the LogSum values due to changes in highway congestion and auto costs (future vs. base year). Data from the ACS and CTR surveys (for the baseline share), highway skims, and auto costs are used in Equation 8 to estimate the DIFF $LogSum_h$ on the auto side.

Stage 2 transit-share forecasts (Stg2Shr) are also calculated as follows:

$$(9) \qquad \mathrm{Stg2Shr} = \frac{\mathrm{Stg2Trn} \times \mathrm{S_t}}{\mathrm{Stg1Trn}}$$

Resulting from the Stage 2 forecasting analysis are the transit trips for a future year, having accounted for factors external to the transit service itself. These results then serve as a platform for analysis of ridership on alternative transit networks. Note that bus speed degradations are used in the Stage 3 forecasting analysis.

They are, however, based on changes in the level of highway congestion estimated using the Stage 2 PSRC model runs.

Note also that the final distance skim matrices from Stage 2 are saved for subsequent calculation of Vehicle-Miles Traveled (VMT) when estimating the environmental effects of various transit alternatives. This simple multiplication of a vehicle miles matrix by a New Riders matrix is now incorporated in the FTA's Final Policy Guidance for estimating the environmental effects for New and Small Starts evaluations.[23]

In most project planning ridership forecasting, Stages 1 and 2 need not be calculated as often as Stage 3. It is only when a transit alternative is presumed to have a strong effect on external factors, such as the regional highway network, that the entire process would have to be cycled through. However, for the New Starts project rating purposes, FTA discourages forecasts that are based on different externalities for different alternatives.[24]

2.7.2 Representation of conditions on the highway/HOV networks

WSDOT maintains a number of coded highway networks that represent the highway system in the Puget Sound region at various points in time. Future highway networks represent the adopted highway and HOV improvement plans, including planned changes such as tolls on the cross-lake bridges and other highways. ST usually relies on a recent version of the PSRC model that has been used by WSDOT for major capital projects, such as the SR 520 project, SR 99 Alaskan Way Viaduct (AWV) & Seawall Replacement project, or the I-90 tolling analysis project, after that version has been through a documented project level validation.

The PSRC model version currently used to interface with the ST model reflects project-level base year validation and future network updates in support of the Final Environmental Impact Statement (FEIS) and toll modeling and traffic forecasting for the SR 520, I-90, and AWV projects. It also includes additional network refinements and validation analysis (see Appendix C).

2.7.3 Estimation of parking costs

For the purpose of representing daily and hourly parking costs more accurately, a survey of parking costs scattered around the parts of the region that have paid parking was conducted in 2014. Based on the findings from this survey, base year (2014) daily parking costs were updated and 30 percent of daily parking costs were used to represent off-peak parking costs.

According to the limited historic information available, real parking costs have averaged an annual growth of approximately 1.5 percent since 1960. This is primarily attributable to changes in employment density which has averaged similar growth over the last five decades. Forecast increases in employment density are used to estimate future year changes in real parking costs. This results in parking cost increases around the region varying between 0.5 and 2.0 percent per year between 2014 and 2040. The average for all zones for which there are parking cost increases is around 1.0 percent annually, with the weighted average being considerably lower. Since these parking cost increases are normalized to a 1.0 percent growth in real income, their effect on the transit ridership forecasts for future years is relatively small.

[23] New and Small Starts Evaluation and Rating Process—Final Policy Guidance, August 2013.
[24] New and Small Starts Evaluation and Rating Process—Final Policy Guidance, August 2013.

2.7.4 Estimation of other costs and median income

Because auto operating costs in the Puget Sound region are usually assumed to increase only at the rate of overall inflation, they are less significant to ST models. Base-year (2014) and future auto operating costs are estimated at about $0.24 per mile (in 2014 dollars). The ST model assumes a conservative 1-percent annual (real) growth in income as indicated previously. When travel costs are assumed to remain constant over time, the terms have minimal effect on ridership, other than the effect related to an assumed increase in regional real income.

2.8 Stage 3—Changes in transit service

2.8.1 Formulation of Stage 3 forecasting analysis

In the third and final stage of the forecasting analysis, the incremental changes in the transit level of service, including transit fares, are considered. This change (as indicated in Section 2.4.1) is reflected in the resulting relative values of the LogSum_t variable using the base-year and future transit networks.

The Stage 3 transit shares and ridership forecasts are calculated as follows:

$$(10) \qquad P'ac = \frac{P_{ac} \times LOS_{ac}}{P_{ac} \times LOS_{ac} + (1 - P_{ac}) \times LOS_{wlk}}$$

and

$$(11) \qquad Stg3Trn = \frac{Stg2Trn \times [\exp(K \times DIFF\ LogSum_t)]}{Stg2Shr \times [\exp(K \times DIFF\ LogSum_t)] + [1 - Stg2Shr]}$$

where

LOS_{ac} = Difference in (future vs. base year) utility of the park-and-ride access submode

LOS_{wlk} = Difference in (future vs. base year) utility of the walk-access submode

$P'ac$ = Forecasted Stage 3 shares for the auto-access mode

P_{ac} = Base-year observed shares for the auto-access mode, derived from the base year trip table development process reflecting actual counts on park-and-ride facilities.

K' = Nesting coefficient

$DIFF\ LogSum_t$ = Difference in the LogSum values due to changes in transit level-of service (future vs. base year)

Transit service that is taken into consideration in the ST model Stage 3 forecasting analysis is represented by means of a coded network. Details on transit network preparation are included in Appendix D. Treatment of bus speeds in the ST model includes the degradation of bus speeds due to roadway congestion, estimated by the PSRC model in a manner developed in consultation with the FTA.[25] Bus speed degradation is considered in Stage 3 forecasting analysis and held constant among alternatives. It is applied only to bus run time in mixed traffic (excluding HOV lanes) and not to dwell and lay-over time components.

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[25] Billen, D., Sound Transit, “Updated Treatment of Bus Speeds in the Sound Transit Model,” Memorandum to Eric Pihl of FTA, dated August 1, 2002. A copy of this memorandum is included in Appendix D.

2.8.2 Transit fares

Any changes in transit fares are considered in Stage 3 of the ST model, along with changes in transit service. However, fares are always held constant among alternatives. Transit fare matrices were developed for the ST model, and were assumed to be:

- The zone-to-zone averages in effect in 2014 (for the base year)
- The zone-to-zone averages in effect in 2015 (for all future years)
- Independent of transit path choices

Independence from path choice is a reasonable approach to fares with the RTA District. The path-independent approach to transit fares also aligns with FTA's guidance to keep any fare-related utility differences between alternatives to a minimum. Upon the introduction of the ORCA smart card as the primary fare medium for all transit operators in the District, zonal fares are more appropriate than path-based fares. For most trips within the District, the fare implications of path choice and transfers have become less critical for forecasting. This is due to the very high market penetration of the regional employer pass programs, to the wide use of ORCA cards, and to the refined agreements among the transit operators for assigning cash value to trips involving more than one transit vehicle or more than one transit agency.

3 Base Year Transit Trip Table Development and Validation

Before a model can be used for analysis, it must be validated. The process of validation involves comparing the performance of the model to the most recent observed data sources available in order to confirm that the model is accurately replicating current transit travel patterns and transportation system performance.

In project planning, travel forecasting models are expected to predict changes in travel patterns caused by

- General changes, such as population, employment, and economic changes, between the base year and the forecast year
- Specific changes introduced by each alternative

Consequently, the best validation tests are those that test the ability of the forecasting methods to accurately capture response to changes in population and employment levels, parking and gasoline prices, transit fares and service levels, as well as other conditions.

The incremental approach, which is used in the ST model, generally reduces the need for validation because it relies on surveys and extensive ridership counts to establish current transit travel patterns. However, it is still useful to check the overall performance of the forecasting against current known conditions.

This chapter is organized into two sections. The first section describes the overall analysis process for creating the 2014 p.m. peak and off-peak transit-trip tables, while the second section presents validation analysis results.

3.1 Base year (2014) transit-trip table development

A centerpiece of the ST incremental model is its reliance on observed transit travel patterns, as determined through transit ridership data, to create base year (2014) p.m. peak and off-peak transit-trip tables. The most accurate and reliable information on observed transit travel is detailed rider counts.

Current passenger counting techniques have improved greatly, both in their accuracy and their level of detail. This may be especially true here in the Puget Sound Region, although the technologies used are now widely available. The sampling rate for counts in this region is now over 20 percent on local bus lines, 30 percent on Link light rail, 50 percent on bus rapid transit lines, and 100 percent on commuter rail lines. Likewise, the detail available includes all stop-to-stop segments and all times of day by direction and vehicle trip.

The resulting data, averaged over an entire year or over a quarter, should be considered perfectly reliable as a precise snapshot of current transit travel. Use of this level of existing detail resolves a significant portion of the need for validation.

In addition, the use of stored-value fare media, called ORCA cards in the Puget Sound Region, offers a new extremely rich data source, supplementing on-vehicle count data with fare payment data. This data will soon be available to supplement the counts data with new knowledge of transfer rates and locations and relating boarding locations to alighting locations. Although the use of fare payment data in the current model has been supplemental only, the next generation of incremental models in the Puget Sound Region will be able to fully integrate these two sources.

On-board transit surveys can provide estimates of origin-destination data, yet it is extremely difficult and costly for transit agencies to establish "observed" transit travel patterns solely from survey data. A typical on-board transit survey collects origin and destination data for only 5 to 15 percent of riders. Furthermore, survey experience indicates that on-board surveys include strong sample biases that cannot easily be corrected. The sample biases, combined with the sparseness of the origin-destination data, would compromise the accuracy of base year trip tables when the tables are based solely on survey responses. Because of these shortcomings, an alternative approach to building base-year transit-trip tables was developed at ST in 2005, using ridership count data as the primary source of current ridership patterns supplemented by survey data.

The survey data is primarily used to establish a set of "seed" transit-trip table matrices, embodying a large collection of cells (i.e., zone interchanges) in the matrices. This ensures that important transit markets are represented in the base year trip tables.

The ridership data used to develop transit-trip tables includes the following:

- **2014 passenger load data**—Detailed ridership counts data were obtained from each transit agency. The route-level counts data were all collected using APC technology, with the exception of the smallest operator, Everett Transit. Everett Transit accounts for 0.7 percent of the transit passenger-miles in the ST district. These data include average weekday passenger loads by route segment, direction, and time of day, which provided the necessary information to establish ridership profiles along each route by time of day. All of the APC data is from Spring 2014 from the following operators:
  - King County Metro (KCM) bus routes, including Rapid Ride routes
  - ST Express bus routes
  - ST Sounder commuter trains and Link light rail
  - Community Transit (CT) local and express bus routes
  - Pierce Transit (PT) bus routes
- **2014 boarding counts**—Route-level total boardings were obtained for all routes from all transit agencies, including KCM, ST, CT, PT, and Everett Transit.
- **2004 and 2009 Sound Transit on-board surveys**—Between September 2003 and May 2004, ST conducted an extensive on-board survey of all of its transit services over a 9-month period, followed by a similar survey in 2009.
- **1992 on-board transit surveys**—In 1992, transit agencies in the Puget Sound region conducted six on-board transit surveys that provided base-year 1992 transit-trip tables for the earlier versions of the ST model.[26]
- **2006 PSRC household activity and travel survey**—In 2006, PSRC undertook a survey to obtain region-wide information on household activities and the travel these activities generate. It surveyed about 4,700 households during a consecutive 48-hour time period. Transit demand matrices were then estimated by PSRC with the version of the traditional regional four-step synthetic model in use at the time.
- **2011 Sound Transit on-board surveys**—In 2012 ST completed a Before and After Study for the Central Link light rail project. One component of the study was to investigate ridership characteristics of the project. To study these characteristics, ST undertook an on-board passenger survey on all routes through the Central Link Study Area, to collect data about passenger trip characteristics, such as origins, destinations, fare payment, transfers, etc. The survey was conducted in October and November 2011 on

[26] "Transit Ridership Forecasting Technical Report," Central Link Light Rail Transit Project (North Link), Sound Transit, November 2003

weekdays during peak and off-peak periods. A sample of trips of Link trains and KCM buses was developed for the survey. For each sampled trip, survey staff attempted to approach all passengers to distribute a survey form. Passengers could return the survey on-board, through postal mail, or complete a web-based survey. This survey data was used to open additional cells in the base year trip tables and to validate transfer rates in the corridor.

- **2012 Sound Transit on-board survey**—In 2012, ST completed on-board surveys on ST bus routes, Sounder Commuter Rail, and Tacoma Link light rail. The Tacoma Link light rail survey was used to open additional cells in the base year trip tables.
- **American Community Survey**—The five-year (2006–2010) estimates of ACS data collected by the Census Bureau, prepared as Census Transportation Planning Product worker flows, were used to open new cells as well as providing base share data.
- **2007–2014 commute trip reduction act surveys**—The State of Washington passed the CTR law in 1991 to encourage commuters to consider transportation alternatives, such as ridesharing or taking the bus. As part of this law, employers with 100 or more employees are required to conduct a survey once every two years to record commute options by their employees. Surveys from the 2007 through 2014 series were processed to obtain origin-destination and modal information on commuters. The CTR surveys have contributed considerably in opening new cells in the base year seed matrix as well as providing base shares in the absence of U.S. Census JTW data.
- **Other counts and survey data**—Supplementary counts data from transit operators and from the National Transit Database (NTD) provided control totals for development of the 2014 base transit trips.

As described above, the survey data are used to establish a set of "seed" transit-trip table matrices. These survey matrices are instrumental in establishing the basic shape of the transit demand matrices. In addition, the PSRC transit-trip tables supplement the survey data by opening additional cells. Transit passenger miles and boardings by operator from the 2013 NTD and 2014 data directly from the operators are then used to slightly adjust the scale of the initial seed matrix.

Transit counts, in particular the passenger load profiles from the APC databases, provide line segment detail by direction and time period on each route. The frequency of segment-load points required for a given route in the trip development process depends on the variability of load profile for that route and the importance of that route's contribution to overall transit demand. For example, a minor bus route that experiences fairly uniform passenger loads throughout its trip does not require more than two or three locations for seeding directional passenger count volumes. Other routes, with more variability in passenger loads or very high ridership, require seeding of counts at more than three or four locations for each direction and time of day. About 1,800 segment-load locations are selected to post passenger volumes into the 2014 network database for matrix estimation, representing over 25 percent of the time point interval (TPI) route segments.

The base trip-table development process relies on a validated base transit network as well as supplementary ridership count data, control totals, and actual average trip length measures. This process involves a rigorous analysis, the results of which are discussed below.

3.1.1 Transit network preparation

The preparation of the base-year transit network is an important and significant part of the overall development of the base-year trip tables. The accuracy of the resulting base-year trip tables depends directly on the validity and quality of the base transit network, as well as on accurate ridership counts. Therefore, the base-year (2014) transit network was prepared and validated to accurately reflect transit service levels, as operated in Spring 2014, as well as actual travel times by time of day for bus and rail lines and on-time performance data for Link light rail and Sounder commuter rail lines.

Systemwide travel times for each TPI were established according to the actual travel time data for the KCM routes and on-time performance reports for other routes as part of previous ST model updates. Upon further examination, certain routes required updates to actual travel times for many segments. This update of base travel times included representative KCM, CT, and PT routes, both local and express, and all ST routes. The route-level dispersion between estimated and actual transit travel times around a simple regression line resulted in an R-square value over 0.91 and a slope close to one. This indicated a well-calibrated transit network that is capable of accurately reflecting service levels. Another base year (2014) transit network validation check included comparison of estimated and reported operating parameters. Estimates of revenue hours, miles, and miles per hour are within 5 percent of those reported in the NTD for all these measures.

3.1.2 Validation of transit service reliability

The current ST model relies on actual transit vehicle speeds to realistically represent transit service reliability. Although the long-term decline in bus operating speeds has been measured for the past 40 years, it has not been easy to measure the accompanying decline in service reliability until recently. However, Automatic Vehicle Locator (AVL) data from KCM and ST now supply rail and bus data with complete information on actual times and schedule adherence. According to a recent analysis performed using AVL data, a rider must plan on a 9.2-minute delay for bus services in the p.m. peak. The corresponding measurement for ST rail services is about a 1.5-minute delay planning requirement.[27]

ST models have been using a boarding penalty to account for uncertainties related to using the transit system, including uncertainties about transferring between vehicles. Recent research on the perceptions of transit users has clarified that schedule adherence and transit stop attributes concerning personal safety are more important to the use of transit than are other station amenities.[28] Consequently, boarding penalties are reduced at stations with documented schedule adherence superiority and at transit centers and stations with positive security attributes (e.g., improved lighting and communication, 20-hour security patrols, fare-controlled platforms, and on-board fare inspectors).

Table 3-1 presents the model's boarding penalties, including wait time factors and time penalties that are assumed on escalator links. Note that in the ST model, walk and wait time resulting from a transfer is accounted for separately, including pedestrian and escalator links at rail stations, and all out-of-vehicle time is factored by 2.0.

Validation results using the boarding penalties indicated in Table 3-1 netted a much closer match to observed transfer behavior since the 2005 model version. Improvements were noted at the system level, the route level, and especially at major bus transit center facilities.

[27] Billen, D., "Application of Transit to LOS Measures in the Seattle North Link Light Rail Corridor," 10th TRB—Transportation Planning Applications Conference, Portland, OR, 2005.
[28] Iseki, H. and B. Taylor, "Style vs. Service? An Analysis of User Perceptions of Transit Stops and Stations," *Journal of Public Transportation*, Center for Transportation Research, Vol. 13, No. 3, 2010.

A special analysis was undertaken in 2011 for transfers to and from Sounder trains. According to prior ST model versions, 90 percent of p.m. peak commuter rail riders were estimated to arrive at King Street Station by transfers from local transit routes. Consequently, the assignment of transfers between the downtown commuter rail station and the downtown transit tunnel were of particular concern. Recent ST surveys have shown that only 45 percent of p.m. peak Sounder riders arrive at King Street Station via downtown transfers from other routes, whereas approximately 50 percent access King Street Station by walking. Other surveyed access modes at King Street include taxi and other auto drop-offs plus a few employer-provided shuttle vans, totaling about 5 percent. Although the current model's estimate of 55 percent arrival by bus is still somewhat high, it is much closer to the surveyed p.m. peak access pattern.

The current updated ST model also more accurately replicated the 2014 three-county transfer rate compared to the earlier ST model versions. Further evaluation will be made when new information on transfers is available from the ORCA card fare payment database.

Table 3-1. Boarding penalty, wait time factor, and escalator link assumptions in the 2011 ST model

	PM peak	Off peak
Regular bus stops		
Boarding penalty	5.0 min	5.0 min
Wait time factor	0.60	0.60
Escalator link	NA	NA
Transit centers[1]		
Boarding penalty	3.0 min	3.0 min
Wait time factor	0.50	0.50
Escalator link	NA	NA
Downtown bus tunnel		
Boarding penalty	3.0 min	3.0 min
Wait time factor	0.50	0.50
Escalator link	1.0 min	1.0 min
Rail stations (surface)		
Boarding penalty	2.0 min	2.0 min
Wait time factor	0.50	0.50
Escalator link	0.5 min	0.5 min
Rail stations (tunnel or elevated, excluding downtown tunnel stations)		
Boarding penalty	2.0 min	2.0 min
Wait time factor	0.50	0.50
Escalator link	1.0 min	1.0 min

In both the path-building and the mode choice applications, all of these out-of-vehicle times are multiplied by 2.0.

[1] List of major bus Transit Centers:

1) Bellevue Transit Center (TC)
2) Federal Way TC
3) Northgate TC
4) Burien TC
5) Kent Station TC
6) Auburn Station TC
7) Kirkland TC
8) Overlake TC
9) Aurora Village TC
10) Renton TC
11) Lynnwood TC
12) Tacoma Dome Station
13) Lakewood TC
14) Everett Station
15) Tacoma Community College TC
16) Tacoma Commerce Street TC

3.1.3 Ridership counts data preparation

Ridership counts data for 2014 were obtained from transit agencies in the region.

- KCM provided GIS-based stop-to-stop ridership information that included boardings, alightings, and volumes for each segment on each trip for each route. This data was collected using APC equipment located on a subset of buses that are rotated on to each trip across KCM's system. This system began operation in 1985 and has been re-calibrated and improved many times over the past 30 years, including gradual sample size increases.
- CT provided stop-level segment ridership information that included boardings, alightings, and loads between each stop. CT's data was collected using APC equipment on all routes.
- PT also provided stop-level and segment ridership information that included boardings, alightings, and loads. These counts data were collected using APC equipment installed on all of PT's buses for a 100-percent sample.
- For ST Express bus, Link light rail, and Sounder commuter rail, the stop-level boardings and alightings data and segment load data were collected by APC equipment.

Using the loads from the count data, segment totals were extracted for the 3-hour p.m. peak period and for the daily 24-hour total. These aggregated segment-level loads are the observed transit volumes that are then posted onto transit line segments in the model network to exactly replicate loading on each route by time of day and by direction. In all cases, the off-peak segment volumes on the network represent peak subtractions from total weekday reported volumes so that the weekday total volumes remain the control totals for each segment and line. In this way, the daily counts represent ridership control totals for the transit system.

