Oregon Department of Transportation

Reliability Performance Analyses Using HERS-ST Phase II – Delay

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List of Acronyms

AADT	Annual Average Daily Traffic
AES	Average effective speed
APLVM	Aggregate Probabilistic Limiting Velocity Model
BI	Buffer Index
CMS	Congestion Management System
DOW	Day of the Week
FFS	Free-flow speed
FHWA	Federal Highway Administration
HCM2000	2000 Highway Capacity Manual
HCM2010	2010 Highway Capacity Manual
HERS-ST	State version of the Highway Economic Requirements System
HPMS	Highway Performance Monitoring System
MAP-21	Moving Ahead for Progress in the 21st Century
MOY	Month of the Year
MPH	Miles per hour
ODOT	Oregon Department of Transportation
PBPP	Performance-Based Planning and Programming
PTI	Planning Time Index, also known as TTI_{95}
SHRP 2	Strategic Highway Research Program
TOD	Time of the Day
TPAU	Transportation Planning Analysis Unit
TTI	Travel Time Index, also known as TTI_{50}
TTI_m	Overall Mean Travel Time Index
TTI_{50}	50th Percentile of TTI
TTI_{80}	80th Percentile of TTI
TTI_{95}	95th Percentile of TTI, also known as PTI
VCR	Volume-to-capacity ratio
VMT	Vehicle miles traveled
VPH	Vehicles per hour
VPHPL	Vehicles per hour per lane

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Executive Summary

The state version of the Highway Economic Requirements System (HERS-ST) is a complex modeling tool that has been successfully used by state agencies to analyze highway deficiencies for programming and planning purposes. Though most of the focus on the HERS-ST model revolves around the selected improvements, the associated funding elements, and the benefit-cost analysis, many of the internal calculations within the model can also be useful for analysis. This report looks at a reasonable approach for using the internal delay calculations within a roadway system reliability analysis.

HERS-ST evaluates three types of delay: zero-volume delay, incident delay and congestion delay, where:

- Zero-volume delay is the delay associated with traffic control devices.
- Incident delay is the delay associated with crashes.
- Other congestion (or recurring) delay is the average delay due to non-incident congestion.

The FHWA has identified several primary causes or events that account for most delay on a roadway system:

- Inadequate base capacity (40%)
- Incidents (25%)
- Weather (15%
- Work zones (10%)
- Special events (5%)
- Traffic control devices (5%)

HERS-ST can provide reasonable analysis for inadequate base capacity (40%), incidents (25%), and traffic control devices (5%), which make up 70% of the causes of delay on most roadway systems. The effects of weather, work zones, and special events can be evaluated by adjusting the capacity and/or demand input data. The probabilities and impacts from the various delay events can be modeled through an automated batching process that can run numerous scenarios associated with the likelihood that different combinations of delay events occur.

HERS-ST does not directly calculate performance measures associated with reliability analysis, such as Travel Time Index (TTI) and Planning Time Index (PTI), however the delay elements from HERS-ST outputs can be used in post-processing analysis to develop TTI and PTI values.

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Introduction

HERS-ST

The state version of the Highway Economic Requirements System (HERS-ST)[1] is a highly sophisticated highway deficiency analysis tool developed by the Federal Highway Administration (FHWA) that allows states to identify long-term investment needs and performance, and to evaluate the impacts of alternative highway investment levels on the state highway system.

The national version of HERS has been used by the FHWA since the early 1990s to provide estimates of investment requirements for the nation's highway system in the biennial Condition and Performance (C&P) Report to the United States Congress.

The HERS-ST model is an enhanced version of the HERS-National. The logical structure of the two versions is identical, as are most of the input requirements; both models utilize the highway section dataset in the Highway Performance Monitoring System (HPMS) format. The user-friendly Graphical User Interface (GUI) and certain input/output features are the primary differences that distinguish HERS-ST from HERS-National.

A simply summary of the HERS-ST modeling process is as follows:

- Identifies highway condition and performance levels.
- Identifies deficiencies through the use of engineering principles.
- Identifies a set of alternative improvements to correct deficiency.
- Determines a benefit-to-cost ratio for each potential improvement.
- Selects and implements the most economically attractive improvement for each deficiency based on available funding and the resulting improved performance condition.

The HERS-ST model consists of six complex sub-models:

- Fleet Composition Model
- Widening Feasibility Model
- Capacity Model
- Pavement Deterioration Model
- Speed Model
- Travel Forecast Model

The model only identified deficiencies based on capacity and pavement issues. The overall analysis process predicts a wealth of information on a number of performance characteristics and indicators