3.1.4 Matrix adjustment process

A trip matrix adjustment methodology developed by Heinz Spiess[29] and implemented in the EMME software is used to develop the base year (2014) p.m. peak and off-peak transit-trip tables. This methodology, which has been used extensively, minimizes the difference between estimated and observed volumes posted at designated segment locations for each route through an iterative process. While this methodology achieves a close match of estimated-to-actual segment loads, additional refinements are necessary to improve accuracy in the resulting transit-trip tables. These refinements thus far have included the use of:

- New surveys, particularly data from the CTR surveys-- Allows opening of additional non-zero cells in the seed matrices and improved shaping of the demand matrices.
- Route segment count data from all transit operators as highlighted in the previous section—Allows the load profile to be more accurately replicated on each transit route by time of day. This is achieved by using an iterative matrix adjustment process using over 1,800 segment load locations. These constitute about 25 percent of the total TPI segments in the APC databases.
- Performing matrix adjustment in multiple steps rather than in one step as in earlier ST model versions—Allows better alignment of counts data to underlying service characteristics within each subarea and within each route category, resulting in more representative base transit-trip tables.

Further elaboration on the items highlighted above is provided below.

[29] Spiess, H., "A Gradient Approach for the O-D Matrix Adjustment Problem," Formerly with INRO (EMME/2 Support Center), Haldenstrassee 16, CH-2558 Aegerten, Switzerland.

3.1.5 Seed matrix development

The need for careful preparation of a seed matrix is critical, as it underlies the shape of transit travel patterns and representation of transit markets. During earlier ST model updates, it became evident that available survey data were allowing only 3 percent of non-zero cells to be opened to adjustment. For subsequent updates of the ST model, additional non-zero cells were opened based on using new surveys data supplemented by transit-trip tables from the PSRC model. About one-third of the total 28-percent cells opened in the 2012 ST model version was contributed from the CTR surveys.

For this 2015 ST model version, almost all matrix cells have been opened, by seeding 0.1 trips into most cells after seeding of all the survey information. This practice retains the value of the matrix shape and directionality of the survey-based portions of the tables, while permitting the matrix estimation process a little additional flexibility for matching the counts in areas where survey information is sparse.

3.1.6 Matrix adjustments in steps

As indicated above, matrix adjustment is performed in six steps. This method mitigates dominance of routes with relatively large segment loads in the matrix estimation process, ensuring that low and medium ridership routes also contribute to the matrix estimation. This also allows better alignment of counts data to underlying service characteristics in each geographic subarea. The specification of the matrix adjustment process and segment loads considered in each step is shown in Table 3-2.

Table 3-2. Specification of matrix adjustment in steps

Step no.	Segment-loads considered	Number of matrix adjustment iterations
Step 1	Initial run, include all segment loads on all routes	10 iterations
Step 2	Include only segment loads from Pierce Transit, Everett Transit, and Community Transit (excluding BRT routes)	15 iterations
Step 3	Include segment loads from Step 2 + segment-loads for KCM local routes and streetcar	15 iterations
Step 4	Include segment loads from Step 3 + segment loads for KCM trunk and BRT routes, KCM trolleys, CT BRT route, Tacoma Link, and ST Express bus routes (excluding routes 545 and 550)	16 iterations
Step 5	Include segment loads from Step 4 + segment loads for ST Express routes 545 and 550, and Sounder Commuter Rail	16 iterations
Step 6	Include all segment loads (i.e., add Central Link Light Rail segment-loads to Step 5)	20 iterations

The matrix estimation is performed in a sequential and cumulative manner. The segment counts are first grouped based on the markets and the service type. For example, all PT local bus segment counts are grouped together. Then, the matrix adjustment is performed on each group by cumulatively including the segment loads from all the previous groups and using the previous result matrix as a new seed matrix. Such a step-wise matrix adjustment method allows adjusting the transit-trip table for low volume segments before including the next level of higher volume segments. The intent is to give the matrix adjustment method as much of an opportunity to adjust segments with low volumes as segments with high volumes. The adjustments to low-volume segments are not greatly modified as the higher-volume segments are brought in, so low-volume information is retained.

Conditions outlined above are complemented by an extensive and rigorous analysis effort. This involves comparisons over many runs of matrix estimation against NTD and agency data on boardings, trip lengths, route volumes, and other available 2014 data. The analysis results for base year (2014) transit-trip development are discussed below.

3.2 Base year (2014) validation analysis results

The validation analysis focused on evaluating (1) the updated transit-trip tables from the matrix adjustment process and (2) the accuracy of the assignment results, which is reflected in:

- Systemwide boardings and transfer rate
- Boardings comparisons by transit agency and mode
- Passenger-miles by transit agency and mode
- Route-level boardings
- Route-segment volumes by direction and time period

Table 3-3 presents systemwide linked and unlinked transit trips, including a comparison of average weekday boarding estimates to respective actual boardings. As shown in Table 3-3, the number of estimated versus actual trips is close, reflecting the breadth and quality of the underlying network and ridership counts data used in the trip table development process. The total p.m. peak transit linked trips are estimated at 117,000, which is about 30 percent of an estimated total 387,300 daily transit linked trips.

Table 3-3. Systemwide 2014 linked and unlinked transit trips comparison

	PM peak[1] estimated	Off-peak[2] estimated	Average weekday[3]		
			Actual[4]	Estimated[5]	Est/Act
Linked transit trips	117,000	153,300	NA	387,300	NA
Total boardings by operator					
KC Metro	111,700	163,200	392,300	386,600	0.99
Sound Transit	34,600	38,000	108,200	107,200	0.99
Pierce Transit	9,600	16,600	35,900	35,800	1.00
Community Transit	11,600	9,500	32,200	32,700	1.02
Everett Transit	2,300	2,100	7,000	6,700	0.97
Three-county total boardings	**169,800**	**229,400**	**575,600**	**569,000**	**0.99**
Systemwide transfer rate	1.45	1.50	NA	1.47	NA
Rail and regional bus boardings					
Central Link light rail	7,500	14,800	31,100	29,800	0.96
Tacoma Link light rail	1,000	600	3,600	2,600	0.75
Commuter Rail	6,800	NA	12,700	13,600	1.07
ST Express bus	19,200	22,600	60,800	61,000	1.00

[1] PM peak period represents about 3 hours of highest volumes.
[2] Off-peak period represents about 18 hours outside peak periods.
[3] Daily totals are control totals for peak and off-peak periods.
[4] Actual boardings were obtained from data supplied by transit agencies for April 2014.
[5] Transit trips in the ST model reflect trips with at least one trip end within the ST boundaries.

The systemwide daily boardings shown for 2014 imply an overall transfer rate of 1.47. No reliable source currently exists for actual transfer rates for comparison. There is not a measured "actual" value corresponding to a particular definition of what constitutes a linked trip to be able to consistently calculate transfer rates. Systemwide ORCA card fare collection data will eventually provide an improved basis for estimating transfer behavior in the region, but it will not provide pure transfer rates. This would require a more strict definition of what constitutes a linked trip. Currently ORCA data definitions are based on the parameters of a series of inter-local fare agreements, including implicit definitions of linked trip-making that serve revenue-sharing purposes but do not correspond to the self-defined understanding of a trip inherent in most existing surveys.

The daily transit boarding results in Table 3-3 closely match those reported by the transit agencies for Spring 2014. The total p.m. peak boardings are estimated at 169,800, which is about 30 percent of the reported regional total estimate of 569,000. The close match between estimated and actual daily boardings by agency, and by mode within ST, is evident in Table 3-3. Only the smallest mode, Tacoma Link, shows significant variance from the reported actual values.

Table 3-4 and Table 3-5 illustrate the close match of the base year (2014) model to the April 2014 counts at the existing rail stations. Closely adjacent stations are paired for this comparison. The closeness of the estimates to the counts validates the use of matrix estimation from line segment volumes for replicating station-level counts on major rail lines.

Table 3-4. 2014 daily estimated and actual light rail station boardings comparison

			Station groupings	
Station name	Actual	Estimated	Actual	Estimated
Westlake	5,800	5,500	8,300	8,300
University Street	2,500	2,800		
Pioneer Square	1,900	1,500	4,800	3,600
International District	2,900	2,100		
Stadium	900	600	1,900	1,600
Sodo	1,000	1,000		
Beacon Hill	1,800	1,500	3,600	3,600
Mt. Baker	1,800	2,100		
Columbia City	1,700	2,000	1,700	2,000
Othello	1,900	1,900	3,200	3,300
Rainier Beach	1,300	1,400		
Tukwila International Blvd	2,700	2,600	2,700	2,600
SeaTac/Airport	4,900	4,800	4,900	4,800
Total station boardings	**31,100**	**29,800**	**31,100**	**29,800**

Table 3-5. 2014 daily estimated and actual commuter rail station boardings comparison

			Station groupings	
Station name	Actual	Estimated	Actual	Estimated
Everett	200	200	200	200
Mukilteo	200	200	200	200
Edmonds	300	400	300	400
King Street	5,200	5,400	5,200	5,400
Tukwila	800	600	800	600
Kent	1,600	1,800	2,900	3,300
Auburn	1,300	1,500		
Sumner	1,000	1,200	2,100	2,200
Puyallup	1,100	1,000		
Tacoma Dome	700	500	700	500
South Tacoma	100	700	300	800
Lakewood	200	100		
Total station boardings	**12,700**	**13,00**	**12,700**	**13,600**

Table 3-6 and Table 3-7 contain summaries of base year (2014) p.m. peak and daily trip tables at 11x11 districts. A map of the 11 districts is shown in Figure 3-1. These tables are the final result of the matrix estimation process, representing a snapshot of the 2014 transit demand within the 3-county ST district. The matrices are the platform for subsequent work using the staged incremental transit demand model as described in Chapter 2.

Comparative analyses of load volumes at route segment locations and line boardings were performed throughout the process, providing quality control and reasonableness checks, including comparisons of transit passenger-miles by operator.

Estimated and actual transit passenger-miles are compared in Table 3-8 for each transit agency. Modeled passenger-miles are within 7 percent of actual passenger-miles. Note that passenger-miles for CT and PT are expected to be slightly lower in the ST model because the actual CT and PT service areas and routes extend beyond the ST model area.

Weekday passenger-miles presented from the 2013 NTD data necessarily relied on annual reporting and had to be scaled to weekday values. Since both average weekday and annual boardings are reported in the NTD, the resulting annualization factors were used for scaling to approximate weekday values.

Figure 3-2 and Figure 3-3 highlight the very close match of estimated to actual loads at segment locations for 2014 PM peak direction and off-peak transit trips as exhibited in the respective slope and R-squared statistics for goodness-of-fit measures. This is to be expected, given that the segment counts that enter the model are the same counts that the base year output volumes are being compared against. Nonetheless, the p.m. peak results of a 0.99 slope and a 0.99 R-squared value and the off-peak results of a perfect 1.00 slope and a 1.00 R-squared value provide a solid quality control check on the base year demand development process.

Note that these comparisons by route are a far more rigorous validation test than the typical comparison against counts across a limited selection of transit screenlines. This attention to line segment detail is particularly important when a network-based model is to be used to estimate line segment volumes on future rail line extensions. Validations against transit screenline counts do not provide sufficient confidence for forecasts of ridership volumes on specific lines or line segments.

Figure 3-4 shows a comparison of actual to estimated daily line boardings for all 291 transit lines. The 2015 model version is the first one for which this comparison has been carried out and displayed with the model validation. It is immediately evident that this comparison is a much more difficult test of the base year model than those shown in Figure 3-2 and Figure 3-3. The R-squared value of 0.97 is acceptable, but the slope of 0.91 indicates a tendency of the constructed matrices to under-represent shorter trips and intra-line ridership turnover.

This validation test gave rise to supplemental analysis of the larger outlier bus lines, especially those clearly visible on the scatter plot in the 10,000 to 13,000 daily riders range. Network-based investigation confirmed that this discrepancy is independent of network coding detail and likely related to the shape of the seed matrices. Analysis of the demand sheds for the individual outlier lines illustrated a few cases where the base network was weak at representing zonal connections to transit stops at locations where the counts indicated ridership turnover within a route profile, and these were improved.

These minor corrections provided only minor improvement to the slope of the regression line. This has led to the conclusion that the shape of the seed matrix has weaknesses around short transit trips, and that this weakness should receive further investigation for improvement prior to the next model version. This investigation will have to include methods for the use of ORCA data in modifying the seed matrices at an early stage in the model building effort.

Table 3-6. 11-district 2014 PM peak transit trip table

ORIGIN	DESTINATION	Everett 1	SW Snohomish 2	Shoreline 3	North Seattle 4	Seattle CBD 5	South Seattle 6	East King 7	South King 8	Tacoma 9	Pierce 10	External 11	Origin totals	Origin shares
Everett	1	1,900	600	100	100	–	100	–	100	–	–	200	3,100	2.6%
SW Snohomish	2	700	1,000	100	100	–	100	100	100	–	–	100	2,300	2.0%
Shoreline	3	100	100	100	400	–	100	100	–	–	–	–	900	0.8%
North Seattle	4	500	1,300	1,100	6,300	1,400	3,400	2,300	1,000	400	300	100	18,100	15.5%
Seattle CBD	5	700	3,200	1,000	7,900	1,600	10,900	5,500	5,100	700	1,100	300	38,000	32.5%
South Seattle	6	500	1,400	800	4,700	2,300	8,900	2,200	4,000	600	700	400	26,500	22.6%
East King	7	300	700	200	1,500	300	1,100	5,200	1,300	200	200	–	11,000	9.4%
South King	8	100	200	100	300	400	1,500	300	5,300	300	700	–	9,200	7.9%
Tacoma	9	–	–	–	–	–	100	–	200	3,500	1,300	–	5,100	4.4%
Pierce	10	–	–	–	–	–	–	–	200	900	1,400	–	2,500	2.1%
External	11	–	–	–	–	–	100	100	100	–	–	–	300	0.3%
Destination totals		4,800	8,500	3,500	21,300	6,000	26,300	15,800	17,400	6,600	5,700	1,100	117,000	100.0%
Destination shares		4.1%	7.3%	3.0%	18.2%	5.1%	22.5%	13.5%	14.9%	5.6%	4.9%	0.9%	100.0%	

Table 3-7. 11-district 2014 average weekday transit trip table

ORIGIN \ DESTINATION		Everett 1	SW Snohomish 2	Shoreline 3	North Seattle 4	Seattle CBD 5	South Seattle 6	East King 7	South King 8	Tacoma 9	Pierce 10	External 11	Origin totals	Origin shares
Everett	1	6,500	2,200	200	600	900	700	500	300	–	–	300	12,200	3.2%
SW Snohomish	2	2,200	3,500	400	1,900	3,400	1,800	1,100	400	100	100	200	15,100	3.9%
Shoreline	3	200	400	300	2,100	1,300	1,400	500	200	100	–	100	6,600	1.7%
North Seattle	4	600	1,900	2,100	23,500	13,200	14,100	5,300	2,200	600	400	400	64,300	16.6%
Seattle CBD	5	900	3,400	1,300	13,200	12,200	25,400	7,600	7,900	800	1,200	500	74,400	19.2%
South Seattle	6	700	1,800	1,400	14,100	25,400	34,200	5,500	10,200	1,000	1,000	900	96,200	24.8%
East King	7	500	1,100	500	5,300	7,600	5,500	15,800	2,500	400	300	100	39,600	10.2%
South King	8	300	400	200	2,200	7,900	10,200	2,500	18,500	700	1,000	200	44,100	11.4%
Tacoma	9	–	100	100	600	800	1,000	400	700	12,200	4,000	–	19,900	5.1%
Pierce	10	–	100	–	400	1,200	1,000	300	1,000	4,000	4,200	–	12,200	3.2%
External	11	300	200	100	400	500	900	100	200	–	–	–	2,700	0.7%
Destination totals		12,200	15,100	6,600	64,300	74,400	96,200	39,600	44,100	19,900	12,200	2,700	387,300	100.0%
Destination shares		3.2%	3.9%	1.7%	16.6%	19.2%	24.8%	10.2%	11.4%	5.1%	3.2%	0.7%	100.0%	

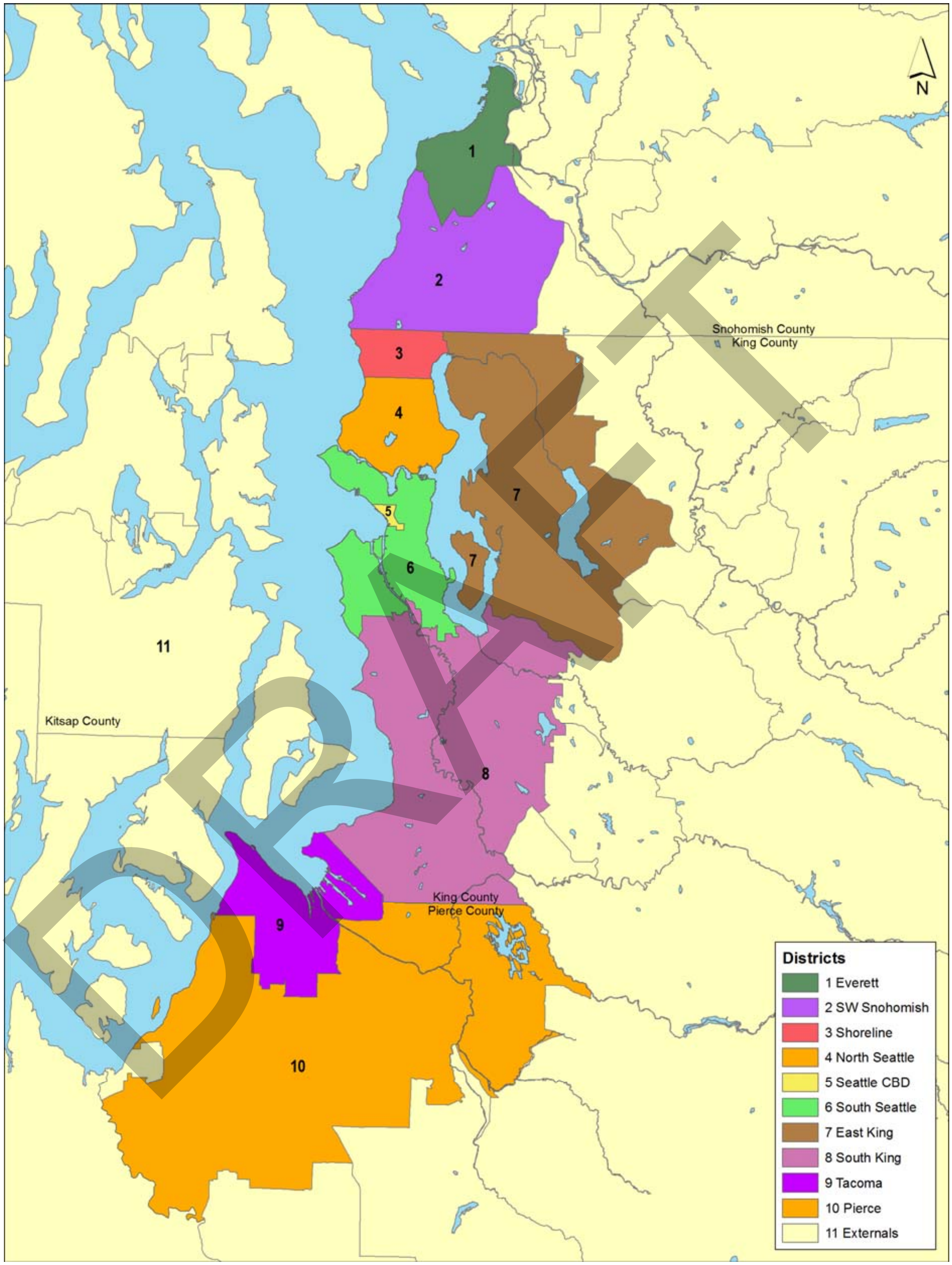

Figure 3-1. 11-district boundary map

Table 3-8. Estimated and actual average weekday passenger-miles comparison

Transit operator	Actual[2]	2014 Estimated	Est/Obs
King County Metro	1,694,000	1,752,000	1.03
Pierce Transit[1]	138,000	131,000	0.95
Everett Transit	24,400	26,000	1.07
Community Transit[1]	294,000	283,000	0.96
Sound Transit bus	883,000	869,000	0.98
Sound Transit rail	522,000	531,000	1.02
Regional	**3,555,400**	**3,592,000**	**1.01**

[1]Note that Community Transit and Pierce Transit service areas extend beyond the ST district.
[2]Actual values are from the 2013 National Transit Database except ST bus and rail which are figures for 2014. 2013 NTD annual mileage converted to weekday using annualization factors for NTD boardings.

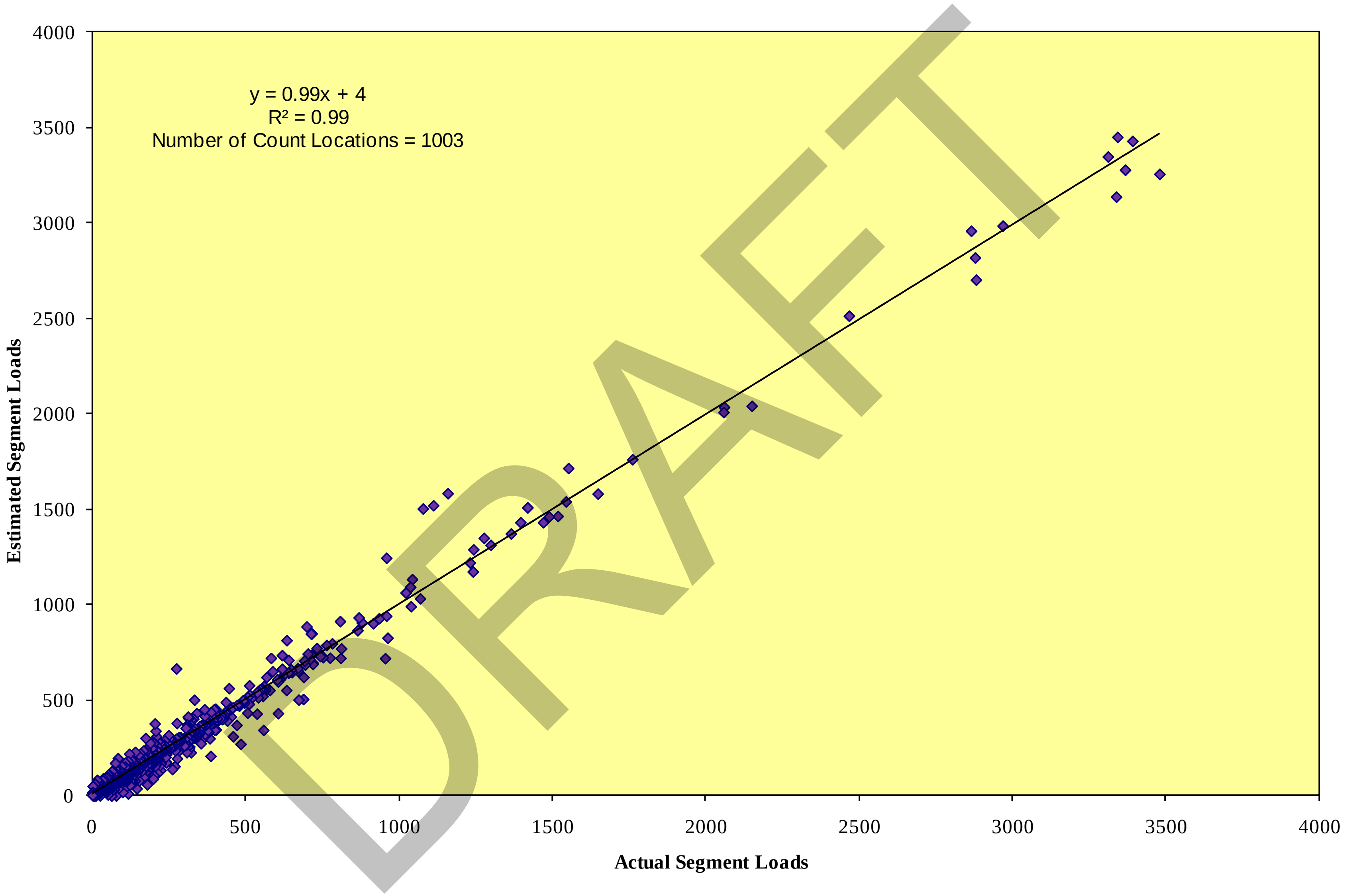

Figure 3-2. Comparison of 2014 PM peak actual vs. estimated segment loads for all transit agencies

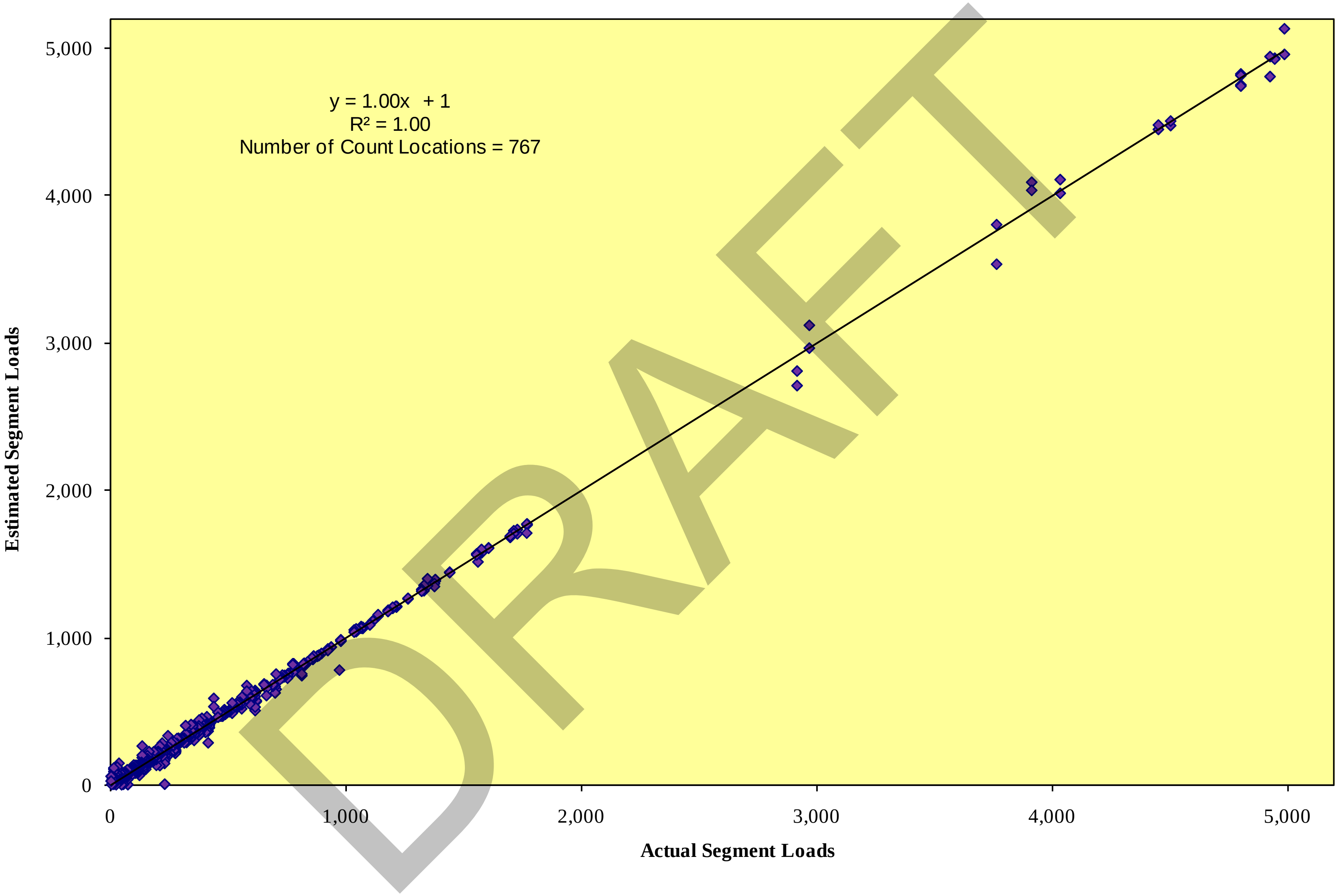

Figure 3-3. Comparison of 2014 off-peak actual vs. estimated segment loads for all transit agencies

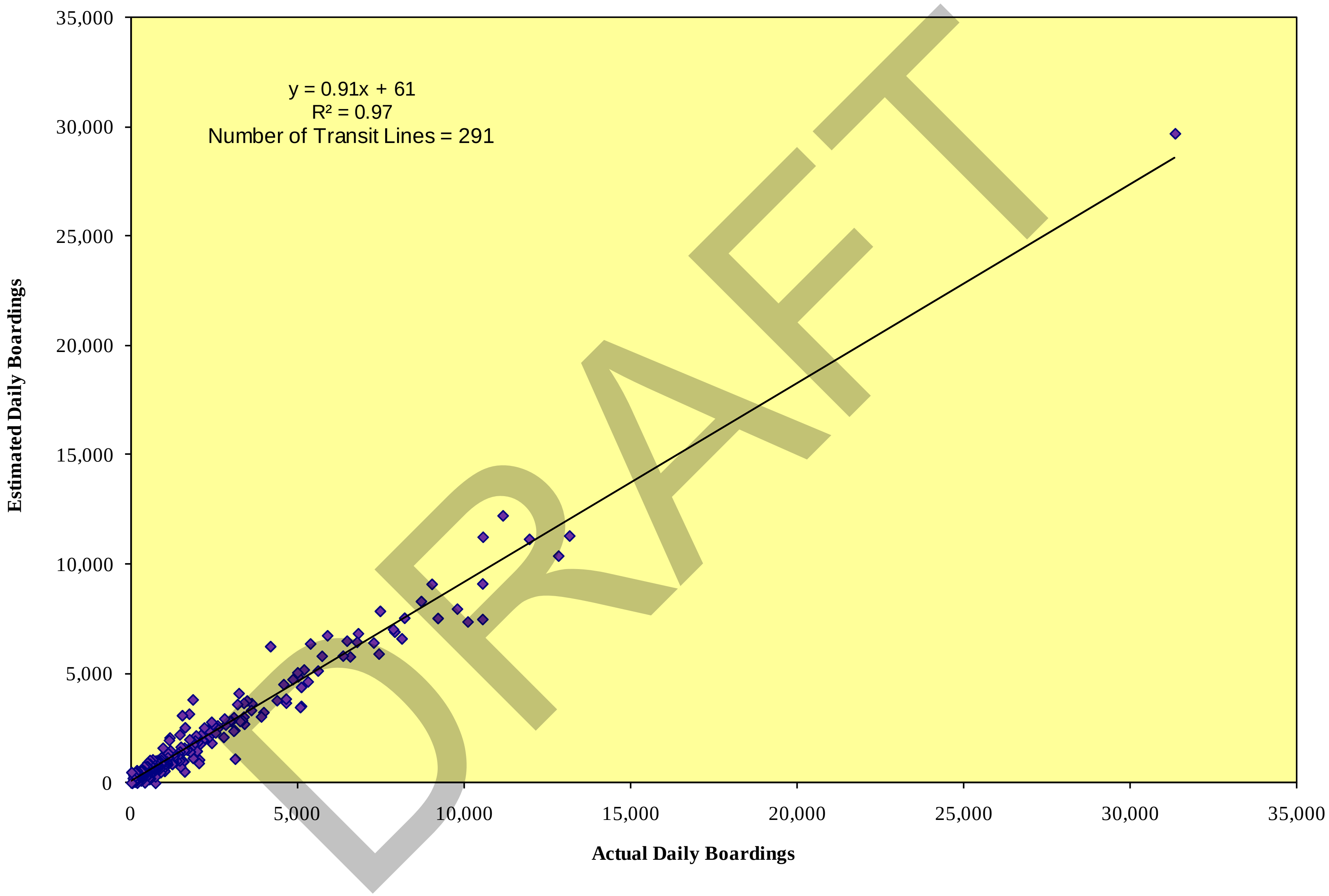

Figure 3-4. Comparison of 2014 daily line boardings actual vs. estimated

Appendix A: Maps

- Forecasting Analysis Zones (FAZs)
- Alternative Analysis Zones (AAZs)
- 11 and 27 Districts

Figure A1. PSRC FAZ Map—Snohomish County

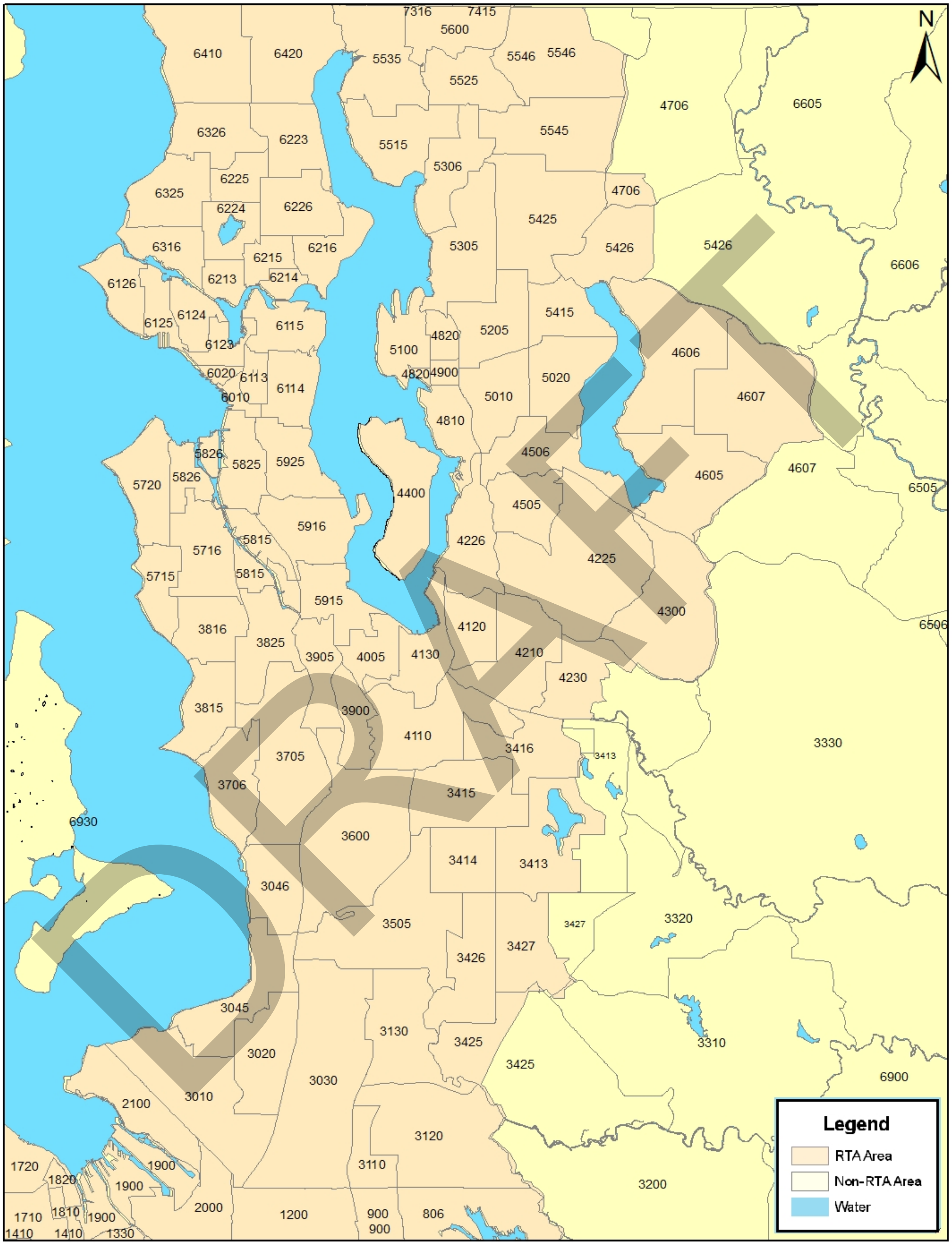

Figure A2. PSRC FAZ Map—King County

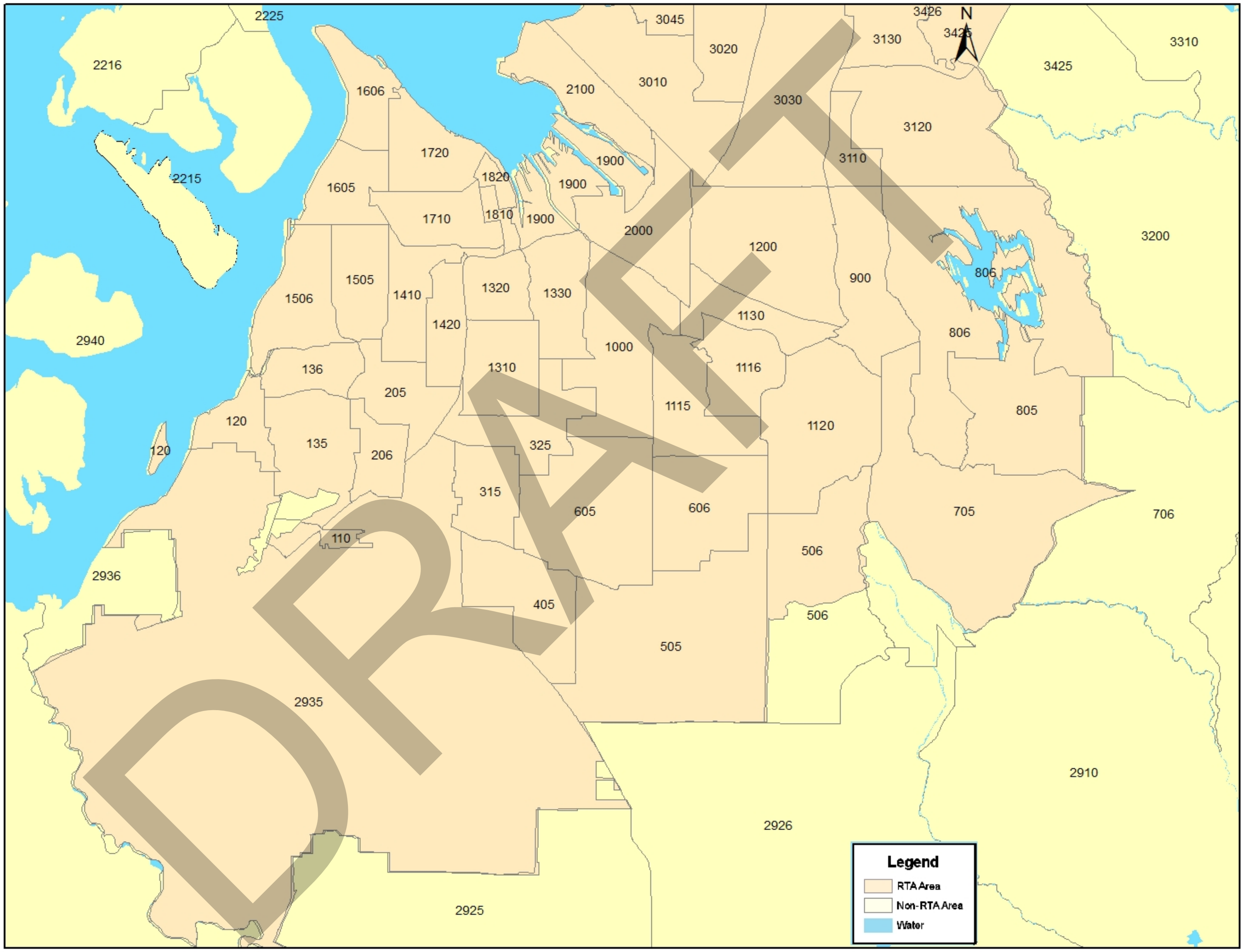

Figure A3. PSRC FAZ Map—Pierce County

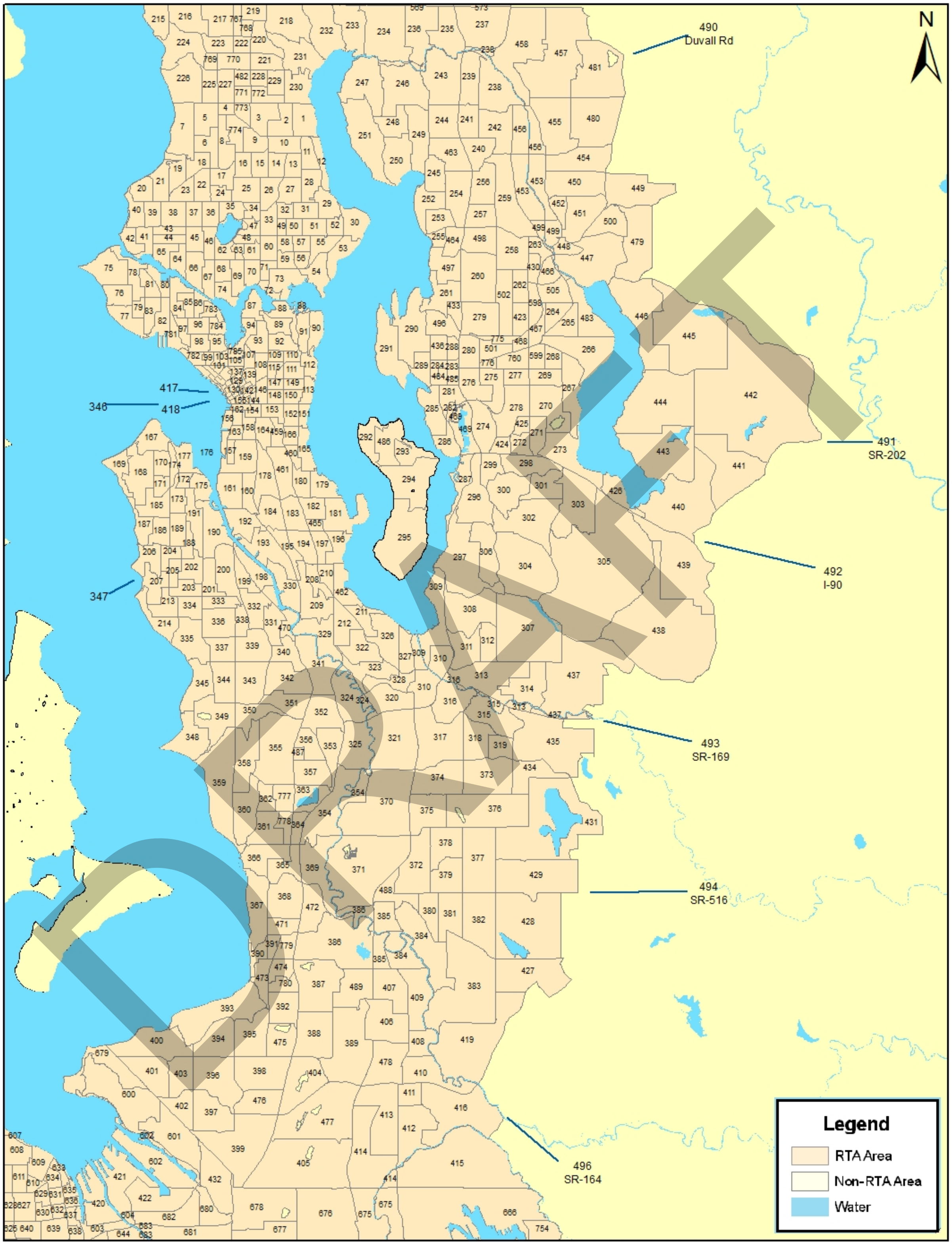

Figure A4. 785 AAZ Map—King County

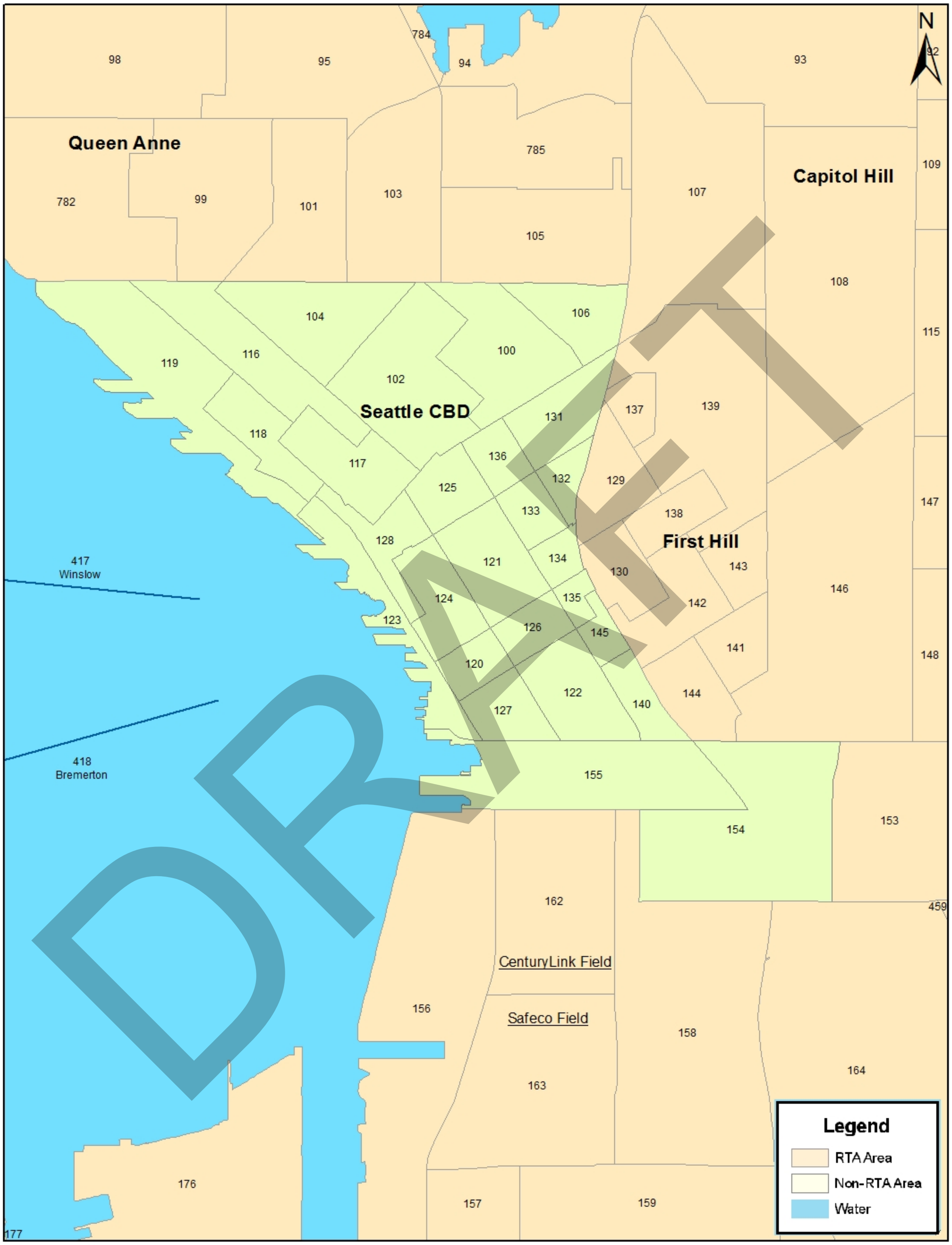

Figure A4a. 785 AAZ Map—Central Seattle

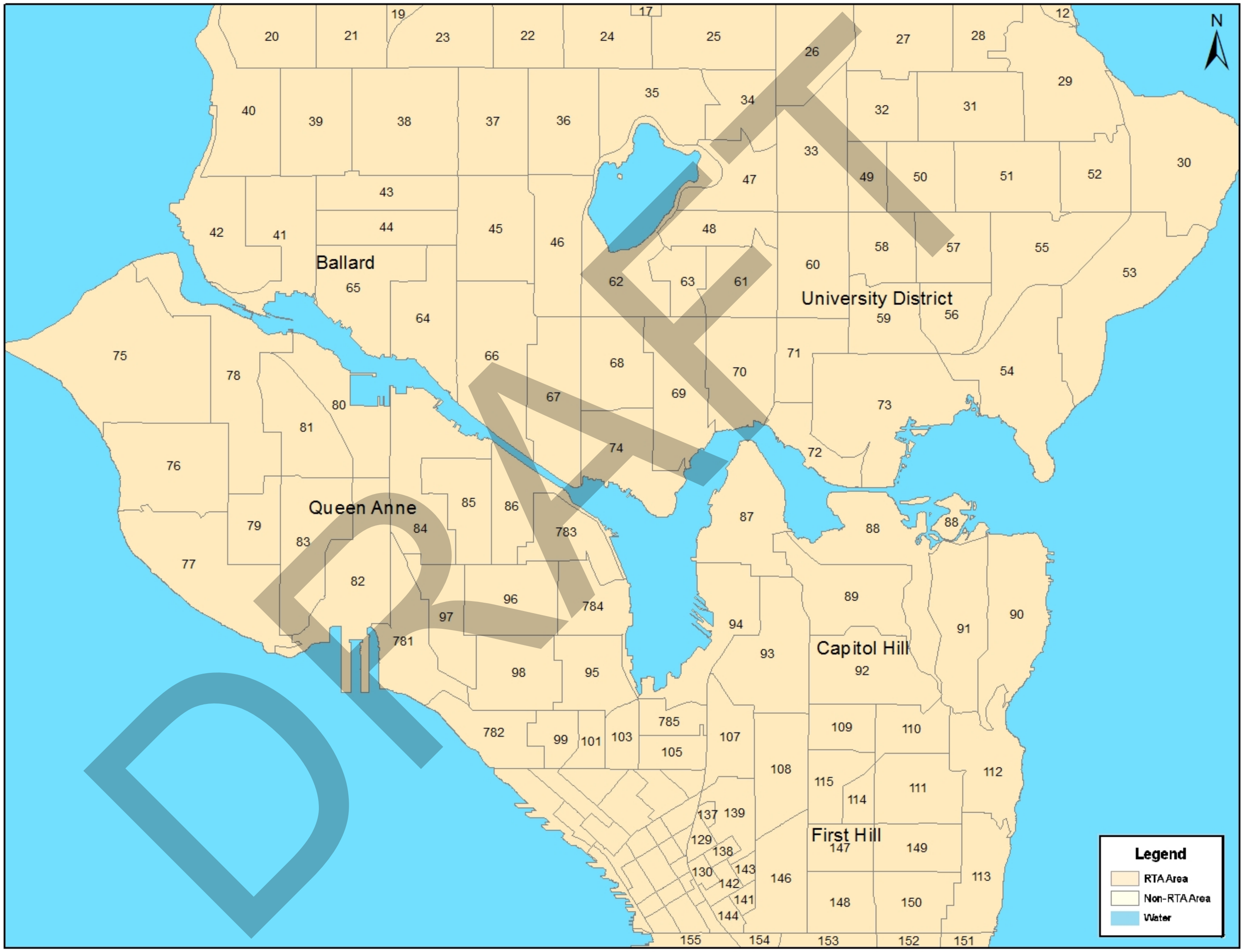

Figure A4b. 785 AAZ Map—Capitol Hill, First Hill, Ballard & Queen Anne

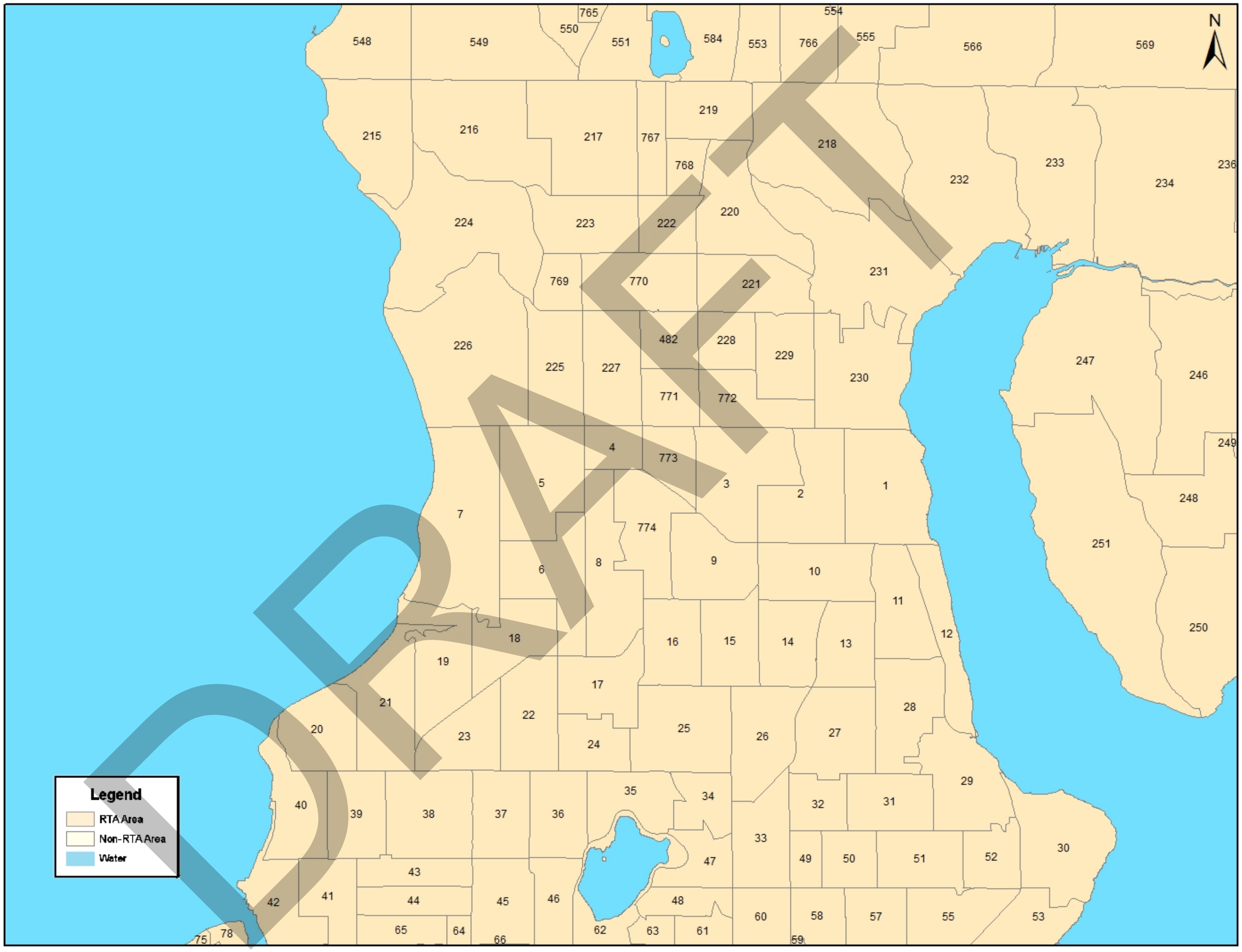

Figure A4c. 785 AAZ Map—North Seattle

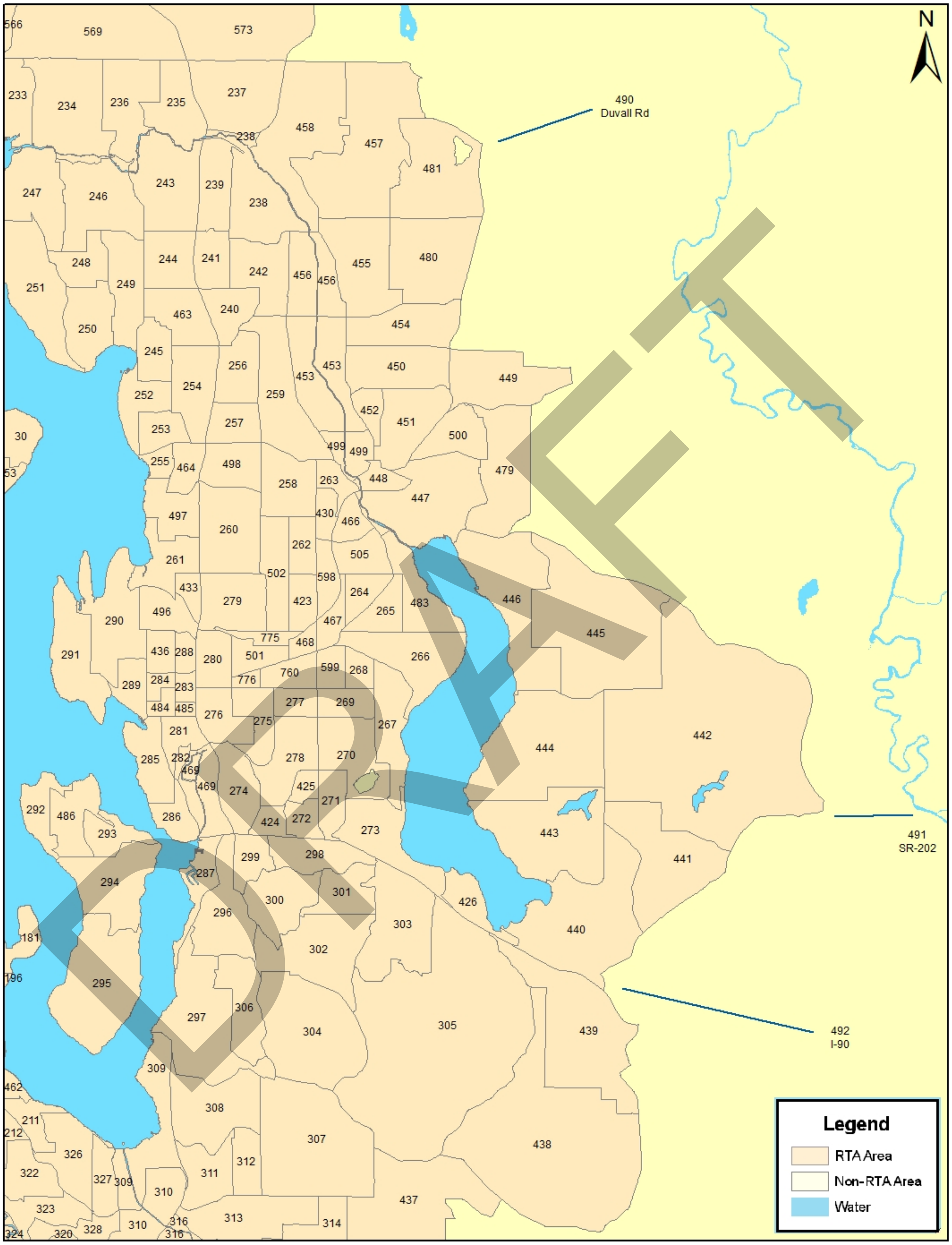

Figure A4d. 785 AAZ Map—East King County

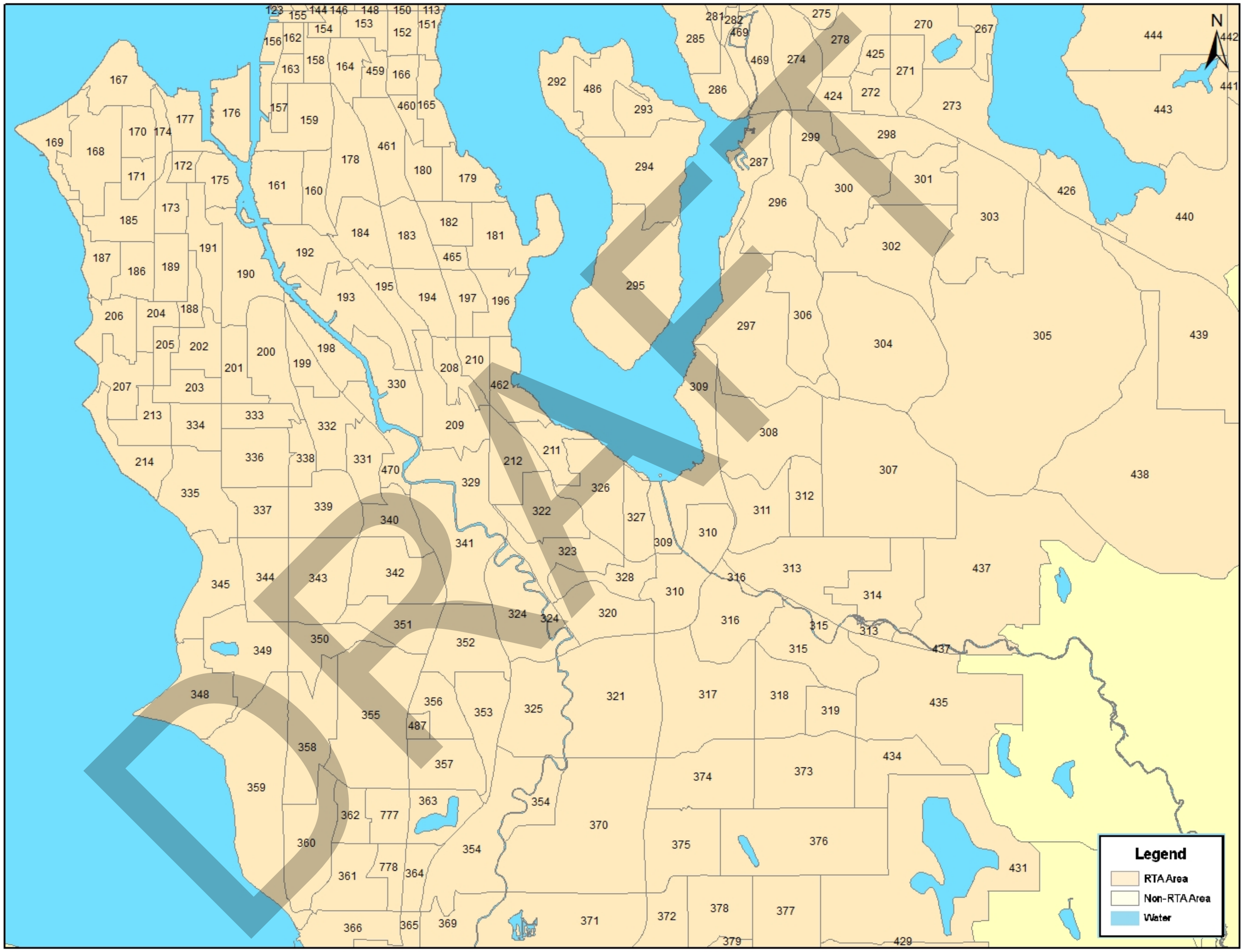

Figure A4e. 785 AAZ Map—Southeast/West Seattle

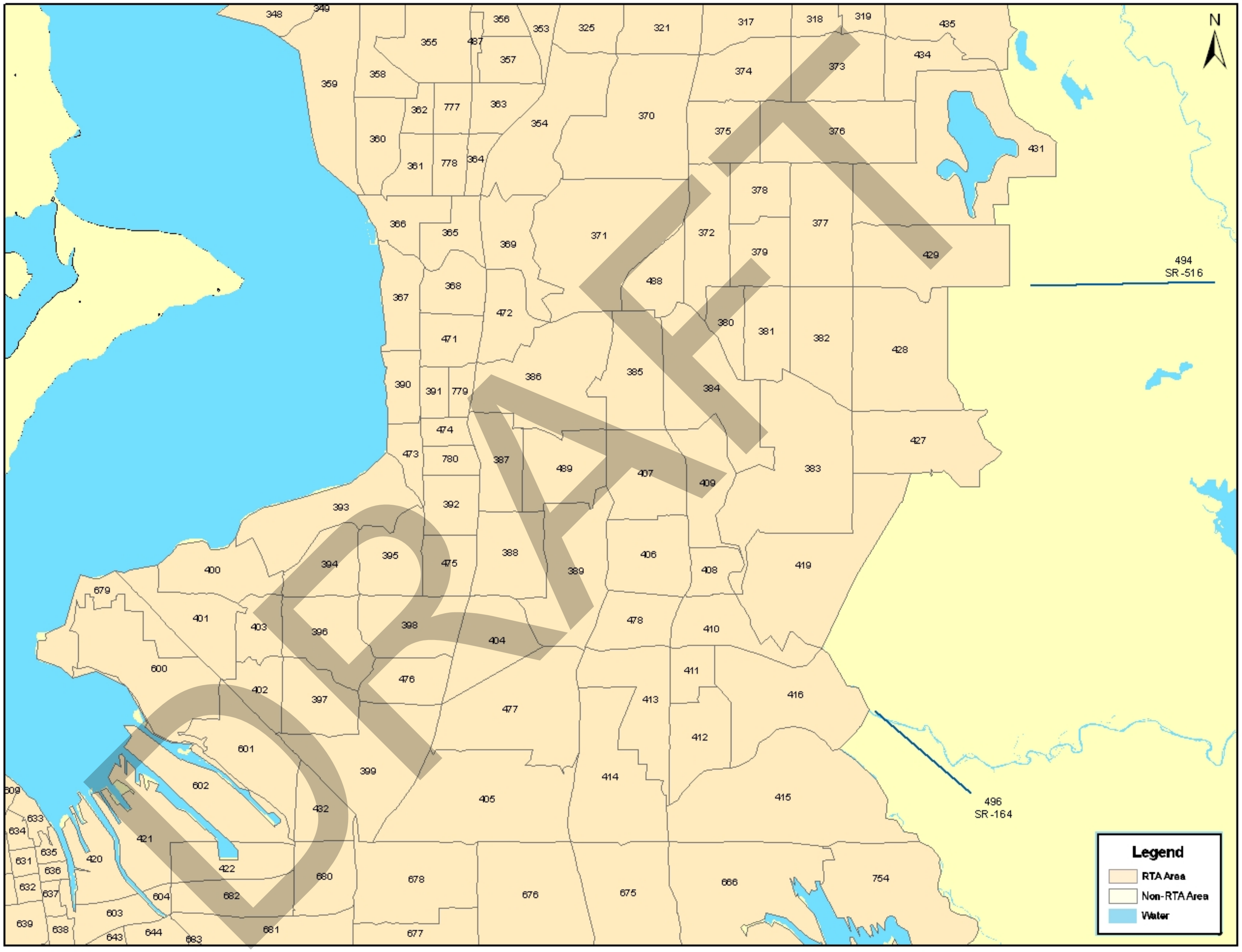

Figure A4f. 785 AAZ Map—South King County

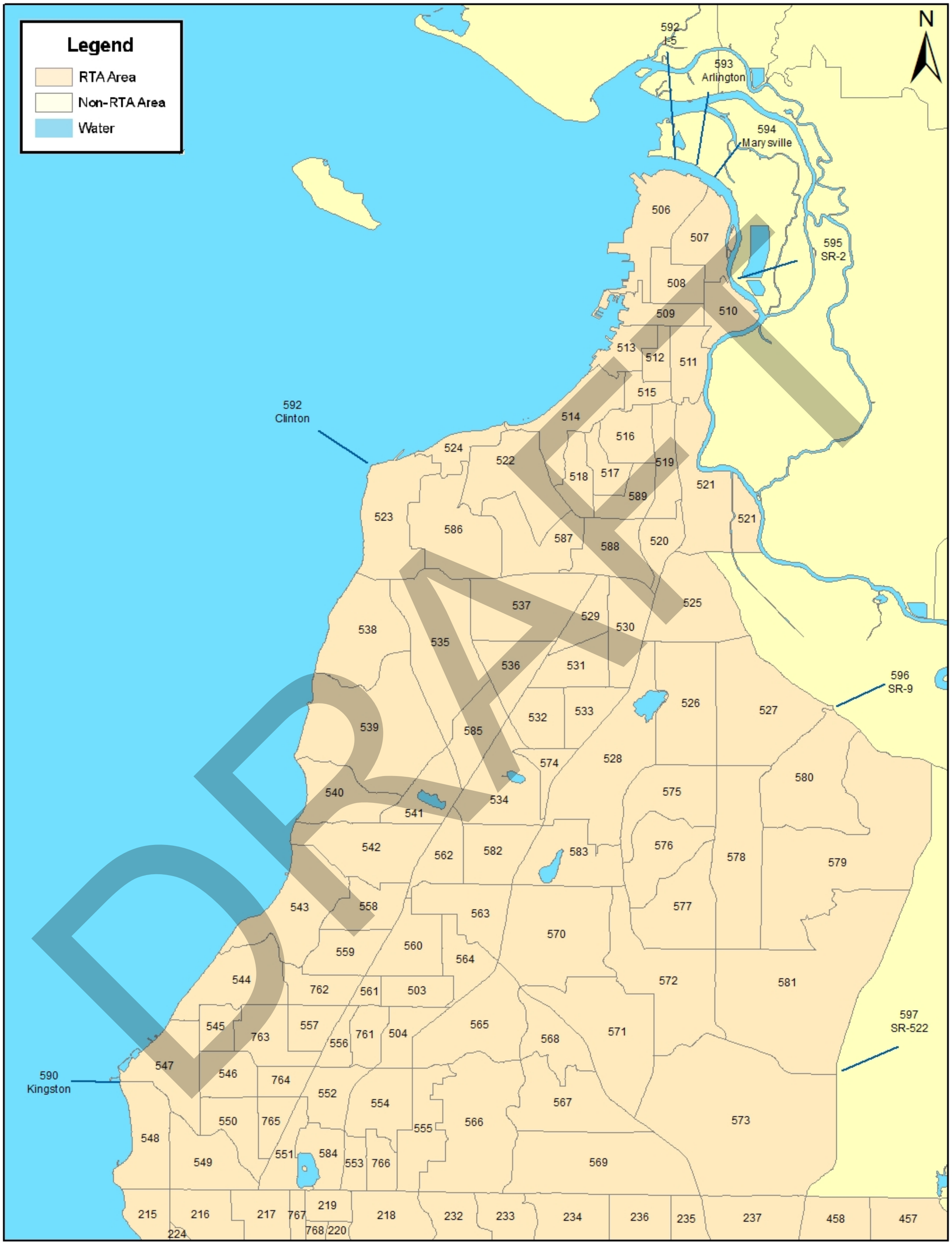

Figure A5. 785 AAZ Map—Snohomish County

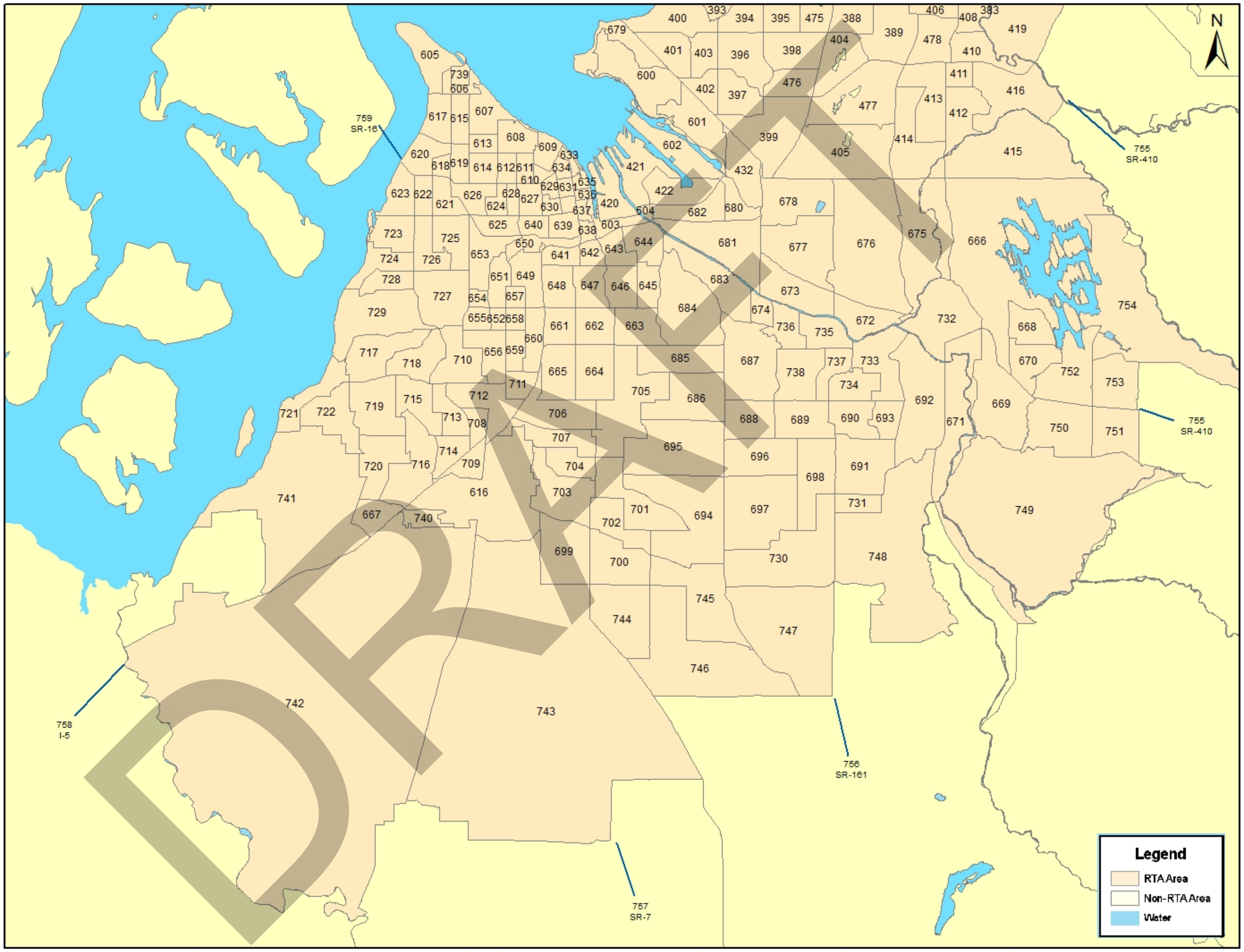

Figure A6. 785 AAZ Map—Pierce County

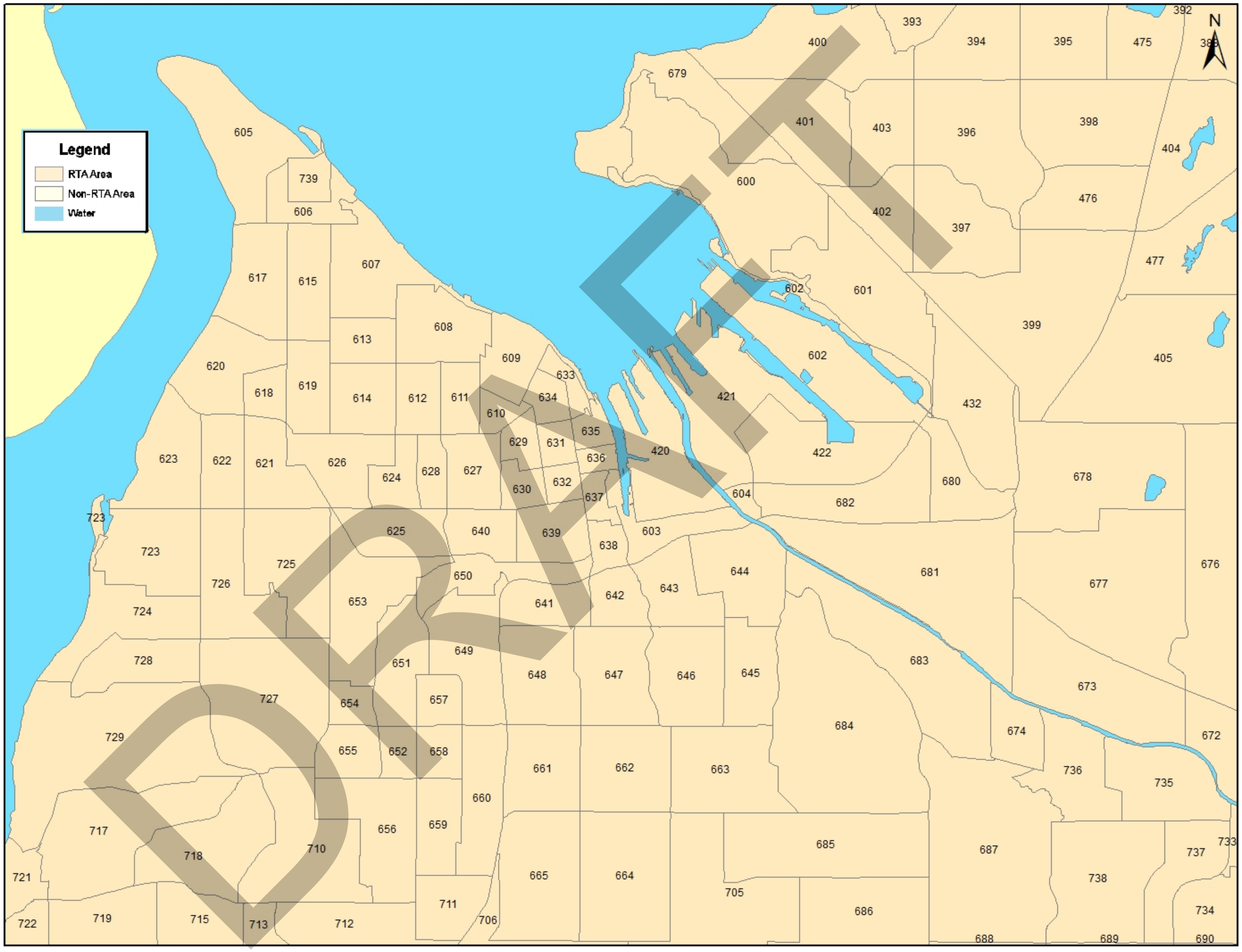

Figure A6a. 785 AAZ Map—Tacoma

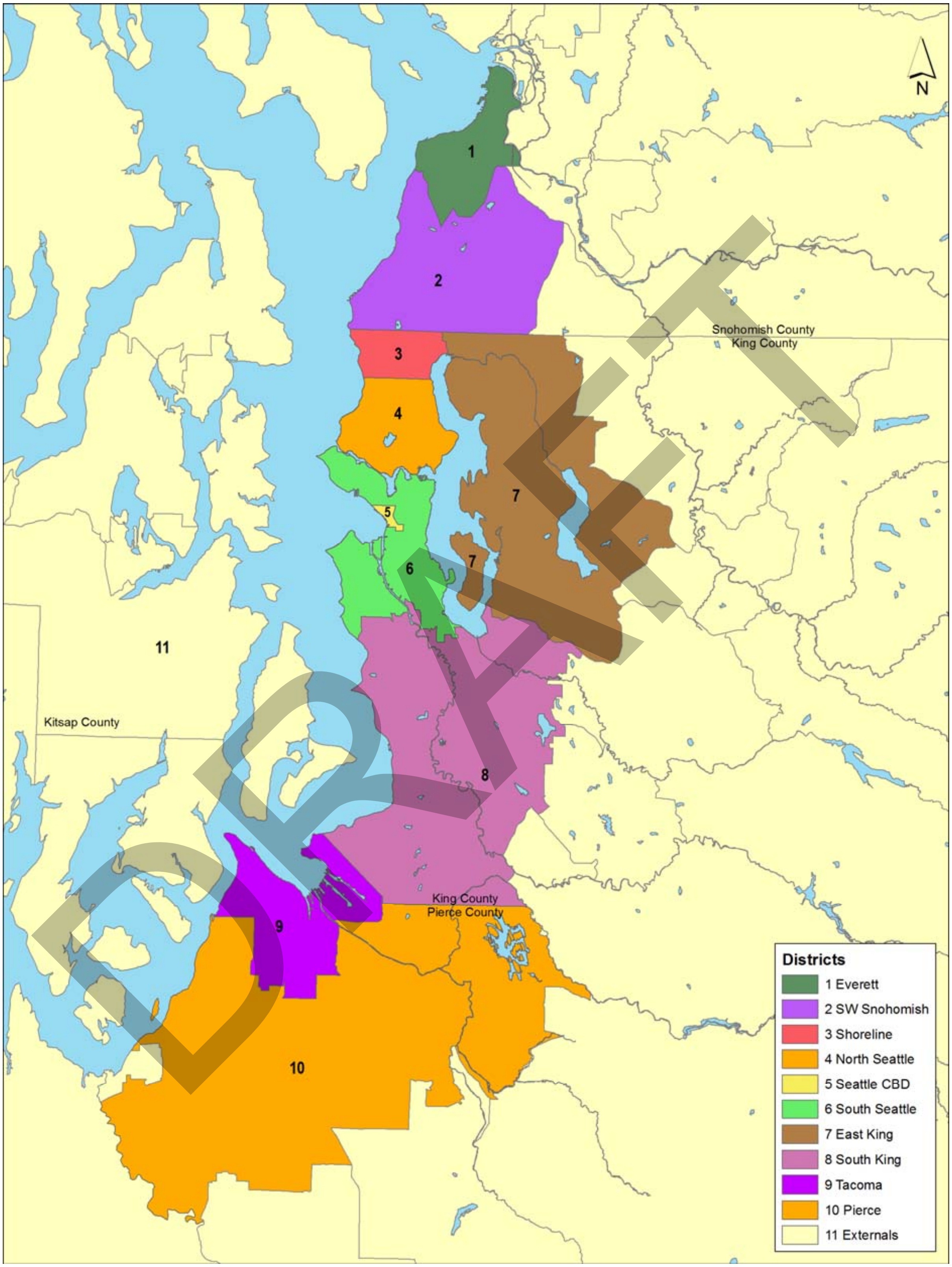

Figure A7. 11-district boundary map

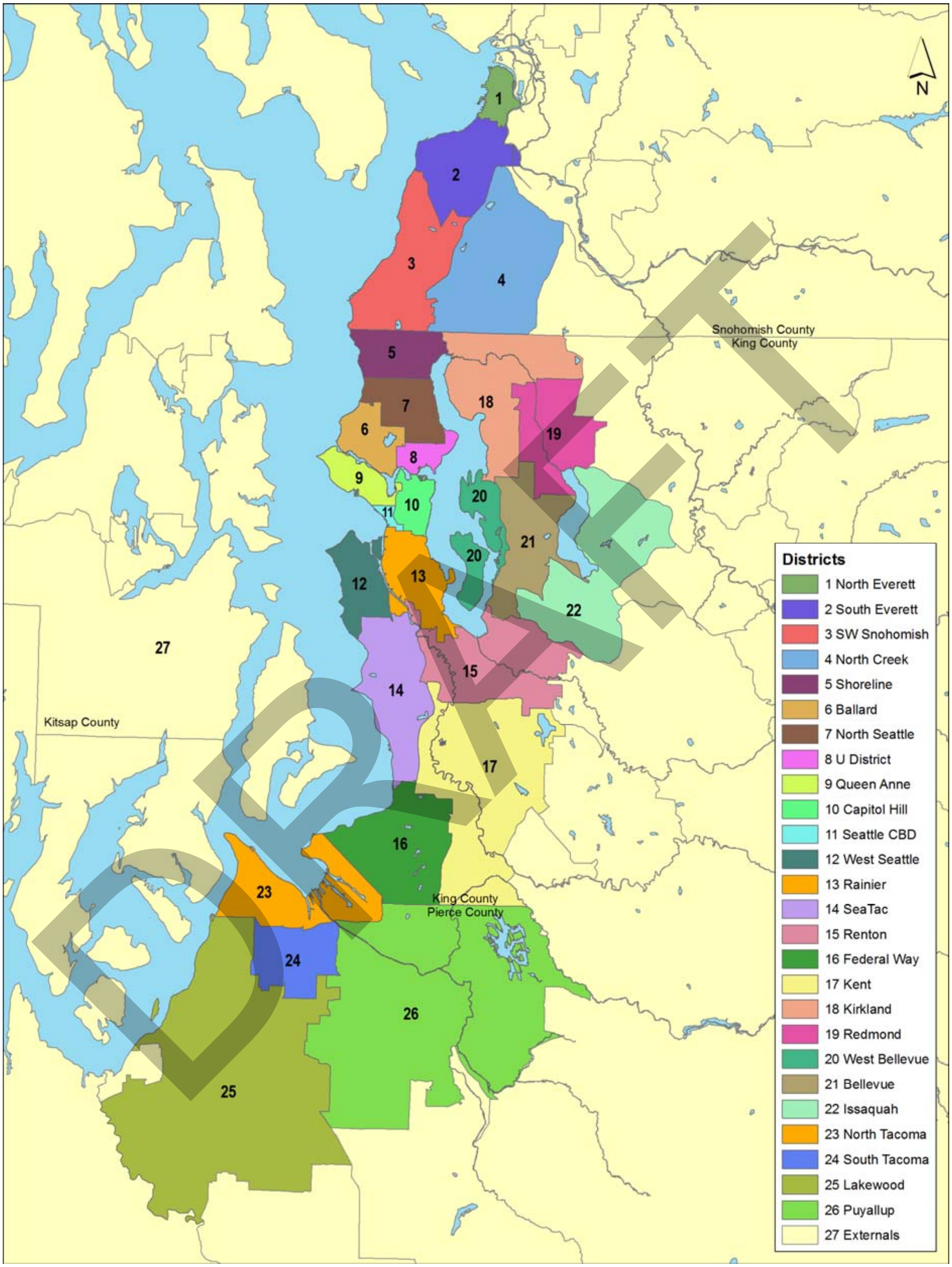

Figure A8. 27-district boundary map

Appendix B: Surveys

Appendix B: Surveys

This appendix includes a summary of the recent surveys which are available to supplement past surveys that were used in the initial development of the Sound Transit (ST) Ridership Model. The new surveys were geo-coded to the ST model alternatives analysis zonal system and analyzed to provide pertinent information in support of the ST model update (2012 version). This included information for development of the base year (2011) transit trip table, base shares, average trip length, trip purpose, and transfer rates.

B.1 Sound Transit surveys—2003 to 2012

B.1.1 ST survey—2003/2004

ST conducted an on-board survey of riders using Sounder Commuter trains and buses between September 2003 and May 2004. This survey yielded a variety of data, including route number, time period of trip, origin and destination locations, and an expansion factor. The data was subsequently sorted into usable and unusable records, each of which was assigned an origin and destination Alternative Analysis Zone (AAZ). Finally, expansion factors were revised to reflect the lower number of usable records.

Records were deemed unusable if they were missing x,y coordinates either for the origin or the destination. Table B1 summarizes the percentage of "usable" records.

Table B1. Usable records

Location (home end)	Bus	Sounder
Total records	10,386	2,618
Total usable records	6,867	1,966
% usable records	66%	75%

Some of the usable records had either an origin or destination that did not lie within the ST district but did lie within the PSRC region. These records were overlayed with the PSRC transportation analysis zones (TAZ) map and were assigned the corresponding PSRC TAZ. An equivalency table was then used to assign an appropriate external AAZ from the ST zonal system to these records. Table B2 summarizes the number of usable records by mode and time period.

Table B2. Usable Records by Mode and Time Period

Location (home end)	Bus	Sounder
AM total records	2,470	1,243
AM usable records	1,784	985
AM % usable records	72%	79%
PM total records	3,193	1,375
PM usable records	2,130	981
PM % usable records	67%	71%
Off-peak total records	4,723	n/a
Off-peak usable records	2,953	n/a
Off-peak % usable records	63%	n/a

B.1.2 ST survey—2009

ST conducted another on-board survey of riders using Sounder Commuter trains, ST Express bus routes, and Tacoma Link light rail in February and March 2009. Bus and commuter rail riders were surveyed between Tuesday and Thursday throughout the day, while Tacoma Link also included a Saturday survey. About 6,700 riders were approached for the survey with a total of 4,274 responding. This resulted in a response rate of 63 percent.

This survey yielded a variety of data, including route number, time period, origin and destination locations, as well as an expansion factor to expand from the surveyed sample to an average weekday. The data was subsequently sorted into usable and unusable records, each of which was assigned an origin and destination AAZ. Finally, expansion factors were revised to reflect the lower number of usable records.

Records were deemed "unusable" if they were missing x,y coordinates either for the origin or the destination. Table B3 summarizes the percentage of "usable" records. Only the records that have both origin and destination within the ST district are considered usable records.

Table B3. Usable records

Location (home end)	Bus	Sounder	Tacoma Link
Total records	2,771	1,078	425
Total usable records	2,027	847	186
% usable records	73%	79%	44%

The survey records were further classified based on the time of the day (TOD) the transit trip had taken place. This classification was necessary to use the survey data for ST modeling purposes. Three TODs were used for the classification purposes—AM period between 6 AM and 9 AM, PM period between 3 PM and 6 PM, and an off-peak period that represents all time periods that are not the AM or PM period. The distribution of trips for various ST services between these periods is shown in Table B4.

Table B4. Usable records by mode and time period

Location (home end)	Bus	Sounder	Tacoma Link
AM period (6 AM to 9 AM)	593	208	20
PM period (3 PM to 6 PM)	368	216	34
Off-peak period	1,066	423	132
Total daily	2,027	847	186

B.1.3 ST survey—2011

ST conducted a survey in October and November 2011 on weekdays during peak and off-peak periods. This survey was in support of the FTA Before-and-After Study for the Initial Segment light rail project. A sample of riders on Link light rail and King County Metro buses was surveyed. For each sampled trip, survey staff attempted to approach all passengers to distribute a survey form. Passengers could return the survey on-board, through postal mail, or complete a web-based survey. One component of the study was to investigate ridership characteristics of the project. To study these characteristics, ST undertook an on-board passenger survey to collect data about passenger trip characteristics, such as origins, destinations, fare payment, transfers, etc. This survey was processed and geo-coded to the ST model zonal system for further analyses that included opening of additional new cells in the base year trip tables.

Like the 2009 survey, the data contained demographic and travel information, plus expansion factors to expand the dataset to represent an average weekday on the routes surveyed. Only unweighted records were used for the ST model matrix estimation, since this expansion is performed through the matrix estimation process based on actual segment counts. Records were deemed “unusable” if they were missing x,y coordinates either for the origin or the destination. Additional analysis also resulted in rejection of some records if they did not meet certain criteria for reasonability. Records were also deemed unusable if either the origin or destination was not within the ST district. Table B5 summarizes the percentage of “usable” records.

Table B5. Usable unweighted records

Location (home end)	Records
Total records	12,978
Total usable records	8,737
% usable records	67%

The survey records were further classified based on the time of day (TOD) the transit trip had taken place. This classification was necessary to use the survey data for ST modeling purposes. Three TODs were used for the classification purposes—AM period between 6 AM and 9 AM, PM period between 3 PM and 6 PM, and an off-peak period that represents all time periods that are not the AM or PM period. The distribution of trips for various ST services between these periods is shown in Table B6.

Table B6. ST 2011 usable unweighted records by time period

Location (home end)	Records
AM period (6 AM to 9 AM)	2,033
PM period (3 PM to 6 PM)	2,384
Off-peak periods	4,320
Total daily	8,737

B.1.4 ST survey—2012

ST completed additional on-board surveys on ST bus routes, Sounder Commuter Rail, and Tacoma Link light rail in February 2012. These surveys were performed on two weekdays and one weekend day. The processed and geo-coded survey data for the Tacoma Link light rail was available for further analyses that included opening of additional new cells in the base year trip tables.

Similar once again to the 2009 ST Survey, the data contained demographic and travel information, plus expansion factors to expand the dataset to represent an average weekday. However, again only unweighted records were used, since this expansion is performed through the matrix estimation process based on actual segment counts. Records were deemed "unusable" if they were missing x,y coordinates either for the origin or the destination. Additional analysis also resulted in rejection of some records if they did not meet certain criteria for reasonability, and records were also unusable if either the origin or destination was not within the ST district. Both weekday and weekend records were used. Table B7 summarizes the percentage of "usable" records.

Table B7. Usable unweighted records

Location (home end)	Records
Total records	658
Total usable records	415
Total usable weekday records	295
% usable weekday records	45%

The survey records were further classified based on the time of the day (TOD) the transit trip had taken place. This classification was necessary to use the survey data for ST modeling purposes. Three TODs were used for the classification purposes—AM period between 6 AM and 9 AM, PM period between 3 PM and 6 PM, and an off-peak period that represents all time periods that are not the AM or PM period. The distribution of trips for various ST services between these periods is shown in Table B8.

Table B8. ST 2012 usable unweighted records by time period

Location (home end)	Records
AM period (6 AM to 9 AM)	83
PM period (3 PM to 6 PM)	85
Off-peak period	127
Total daily	295

B.2 Commute trip reduction surveys—2007 to 2014

In 1991, Washington State enacted the Commute Trip Reduction (CTR) Law in order to encourage alternatives to drive-alone commuting. This law requires employers with over 100 employees to develop and implement a CTR plan.

In order to measure employer and regional progress toward the stated goal of reducing single-occupant vehicle (SOV) trips, the CTR survey was developed to collect data about commute patterns and measure progress of each company toward its goals as well as progress toward area-wide goals. This survey is performed biannually for each employer, and the results are stored and analyzed by the Washington State Department of Transportation (WSDOT). This data source is unique to Washington State and is attractive as very rich replacement data for the U.S. Census Journey-to-Work (JTW) survey, which has not been performed since 2000.

B.2.1 CTR survey data collection

Employers subject to the CTR law are required to have their employees complete the CTR survey every other year. However, surveys are not done at the same time for all employers given the large number of respondents, so surveys are staggered over a two-year period.

The survey asks employees whether or not they commuted to work on each day of an ordinary work week (no public holidays during the week prior to or during the survey week) and, if so, what mode was primarily used for travel to work. The survey also asks respondents to estimate their one-way travel distance to work and provide their home zip code as well as answer questions about carpooling, paid parking, and drive-alone commuting. Because the surveys are coded to the address to which the employee reports to work, the data represents a very complete geography of home-to-work travel. The CTR data is collected by each county but ultimately resides in a database maintained by WSDOT and is freely available for public use.

B.2.2 Analysis process

CTR data was consolidated for King, Snohomish, and Pierce counties for several survey cycles: 2007–2008, 2009–2010, 2011–2012, and 2013–2014. The general approach was to use survey responses to build an origin-destination (O-D) table for all commuters as well as the transit travel flow matrix.

Unlike former data sources, such as JTW census survey where the home address is known and the workplace location may be vague, the CTR dataset is unique in that the workplace addresses are well-known and are specifically report-to-work locations. On the other hand, respondent home addresses are only at the ZIP code level. To disaggregate home ZIP codes to TAZs, trips occurring at the ZIP code level were disaggregated based upon the distribution of households over the ZIP code, implying an assumption of similar travel characteristics between households in a ZIP code. Household information at the census block level was used to perform this disaggregation in ArcGIS through geospatial analysis. Workplaces were also mapped by their coordinates (provided by WSDOT) in ArcGIS to determine within which TAZ each worksite is located, thus obtaining the destination TAZ. Individual survey responses were then used to fill the O-D table for a typical workday.

This data is used to enrich base year transit trip tables to include new non-zero cells as well as a new database for establishing base year transit shares. Since results from several survey cycles were used, elimination of repeated observations was important.

Generally, the latest survey cycle was used for each employer while discarding most survey results from previous cycles. However, previous cycles with response ZIP codes that were not observed in later survey cycles are preserved since they represent unique trips that were not observed. This is done to maximize the number of non-zero cells in the O-D table. This is considered reasonable since it is likely that such ZIP codes went unobserved in subsequent years because the respondent moved but remained with the same employer or the respondent transferred employers. In either case, the travel characteristics for each trip are different given the different origin and/or destination, so it is no longer a repeated observation.

B.2.3 General results

Table B9 provides results for the analysis of the 2007-2014 combined dataset. Non-motorized modes, such as walking and biking, were removed from consideration as commute modes in order to be consistent with the ST model. This shows that in the Puget Sound region, the overall transit mode share (excluding non-motorized trips) for CTR survey respondents is 20.3 percent.

Table B9. Summary of surveyed CTR commute and transit travel

	All commute modes	Non-motorized modes	Commute modes (excluding non-motorized)	Transit mode
Total surveyed CTR trips	1,553,560	59,225	1,494,335	256,857
Average weekday surveyed CTR trips	310,712	11,845	298,867	51,371
Surveyed trips allocated to O-D table	1,170,438	47,501	1,106,083	237,394
Average weekday allocated trips	234,088	9,500	221,217	47,479
% surveyed trips not allocated to O-D table	24.66%	19.80%	25.98%	7.58%

Transit is defined as bus, train, light rail, streetcar, or walking on a ferry

B.3 American Community Survey—2006–2010

Historically, the U.S. Census JTW data was provided as part of the Census Transportation Planning Package (CTPP), put together using the Census Bureau long form survey. After the final JTW survey in 2000, the Census long form was replaced by the American Community Survey (ACS). The ACS provides up-to-date planning data for communities on an annual basis, but is a much smaller sample than the JTW. Every month, the ACS is distributed to a sample of residences around the country—about 1 in 40 households annually. From the survey responses, the Census Bureau produces three ACS data series: *one-year, three-year, and five-year estimates*. ACS data are accumulated and released once a year for large geographic places (those with 65,000 people or more); however, this yearly data release does not include any worker flow information. Further information about ACS can be found in a document provided by PSRC.[1]

The FHWA has used the ACS to extract three-year and five-year CTPP worker flow estimates, reflecting 2006–2008 and 2006–2010, with the latter released in October 2013. The worker flow estimates are provided at most all geographies, including State, County, Census Place, and TAZ geographies from "Home-to-Work." The TAZ-to-TAZ flows cannot be directly used to calculate TAZ-level or FAZ-level base year transit shares because the sample size is too small to estimate values with sufficient confidence levels.

Upon further examination and analyses, transit shares produced from the available CTPP five-year estimates were deemed to be useful as long as an appropriate geographic aggregation level was maintained to minimize sampling error. Transit shares calculated at the 6-district level provided this sufficiently high confidence level. District-level shares from ACS data were used to scale the zonal transit shares from the CTR survey, neutralizing the large-employer sample bias in the CTR data. Additionally, the TAZ-to-TAZ flows were used to identify new non-zero cells in the base year trip table.

B.4 Survey of SR 520 riders—2005

A special survey of SR 520 riders was conducted by Northwest Research Group, Inc., in May 2005. This survey provided 944 usable O-D records, of which 217 zone-pairs were not represented before in other surveys.

B.5 PSRC household activity and travel survey—2006

In 2006, PSRC undertook a survey to obtain region-wide information on household activities and the travel these activities generate. It surveyed about 4,700 households during a consecutive 48-hour time period.

[1] http://psrc.org/assets/1030/ACS_User_s_Guide_Dec-08.pdf

B.6 ORCA smart card fare payment database

The ORCA card is a smart card technology to allow transit users to easily pay fares by tapping the card against an electronic card reader. The card enables seamless transfers between transit systems thanks to revenue-sharing agreements between transit agencies in the region. Transit users are incentivized to use the card instead of cash since they receive free or discounted transfers between agencies only if they use an ORCA card. The ORCA card allows for enhanced data collection as well, since the particular route, time of boarding, and transfers are logged; additionally for rail, both the boarding and alighting locations are also logged.

The ORCA database is expected to provide useful information for a future ST model update. This dataset can be used to provide insights into the percentage of transfers, both at a systemwide level as well as for particular agencies or technologies (e.g., transfers to and from Link light rail and Washington State Ferries). ORCA information can also be used to augment O-D information used to develop the seed matrix for ridership forecasting by noting the origin and destination of each rail trip. Finally, the ORCA dataset provides a partial illustration of revealed transit ridership against which the model results may be compared in order to implement refinements to the model.

Appendix C: Highway Model

- Overview
- Network Refinements
  - –Base Year
  - –Future Baseline
- Validation Results

Appendix C: Highway Model

The Sound Transit (ST) highway model is a version of the PSRC regional travel forecasting model and provides key inputs into the ST incremental transit ridership model. It also provides key performance measures, as highlighted in Figure C1, which shows the relationship between the ST incremental transit ridership model and the PSRC regional travel forecasting model, along with other related processes. This appendix discusses the background of this highway model and highlights efforts to improve the results from the model to best reflect observed conditions and provide quality inputs into the ST model. This includes presentation of some base year validation results.

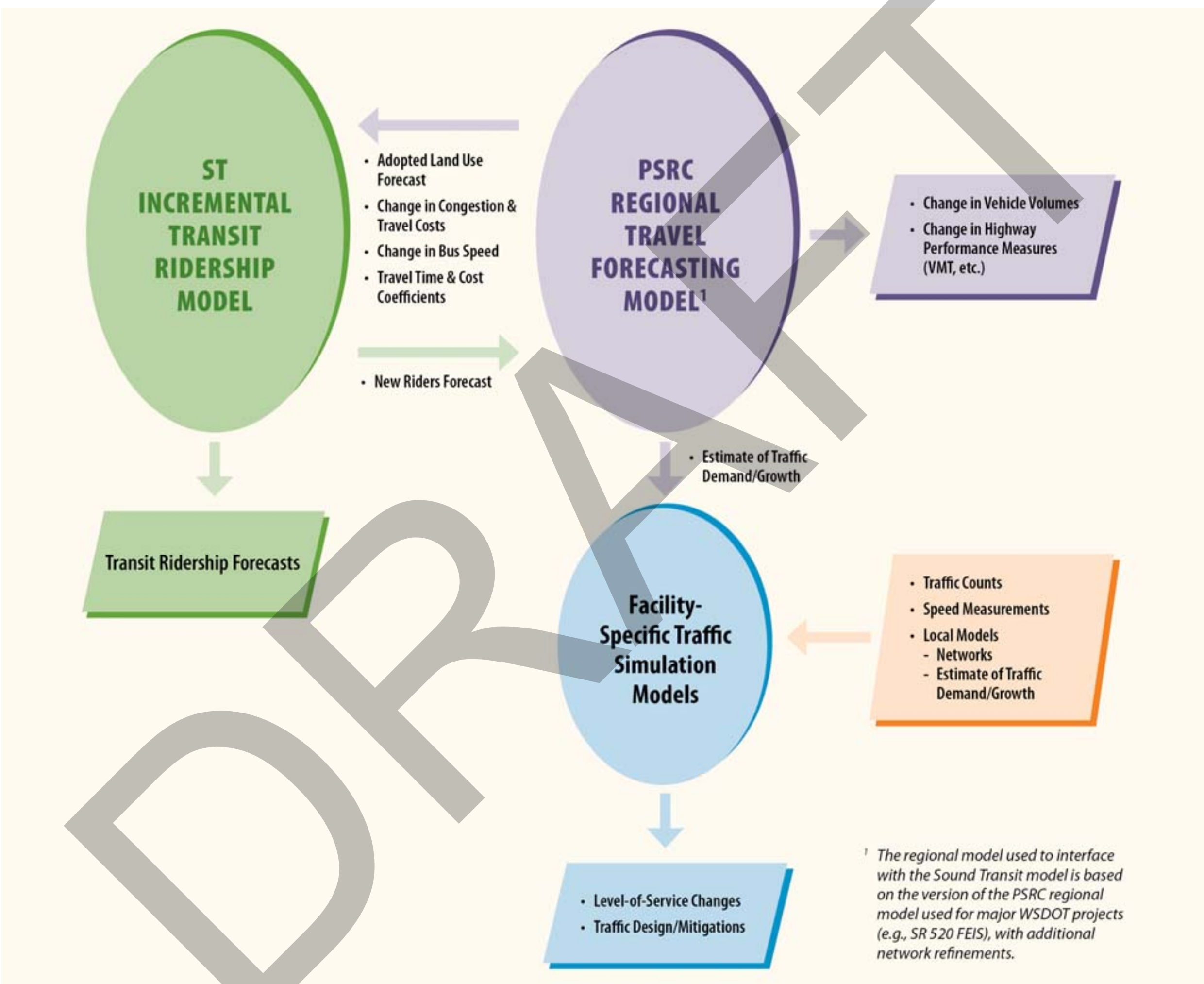

Figure C1. ST incremental transit ridership and PSRC regional models relationship

C.1 Overview

The Sound Transit highway model is based on the model used for the SR 520, I-5 to Medina: Bridge Replacement and HOV Project Final EIS. Experience from the modeling of the Alaskan Way Viaduct (AWV) and Seawall Replacement Program as well as observations and data regarding the operation of facilities in the ST area have provided insight to guide enhancements to the model for the Lynnwood Link Extension.

The SR 520 model is based on the most recent version of the region's planning model, PSRC model version 1bb. Development of the PSRC model is documented in *PSRC Travel Model Documentation (for Version 1.0), Updated for Congestion Relief Analysis* (PSRC 2007b). This version of the PSRC model has been adopted by WSDOT for use on several projects, including environmental impact analyses and other planning and tolling studies. The SR 520 model was developed to incorporate network and procedure modifications that were used in other local modeling efforts in Seattle, Bellevue, Kirkland, and Redmond. These updates allowed this model to represent traffic conditions with relative accuracy, particularly conditions on I-90 and SR 520 across Lake Washington and other facilities that connect to them. Further detail on the model development and validation are documented in *SR 520 Bridge Replacement and HOV Program Final FEIS Travel Demand Model: Base Year Validation Analysis Tech Memo* (Parsons Brinckerhoff 2010). The SR 520 model has also been used by WSDOT for various toll studies, including SR 167, SR 509, and I-5 express lanes.

The model used for the AWV Replacement Project Final EIS is based on the City of Seattle model, which is also based on the most recent version of the PSRC model. This model contains greater detail of the highway network and zones within the City of Seattle. Nearly a decade's worth of knowledge learned from demand modeling, operational analysis, and field observations allowed this model to perform quite well, particularly for downtown Seattle and surrounding areas. Details on the model development and validation are documented in *Alaskan Way Viaduct & Seawall Replacement Program Travel Demand Model Refinement and Validation Report* (2010).

As part of the ongoing analysis for the SR 99 tunnel toll traffic and revenue analysis, a Dynamic Traffic Assignment (DTA) model has been created to analyze traffic and revenue that would be affected by tolling of the new tunnel. The mesoscopic DTA model provides a level of detail between a demand model and operational models, while still using the zonal system from the City of Seattle model.

Using the above model background information, the ST highway model incorporated network attributes and model procedures that would provide the best representation of travel conditions within the ST area. In addition to knowledge provided from these models, additional review of network attributes and existing roadway conditions was performed in proximity to the Lynnwood Link Extension corridor to provide additional updates that might not necessarily have been included in the focus of other recent modeling efforts.

C.2 Network refinements

C.2.1 Base year

Highway network

While many adjustments to Central Seattle and major facilities across Lake Washington had been made as part of the SR 520 Final EIS and the AWV Final EIS, additional changes were made throughout the model, including within the ST area, to better reflect congestion for automobiles and transit. To better reflect existing roadway configurations, the model link attributes were compared to actual conditions. Appropriate adjustments to speed, capacities, and congestion factors were made accordingly including, but not limited, to the following:

- **Arterial speeds**—The model free-flow speeds were compared to the posted speeds in major corridors, and model speeds were adjusted to match those legal speeds.
- **Arterial capacities**—Major arterials in corridors of interest to ST were reviewed for unusually high or low lane unit capacities, and a check was performed for the number of lanes. Capacity assumptions were decreased at some locations, particularly where signalized intersections would constrain capacities, as also reflected in the observed traffic counts. Capacities for other facilities were increased in conjunction with recent lane changes and roadway rechannelizations. The numbers of lanes were adjusted to match actual roadway configurations, including time-of-day parking restrictions and additional cycle lanes.
- **Freeway capacities**—Freeway capacities were reduced by up to 200 vehicles per hour per lane region-wide to better reflect maximum observed traffic counts. This was performed in areas where this had not already been performed for the project EIS work for WSDOT described above.
- **Reversible lanes**—The reversible lanes on I-5 have greater observed peaking characteristics and low usage in off-peak periods while also frequently having one or two congested lanes with adjacent lanes operating at free-flow speeds. The model volume delay function for this facility was adjusted to reflect both peaking and how the speeds change at different volume levels than on the I-5 mainline.

Transit network

The base year transit network in the ST ridership model was used as a guide to update the base transit network in the ST highway model.

Additional refinements

In addition to refinements to the base year network, a number of other refinements were made to the SR 520 model. These refinements include:

- **Time-of-day functionality**—PSRC relies on a choice-based time-of-day procedure. This procedure has been oversensitive for corridors where congestion reaches an oversaturation condition, such as the cross-lake and North Corridor market areas. For example, trips in higher volume corridors shift from the morning period to the night period. For the purpose of mitigating oversensitivity to congestion and thus having a more stable highway model, the choice-based time-of-day procedure was replaced with the traditional time-of-day constant factors. This change in the highway model is believed to provide better estimates of deltas in congestion level and highway performance measures (such as vehicle hours of travel and vehicle miles of travel) as required for the interface with the ST model. This change is also consistent with the SR 520 FEIS model and better reflects observed vehicle volumes. Use of this model for other WSDOT projects has often relied on the PSRC variable time-of-day procedure.
- **Peak hour factors**—A comparison of observed peak hour counts to peak period model volumes showed different peaking characteristics in the north corridor than closer to Seattle or across Lake Washington. Therefore, the peak hour factors in the model volume delay functions were adjusted to reflect observed counts. While the factors were different in the SR 520 FEIS model, that model included factors that reflected peaking within that project's study area.
- **HOV cost sharing**—Traditionally, regional models assume that travel costs are split equally among occupants for vehicles with two or more occupants. This assumption was modified in the ST highway model to reflect anecdotal observations that travel costs may not be equally shared among family members who travel together in one vehicle. Travel costs are split based on using *1/ln(1+average number of*

occupants)[1] for both work and non-work trip purposes. Specifically, total travel costs are factored by 0.91 for two-occupant auto vehicles, 0.66 for auto vehicles with three or more occupants, and 0.88 for auto vehicles with two or more occupants.

C.2.2 Future baseline

The future baseline for the highway model includes several major and minor highway and transit projects that were defined in PSRC's *Transportation 2040* Preferred Alternative (Constrained) network. This network, therefore, includes some projects that are planned but not funded. A single baseline network is used for the transit no-build and build alternatives since none of the build alternatives significantly affect the design of any roadways.

Highway projects

Several major highway projects were included in the future baseline highway model. These projects include the SR 99 tunnel in downtown Seattle, SR 520 bridge replacement and widening across Lake Washington, Mercer Street corridor reconstruction just north of downtown Seattle, I-405 corridor completion, and implementation of tolling on all of the region's freeways by 2040. The regional toll assumption is an important new assumption from the PSRC and, as described by PSRC, is presumed as congestion relief tolling rather than revenue maximization tolling.

Transit projects

Transit changes significant enough to affect regional highway demand levels were also included in the 2040 baseline highway model as background for the transit analysis. The 2040 highway model assumes that the ST Link light rail network extends from Kent-Des Moines Road in the south to Lynnwood Transit Center in the north and Overlake Transit Center to the east. Bus routes and frequencies were adjusted to reflect updated connections to light rail service as well as King County's RapidRide arterial BRT service and Community Transit's Swift arterial BRT service. Additionally, the First Hill streetcar in Central Seattle, scheduled to begin service in 2015, is included.

Demographic forecasts

The ST highway model uses the Land Use Targets forecasts released by PSRC in April 2014. The Land Use Targets forecast[2] is a long-range land use dataset designed explicitly to represent local growth targets that are adopted under state Growth Management Act requirements.[3] It is developed using a set of allocation "decision rules" that distribute jurisdictional growth targets to sub-jurisdictional zones based on (a) available net development capacities and (b) a series of policy-based preferential weights for certain zones, such as designated regional growth centers and other locally defined activity centers.

C.3 System Tolling and Delay

Transportation 2040 assumes tolling all vehicles using all lanes (including HOV lanes) on all limited access facilities in the four-county region. The intent is to set tolls by time of day and direction of travel at levels sufficient to minimize congestion and maintain good traffic flow without unnecessarily diverting traffic to other facilities. PSRC models have been adapted to set tolls within the model that minimize overall network

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[1] Dehghani, Y., Adler, T., et al, "Development of New Toll Mode Choice Modeling System for Florida's Turnpike Enterprise," Transportation Research Board Record #1858, 2003.
[2] www.psrc.org/assets/9017/Methodology Workbook.xlxs.
[3] Revised Code of Washington 36.70A.

travel times.[4] This procedure was implemented in the version of the PSRC travel demand model that is in use for WSDOT project planning and tolling analysis.

Too small to measure

Recent sensitivity tests on the tolling features of the model indicate that regional tolling definitely affects transit ridership, causing increases of about 5 percent in 2040 regional totals. However, the same tolling features of the model mean that differences in transit ridership among 2040 transit scenarios would have to be extreme in order to affect highway delay in the model. When variable-rate tolling is assumed, any differences in delay for highway users related to transit ridership changes are simply too small to measure.

Bus speeds

Historically, the ST transit ridership model has used estimates of long-term speed degradation from the PSRC highway model in order to slightly reduce future bus speeds. This degradation typically was in the 7- to 9-percent range per decade, depending on the location and type of highway segment used by the bus route. The historical justification for this approach included review of actual bus operating speeds over the four decades from about 1960 to 2000; degradation of about 9 percent per decade was observed. HOV lanes and other protected bus paths have always been exempted from this method in application.

The speed degradation factors from the PSRC model have been noticeably less pronounced over recent applications of the model. Application of this method today is yielding degradation rates in the 2- to 5-percent per decade range. There is no defensible reason to change the modeling procedure in current applications of the ST transit model, as this lower degree of speed degradation may be realistic.

BRT routes, where arterial route segments are likely to be barrier-separated and grade-separated, are treated identically to rail lines in the ST transit model. That is, the speeds are entered directly on the links, with the addition of reasonable times for deceleration/dwell/acceleration at proposed stops.

Where BRT and ST Express routes are described as operating on limited access facilities, bus speeds are treated the same as existing bus route segments in similar situations since HOV lanes are open to all vehicles and tolled in 2040. That is, the bus speeds are exempted from speed degradation calculation, even if the routing requires weaving across unprotected lanes to reach stops or ramp locations, as the modeling of the tolling strategy limits changes to speeds on freeway segments.

A wide variety of existing BRT-type stopping situations are available within the existing regional bus network for inference of these specified travel times. While there is always a risk of over-optimism in the modeling of BRT operations for ridership estimation, careful reference to existing situational experience with actual bus speeds and station-to-station times reduces this risk.

C.4 Validation results

The focus of the validation analysis was to improve the highway model's performance for areas critical to ST3 system planning.

Base year screenline total vehicle volumes comparison

Model-estimated vehicle volumes were compared to recent observed traffic counts on arterials and highways across the Plan area. The screenlines that were used are shown on the map in Figure C2. As seen in Table C1

[4] "Puget Sound Regional Council Transportation Pricing Alternatives Study—Technical Memorandum 3 Simulating Congestion Pricing," issued by PSRC, February 19, 2000.

through Table C3 the estimated screenline total volumes are mostly within 10 percent of observed during the peak hours and over the entire day.

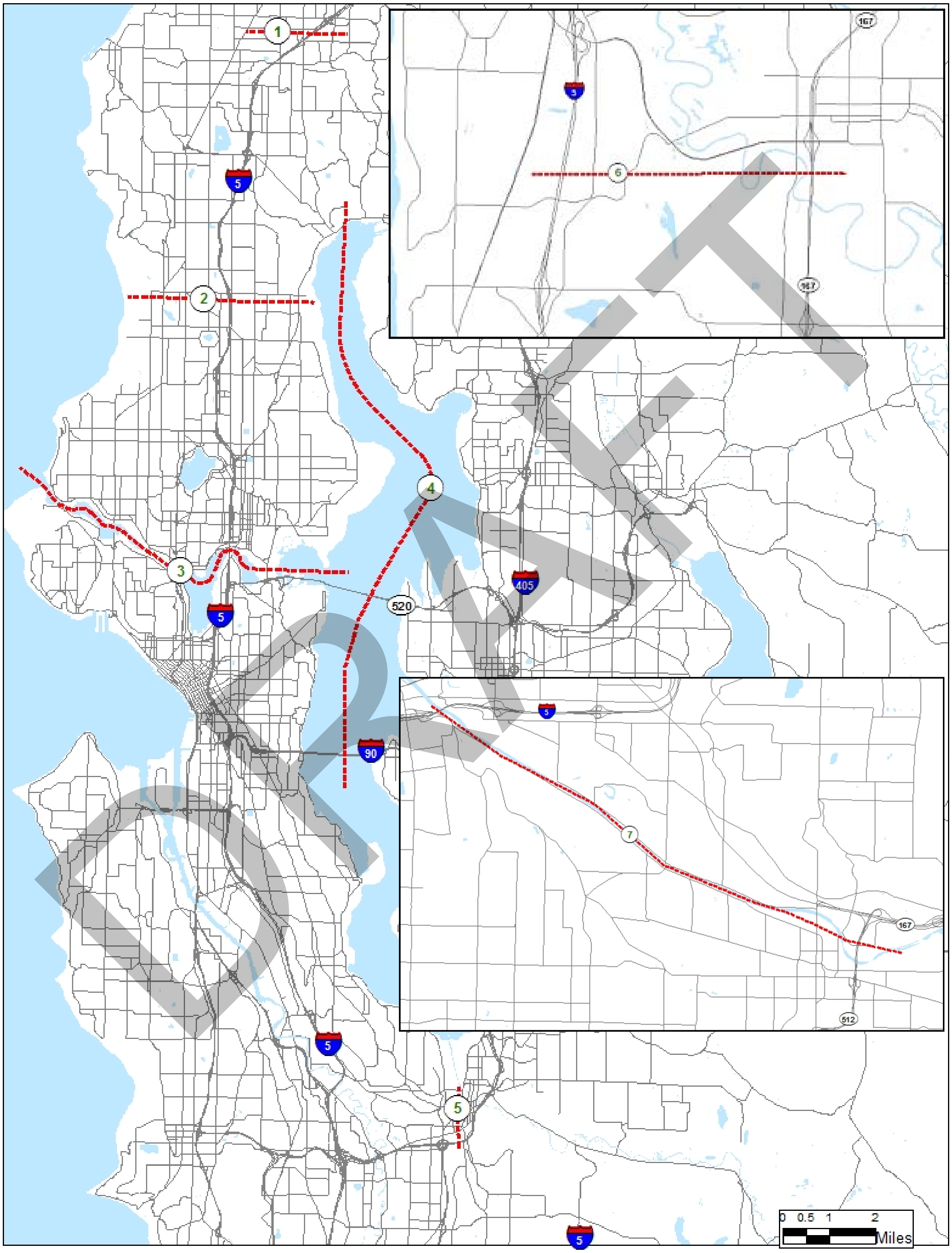

Figure C2. Highway screenlines map

Table C1: Base year (2014) screenline total vehicle volume comparison (AM peak hour)

	Actual volumes			Estimated volumes			
	NB/WB	SB/EB	Total	NB/WB	SB/EB	Total	Est/ Act
Screenline 1 – South of 196th Street SW							
SR 99	1,050	1,980	3,030	1,100	2,200	3,300	1.09
44th Avenue W	600	760	1,360	600	1,200	1,800	1.32
I-5 (all lanes)	4,880	6,530	11,410	3,900	7,300	11,200	0.98
Screenline Total			**15,800**			**16,300**	**1.03**
Screenline 2 – South of N 145th Street							
3rd Avenue NW	371	364	735	0	400	400	0.54
Greenwood Avenue N	636	974	1,610	700	1,400	2,100	1.30
SR 99	1,098	1,357	2,455	500	2,100	2,600	1.06
Meridian Avenue N	98	209	307	0	200	200	0.65
I-5 (all lanes)	5,280	8,270	13,550	4,800	9,200	14,000	1.03
5th Avenue NE	208	220	428	300	700	1,000	2.34
15th Avenue NE	400	917	1,317	300	1,300	1,600	1.21
20th Avenue NE	80	80	160	0	100	100	0.63
30th Avenue NE	181	292	473	0	500	500	1.06
SR 522	1,075	2,278	3,353	1,100	2,100	3,200	0.95
Screenline Total			**24,388**			**25,700**	**1.05**
Screenline 3 – Ship Canal							
Ballard Bridge	1,840	2,950	4,790	1,000	2,100	3,100	0.65
Fremont Bridge	966	1,188	2,154	1,400	2,000	3,400	1.58
SR 99	2,540	4,740	7,280	2,100	3,700	5,800	0.80
I-5 (all lanes)	6,130	11,970	18,100	6,900	12,800	19,700	1.09
University Bridge	763	1,357	2,120	1,000	1,400	2,400	1.13
Montlake Bridge	1,985	2,066	4,051	2,200	1,900	4,100	1.01
Screenline Total			**38,495**			**38,500**	**1.00**
Screenline 4 – Midlake							
SR 522	1,210	1,950	3,160	2,000	2,000	4,000	1.27
SR 520 (all lanes)	3,000	3,360	6,360	3,000	2,000	5,000	0.79
I-90 (all lanes)	7,180	5,380	12,560	7,900	5,500	13,400	1.07
Screenline Total			**22,080**			**22,400**	**1.01**
Screenline 5 – East of SR 167/Rainier Avenue							
I-405 (All lanes)	4,600	4,980	9,580	5,400	6,500	11,900	1.24
Airport Way	1,300	1,530	2,830	1,000	1,700	2,700	0.95
S 2nd Street	670	NA	670	900	NA	900	1.34
S 3rd Street	NA	520	520	NA	700	700	1.35
S 7th Street	610	230	840	200	700	900	1.07
S Grady Way	1,760	1,340	3,100	1,000	1,300	2,300	0.74
Screenline Total			**17,540**			**19,400**	**1.11**
Screenline 6 – South of SR 516 (Kent-Des Moines Road)							
SR 99 (all lanes)	1,470	520	1,990	3,600	800	4,400	2.21
I-5 (all lanes)	8,870	5,150	14,020	9,800	4,700	14,500	1.03
SR 167 (all lanes)	5,020	3,360	8,380	6,200	2,900	9,100	1.09
Screenline Total			**22,400**			**23,600**	**1.05**
Screenline 7 – At Puyallup River							
I-5 (All lanes)				8,600	5,900	14,500	
SR 167 (All lanes)				1,900	800	2,700	
SR 512 (All lanes)				4,100	2,400	6,500	
Screenline Total						**23,700**	

Table C2: Base year (2014) screenline total vehicle volume comparison (PM peak hour)

	Actual volumes			Estimated volumes			
	NB/WB	SB/EB	Total	NB/WB	SB/EB	Total	Est/Act
Screenline 1 – South of 196th Street SW							
SR 99	2,400	1,390	3,790	2,100	1,400	3,500	0.92
44th Avenue W	1,190	870	2,060	1,200	900	2,100	1.02
I-5 (all lanes)	6,670	6,050	12,720	6,800	4,800	11,600	0.91
Screenline Total			**18,570**			**17,200**	**0.93**
Screenline 2 – South of N 145th Street							
3rd Avenue NW	481	392	873	300	0	300	0.34
Greenwood Avenue N	1,253	836	2,089	1,300	1,000	2,300	1.10
SR 99	1,722	1,172	2,894	2,000	1,200	3,200	1.11
Meridian Avenue N	320	166	486	100	100	200	0.41
I-5 (all lanes)	8,420	5,500	13,920	8,700	5,900	14,600	1.05
5th Avenue NE	340	210	550	700	500	1,200	2.18
15th Avenue NE	896	642	1,538	1,300	600	1,900	1.24
20th Avenue NE	110	70	180	100	100	200	1.11
30th Avenue NE	438	210	648	500	100	600	0.93
SR 522	1,739	1,422	3,161	2,000	1,600	3,600	1.14
Screenline Total			**26,339**			**28,100**	**1.07**
Screenline 3 – Ship Canal							
Ballard Bridge	3,200	2,010	5,210	2,200	1,900	4,100	0.79
Fremont Bridge	1,650	1,176	2,826	2,100	1,900	4,000	1.42
SR 99	4,800	3,650	8,450	4,100	3,500	7,600	0.90
I-5 (all lanes)	11,520	6,390	17,910	12,700	7,500	20,200	1.13
University Bridge	1,265	1,642	2,907	1,700	1,900	3,600	1.24
Montlake Bridge	2,249	2,160	4,409	2,100	2,400	4,500	1.02
Screenline Total			**41,712**			**44,000**	**1.05**
Screenline 4 – Midlake							
SR 522	2,300	1,480	3,780	1,900	2,000	3,900	1.03
SR 520 (all lanes)	3,340	2,480	5,820	2,700	2,800	5,500	0.95
I-90 (all lanes)	5,000	6,990	11,990	6,200	7,900	14,100	1.18
Screenline Total			**21,590**			**23,500**	**1.09**
Screenline 5 – East of SR 167/Rainier Avenue							
I-405 (All lanes)	5,510	4,670	10,180	6,200	6,000	12,200	1.20
Airport Way	1,410	1,690	3,100	1,800	1,200	3,000	0.97
S 2nd Street	700		700	0	900	900	1.29
S 3rd Street		1,050	1,050	1,100	0	1,100	1.05
S 7th Street	380	630	1,010	600	600	1,200	1.19
S Grady Way	1,330	1,650	2,980	1,400	1,300	2,700	0.91
Screenline Total			**19,020**			**21,100**	**1.11**
Screenline 6 – South of SR 516 (Kent-Des Moines Road)							
SR 99 (all lanes)	810	1,740	2,550	1,500	3,300	4,800	1.88
I-5 (all lanes)	5,740	8,850	14,590	6,200	9,200	15,400	1.06
SR 167 (all lanes)	3,580	4,720	8,300	3,400	5,600	9,000	1.08
Screenline Total			**25,440**			**29,200**	**1.15**
Screenline 7 – At Puyallup River							
I-5 (All lanes)				6,900	8,500	15,400	
SR 167 (All lanes)				1,000	1,900	2,900	
SR 512 (All lanes)				2,900	3,800	6,700	
Screenline Total						**25,000**	

Table C3: Base year (2014) screenline total vehicle volume comparison (average weekday)

	Actual volumes			Estimated volumes			
	NB/WB	SB/EB	Total	NB/WB	SB/EB	Total	Est/Act
Screenline 1 – South of 196th Street SW							
SR 99	24,400	19,400	43,800	21,700	21,600	43,300	0.99
44th Avenue W	13,600	12,200	25,800	13,300	13,600	26,900	1.04
I-5 (all lanes)	86,900	87,800	174,700	75,000	76,100	151,100	0.86
Screenline Total			**244,300**			**221,300**	**0.91**
Screenline 2 – South of N 145th Street							
3rd Avenue NW	4,600	4,000	8,600	900	1,000	1,900	0.22
Greenwood Avenue N	12,100	12,800	24,900	13,600	14,700	28,300	1.14
SR 99	17,600	16,700	34,300	16,100	18,900	35,000	1.02
Meridian Avenue N	2,000	1,900	3,900	1,400	1,400	2,800	0.72
I-5 (all lanes)	99,800	100,500	200,300	96,800	96,400	193,200	0.96
5th Avenue NE	3,600	2,400	6,000	7,900	7,300	15,200	2.53
15th Avenue NE	7,800	8,200	16,000	9,900	10,300	20,200	1.26
20th Avenue NE	1,000	700	1,700	800	800	1,600	0.94
30th Avenue NE	3,600	2,700	6,300	2,300	2,500	4,800	0.76
SR 522	18,600	22,800	41,400	23,500	24,600	48,100	1.16
Screenline Total			**343,400**			**351,100**	**1.02**
Screenline 3 – Ship Canal							
Ballard Bridge	31,200	30,700	61,900	24,600	26,200	50,800	0.82
Fremont Bridge	15,800	14,300	30,100	25,100	25,600	50,700	1.68
SR 99	40,700	44,900	85,600	41,400	43,900	85,300	1.00
I-5 (all lanes)	135,900	124,200	260,100	134,100	130,300	264,400	1.02
University Bridge	11,300	14,900	26,200	17,600	19,600	37,200	1.42
Montlake Bridge	28,200	28,500	56,700	27,600	30,400	58,000	1.02
Screenline Total			**520,600**			**546,400**	**1.05**
Screenline 4 – Midlake							
SR 522	NA	NA	49,000	24,700	25,700	50,400	1.03
SR 520 (all lanes)	37,200	34,500	71,700	38,900	36,300	75,200	1.05
I-90 (all lanes)	79,000	77,900	156,900	86,700	87,000	173,700	1.11
Screenline Total			**277,600**			**299,300**	**1.08**
Screenline 5 – East of SR 167/Rainier Avenue							
I-405 (All lanes)	75,300	75,800	151,100	82,000	84,700	166,700	1.10
Airport Way	21,100	20,600	41,700	17,400	16,800	34,200	0.82
S 2nd Street	NA	10,900	10,900	NA	12,200	12,200	1.12
S 3rd Street	12,100	NA	12,100	13,000	NA	13,000	1.07
S 7th Street	6,900	6,700	13,600	6,200	7,700	13,900	1.02
S Grady Way	19,700	19,200	38,900	13,100	15,400	28,500	0.73
Screenline Total			**268,300**			**268,500**	**1.00**
Screenline 6 – South of SR 516 (Kent-Des Moines Road)							
SR 99 (all lanes)			30,800	28,700	28,600	57,300	1.86
I-5 (all lanes)	103,700	101,100	204,800	105,600	102,900	208,500	1.02
SR 167 (all lanes)	61,500	64,600	126,100	61,600	59,400	121,000	0.96
Screenline Total			**330,900**			**329,500**	**1.00**
Screenline 7 – At Puyallup River							
I-5 (All lanes)			188,100	105,600	105,100	210,700	1.12
SR 167 (All lanes)			38,300	15,800	17,100	32,900	0.86
SR 512 (All lanes)			84,800	47,300	45,400	92,700	1.09
Screenline Total			**311,200**			**336,300**	**1.08**

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Appendix D

- *Procedures for Transit Network Preparation*
- *Bus Speed Degradation Rates*

Appendix D: Procedures for Transit Network Preparation

Actual transit service is represented in a transit ridership forecasting model by means of a coded network. This service representation actually consists of two elements:

- A highway network, or "base network," is coded to create a computerized representation of existing and planned roads and exclusive transitways and tracks in the study region
- Transit service assumptions are overlaid on this base highway network

Significantly, for Sound Transit (ST) studies, the base network does not vary among alternatives. A single base network is used for all alternatives—meaning that for each alternative, elements of the base network may exist on which no transit service is coded. For example, rail rights-of-way are coded in every network although no rail service is coded for an all-bus alternative.

ST decided to construct a single base network for several reasons. One advantage of keeping the base network constant is that it eliminates spurious errors caused by roads or walkways which could accidentally be coded differently in different alternatives. A second reason for maintaining a single base network is that it minimizes differences in results due to accidental differences in access coding. Because a major aim of any forecasting effort is to capture differences among various alternatives, it is important that these differences are attributable to actual differences among the alternatives, rather than to coding inconsistencies.

In contrast to the base network, the transit service that operates on this network does vary, both by forecast year and by alternative. The transit service network created for each alternative is represented by a set of bus and rail transit routes operated by local transit agencies.

D.1 Development of the base network

The base network is coded within the ST boundary and consists of links and nodes that represent the road system on which transit and automobiles travel. As mentioned, exclusive rights-of-way for transit and HOVs (e.g., transitways and rail tracks) are also coded, although they may not be used in every alternative. Park-and-ride lots are also coded, although they too may not be served by transit in every alternative.

Each of the links coded in the base network has a set of attributes consisting of the length of the link, the link type, the modes allowed on the link, the number of lanes on the link, a link speed, and a volume delay function. The link type codes, the modes, the volume delay functions, and link speeds are described in more detail below.

The network outside the study area is not coded, although the major roads leaving the study area are coded by means of external links. These links serve as a method of accounting for travel into the study area from areas beyond the study area boundaries.

Mode types

The following eight modes are specified on links within the base network:

Symbol	Mode represented
c	Car
b	Bus
t	Trolley Bus
r	Rail (including streetcar)
a	Auto access (directional link)
w	Walk access
p	General pedestrian link
x	Park-and-ride lot connection (directional link)

The access modes (i.e., modes "a," "w," "p," and "x") are an important aspect of the base network. There is a minor variation in the way these access modes are represented in the PM-peak and off-peak networks. In the peak networks, both auto access and walk access modes are allowed, while in the off-peak only walk access is allowed.

Walk-access links are coded with a speed of 3 miles per hour (mph). The "w" mode allows walking from the base network to the zone centroid. The "p" mode accommodates all other walking, including walking from the zone centroid to the base network and streets and walking on all sidewalks and pedestrian paths, including station escalators and transfer paths. The separation of these two walk access modes makes it possible to differentiate between walk access transit trips and auto access transit trips.

The other two access modes, modes "a" and "x," are associated with the use of park-and-ride lots to access transit. Mode "a" allows auto trips between zone centroids and park-and-ride lots, and mode "x" represents walking between car and platform. A sample representation of the PM-peak network using the access modes is shown in Figure D1a.

There are several reasons for including the x-links to represent park-and-ride access to transit. First, using such links allows for counting the number of trips that use park-and-ride locations to access transit. Second, the use of such links will allow for modeling the effect of charging fees at park-and-ride lots should this be desired. Third, there is a certain disutility associated with having to park one's car and walk through a park-and-ride lot in order to get on a bus or train. Using x-links allows for the inclusion and variation of this disutility in the model.

Finally, the use of x-links allows for a more even-handed comparison of park-and-ride access to transit between rail and non-rail alternatives. The use of x-links allows one to connect a single park-and-ride lot to both the street network and rail tracks. This means that under an all-bus alternative (where transit would access the park-and-ride lot via the street network) and a rail alternative (where transit, such as rail transit, would access the same park-and-ride lot via the rail system), the park-and-ride lot in question would be connected to the exact same zones.

In the off-peak network, each of the AAZs in the network is connected with walk access links only. As in the PM peak, the walk access links are coded with a speed of 3 mph. Both modes "w" and "p" allow walking from the base network to the zone centroid and vice versa. Mode "p" also allows walking on all surface streets in the network. The other two access modes, modes "a" and "x," are not used in the off-peak network. A sample representation of the off-peak network using the access modes is shown in Figure D1b.

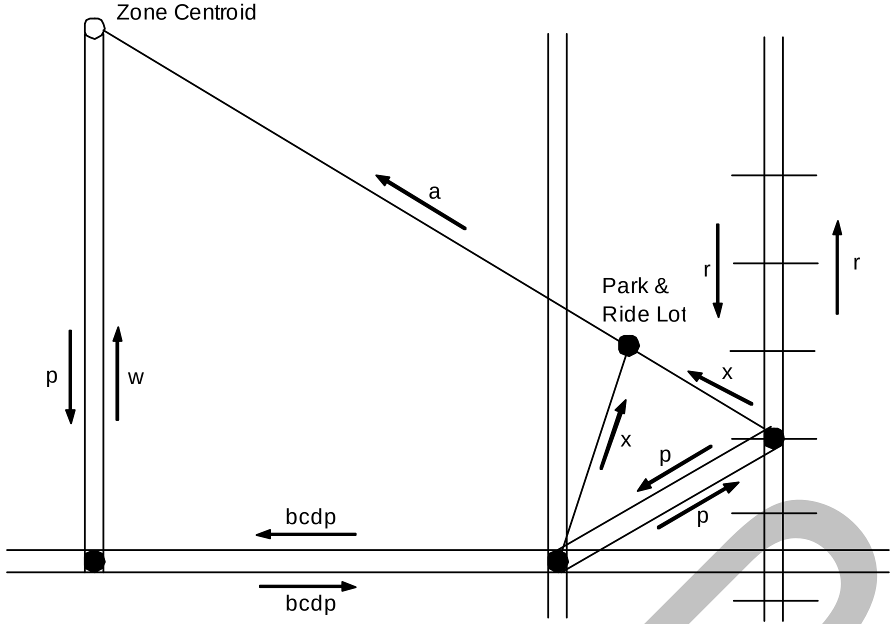
Development of the future transit service networks

Transit service networks are created to represent the transit service planned for each alternative and forecast year, as well as the service operated in the base years used to validate the model. Each service network is characterized by a unique set of routes, which may include rail lines, service on exclusive transitways, and HOV lanes. Each route is described by the nodes and links over which it travels, the travel time on each link, the locations where it stops, and its peak and off-peak headways. Each of these characteristics is described in detail below.

Route patterns

Each route can be described by its route alignment, or the set of nodes and links over which it travels. The places where passengers are picked up and dropped off are coded by placing a dwell time on the nodes that represent bus stops for each particular route. All Sound Transit, King County Metro, Community Transit, Everett Transit, and Pierce Transit routes within the forecast study area are coded for each alternative and forecast year, with the exception of dial-a-ride services and routes that have less than three trips per direction per day.

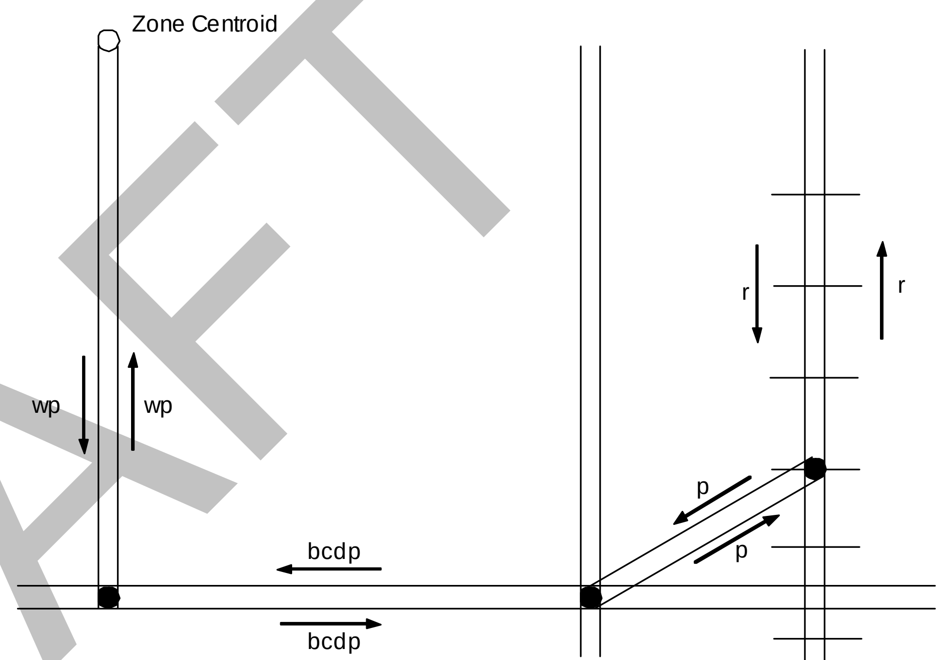
Figure D1a. Sample mode coding on base network links (PM peak)



LEGEND

Symbol	Mode Represented
a	Auto Access (Directional Link)
b	Bus
a	Car
d	Dual Power Bus
p	General Pedestrian Link
r	Rail
w	Walk Access (Directional Link)
x	Park and Ride Lot Connection Link

Figure D1b. Sample mode coding on base network links (off-peak)



LEGEND

Symbol	Mode Represented
a	Auto Access (Directional Link)
b	Bus
a	Car
d	Dual Power Bus
p	General Pedestrian Link
r	Rail
w	Walk Access (Directional Link)

Route headways

PM-peak and off-peak headways are specified for each route in each transit service network. The PM-peak headway reflects the number of trips between 3:00 and 6:00 PM, and the off-peak headway reflects the base headway between 9:00 a.m. and 3:00 p.m. For the base-year network, headways are determined directly from the printed bus schedules from the transit agencies.

Future networks are developed according to the specific definition of alternatives as defined in appropriate Definition of Alternatives reports for DEIS, FEIS, and PE projects.

Link speeds and bus speeds

For fixed guideway facilities, link speeds representing travel time between two successive stations are calculated as part of the operating plan development that is unique to each alternative under consideration. Bus speeds under mixed operation with general traffic are calculated as follows:

- **For the base year**—link speeds are coded so that they result in network bus travel times equal to observed bus travel times.
- **For future years**—base-year link speeds are degraded according to the change in general roadway congestion level estimated by the PSRC model for arterial and freeway facilities and by geographic area.

Since the ST model's development in the early 1990s by the RTA, future-year link speeds have been estimated using a constant degradation rate of 7 to 9 percent per decade. This degradation rate is consistent with historic trends in bus speeds. FTA staff, however, expressed concern about extrapolating historical trends in bus speed degradation into future projections. Instead, the FTA suggested basing link speeds degradation on roadway congestion estimated by the PSRC multi-modal model.

Subsequently, a number of experimental analyses were performed in consultation with PSRC and City of Seattle travel modeling staff. As a result of this effort, analysis results and a recommended procedure were developed and documented by ST staff in a memorandum to the FTA. A copy of this memorandum follows this section. After this improvement, and following further refinement of the PSRC model by WSDOT for major highway projects, the effective speed degradation rates are lower than the historic rate. Currently for 2040 forecasts, the rate is under 4 percent per decade for buses in mixed traffic. Speeds of buses on busways, HOV lanes, and toll-protected facilities are not affected and remain constant into the future.

MEMO

August 1, 2002

TO: Eric Pihl

FROM: Don Billen

SUBJECT: Updated Treatment of Bus Speeds in the Sound Transit Model

This memorandum describes the updated procedures for treating bus speeds in Sound Transit's incremental ridership forecasting process. This is in response to your request that Sound Transit rely on output from the PSRC multi-modal model to estimate changes in bus speeds over time.

Sound Transit incremental ridership model

Sound Transit uses an incremental model to forecast transit ridership consisting of three stages:

- Stage 1: Changes in demographics
- Stage 2: External changes in highway travel time (congestion) and costs (including parking costs), transit fares, and household income are taken into consideration.
- Stage 3: Incremental changes in the transit level-of-service (i.e. access, wait, and ride travel times) are taken into consideration.

The third stage of the forecasting process is where the effects of changes in bus speeds are captured. Base year link speeds in combination with transit travel time functions are used so that they result in network bus travel times equal to observed bus travel times. Individual transit routes are coded with transit travel time functions that account for acceleration/deceleration time, with bus speeds equal to the base year link speed for express portions of a route. Dwell time is similarly coded for individual transit routes, with zero dwell time for express portions of a route.

Future year link bus speeds are degraded relative to base year link speeds and according to the procedures described below. The transit travel time functions which account for acceleration/deceleration time are the same in the base year and future year. Dwell time similarly remains the same in the base and future year.

Since the model's development in the early 1990's by the Regional Transit Project, future year link speeds have been estimated using a constant degradation rate of seven to nine percent per decade. This degradation rate is consistent with historic trends in bus speeds. However, FTA staff have expressed concern about extrapolating historical trends into the future and suggested relating future bus speeds to road speeds in the PSRC multi-modal model.

Updated Procedure for Estimating Future Bus Speeds

Sound Transit and its ridership consultant have investigated several methods for relating road speeds in the PSRC model to bus speeds in the Sound Transit model. After reviewing these methods with Puget Sound Regional Council and City of Seattle modeling staff, we have arrived at the following procedure.

For arterial bus speeds, weighted average auto travel time within the PSRC model is calculated at an intra 26-district level for the base year and forecast year in the PM peak and off-peak. The ratio between the base year and forecast year intra-district times is calculated. This change in intra-district auto travel times is used to estimate the change in bus speeds and is applied to the base year link speed values in the ST model for each geographic district. Table 1 shows the resulting PM peak bus degradation rates for each of the 26 districts for the period of 1998–2020.

Table 1. PM Peak Arterial Degradation Rates

Comparative Analysis of 1998 to 2020 Weighted Average Intra-District Travel Times

District		1998	2020	2020/1998 Ratio	Change Per Decade
North Everett	1	6.13	6.80	1.11	4.8%
South Everett	2	8.24	9.28	1.13	5.6%
Lynnwood	3	8.04	9.95	1.24	10.2%
North Creek	4	10.13	11.17	1.10	4.5%
Shorelin	5	6.47	6.79	1.05	2.2%
Ballard	6	6.32	6.79	1.07	3.3%
North Seattle	7	6.64	7.29	1.10	4.3%
University District	8	4.55	5.52	1.21	9.2%
Queen Anne	9	6.44	6.94	1.08	3.5%
Capitol Hill	10	4.86	5.07	1.04	1.9%
Seattle CBD	11	2.48	2.63	1.06	2.6%
W Seattle	12	7.28	8.63	1.19	8.1%
Rainier	13	9.17	9.92	1.08	3.6%
Sea-Tac	14	8.01	8.81	1.10	4.4%
Renton	15	10.00	11.58	1.16	6.9%
Federal Way	16	8.26	9.50	1.15	6.5%
Kent	17	9.99	11.16	1.12	5.2%
Kirkland	18	8.75	10.10	1.15	6.7%
Redmond	19	8.60	11.42	1.33	13.8%
West Bellevue	20	5.51	5.68	1.03	1.4%
Bellevue	21	8.85	9.69	1.10	4.3%
Issaquah	22	8.62	10.33	1.20	8.6%
North Tacoma	23	8.48	10.58	1.25	10.6%
South Tacoma	24	6.16	6.78	1.10	4.4%
Lakewood	25	8.30	9.72	1.17	7.4%
Puyallup	26	10.51	11.46	1.09	4.0%
External	27	16.97	19.70	1.16	7.0%
Destination Totals		19.33	22.34	1.16	6.8%

For freeway bus speeds, zone to zone travel times between major entry and exit points for buses along regional freeways are calculated for the base year and future year. As with arterial times, the ratio between the base year and forecast year times is calculated. This change in freeway auto travel times is used to estimate the change in bus speeds and is applied to the base year link speed in the ST model for each freeway segment. Table 2 shows the resulting bus degradation rates on two freeway segments in the light rail study area.

Table 2. PM peak freeway degradation rates

Comparative Analysis of 1998 to 2020 Freeway Travel Times				
Freeway Segment	1998	2020	2020/1998 Ratio	Change Per Decade
I-5: Seattle CBD to Northgate	15.50	18.07	1.17	7.2%
SR 520: Seattle to Overlake	22.15	25.12	1.13	5.9%

The resulting rates of degradation for both arterials and highways are somewhat lower than historic changes in bus speeds in the Central Puget Sound Region, so may underestimate actual degradation rates. However, the updated method offers the advantage of being sensitive to varying congestion rates over time and across geographic areas and to changes in these rates with alternative land use or highway network scenarios.

Alternate method investigated

Our ridership forecasting consultant originally proposed to simply average PSRC link speeds within a cross-classification of geography and facility type for a base and future year to estimate changes in bus speeds. (see Parsons Brinkerhoff memo of 12-2-01 from Youssef Dehghani to Don Billen).

Investigation of this method between 1998 and 2020 yielded results that varied greatly between geographic areas and on the aggregate showed changes in road times much lower than other analyses of PSRC model output. The average decline in speeds across all facilities was 1% per decade between 1998 and 2020 compared to previous analysis of zone-zone road skims that showed an average decline of 8% per decade (see Parsons Brinkerhoff memo of 11-19-01 from Youssef Dehghani to Don Billen). Furthermore, the change in arterial speeds in different geographic areas varied by factors as high as 16 to 23 times. For instance, major arterial speed degradation in the Eastside of King County was 17 times as high as in Snohomish County, even though both are high growth areas with very limited road expansion currently funded. (Table 3)

Upon review of these results with PSRC and City of Seattle modeling staff, we concluded that simple averaging of link speeds is inaccurate and that it would be better to rely on zone-zone skim times than link level times. The simple averaging of link speeds results in too much influence from low volume roadways and too little influence from highway volume roadways. Also, using link level rather than zone-zone travel time skims created the possibility for the results to be influenced by the density of road networks coded in a geographic area.

Table 3. Analysis of PM peak speed degradation in PSRC model by facility type and area type

(average change per decade from 1998 to 2020)

Facility Type		Area Type: All	Seattle CBD	Seattle	Eastside	Rest of King County	Snohomish County	Pierce County	Kitsap County
	All	1.5%	0.9%	0.7%	5.6%	3.0%	0.8%	1.8%	0.2%
	Freeway GP Lanes	6.3%	4.48%		8.8%	3.1%	14.4%	4.0%	6.1%
	Freeway HOV Lanes	1.2%	1.95%		4.2%	5.56%			
	Major Arterials	1.4%	3.4%	0.8%	6.8%	3.0%	0.4%	1.9%	0.2%
	Minor Arterials	1.8%	0.1%	0.2%	3.1%	2.7%	2.1%	0.3%	0.0%

Notes :- The data shown above represents the percentage speed degradation over a period of 22 years from 1998 to 2020.
- The percentage degradation in speed was obtained from the "slope" of the regression equation obtained from a linear regression analysis of PM peak link travel times for a particular facility type and area type.
- The regression analysis showed an R^2 of greater 0.9 for all the categories.
- Major arterials include all those arterials in the PSRC model that have a speed greater than 25 mph, e.g., MLK way, Rainier Avenue, NE 8th (in Bellevue etc.). Minor arterials are arterials with a speed less than 25 mph.

These concerns led PSRC and City of Seattle modeling staff to recommend the use of weighted average auto travel times from zone-zone travel time skims and to Sound Transit's development of the procedures described at the beginning of this memo.

CC: John Witmer, FTA Region X
Larry Blaine, Puget Sound Regional Council
Eric Tweit, City of Seattle
Tracy Reed, Ron Lewis, Mike Williams, Sound Transit

DB <Updated bus speed degradation method.doc>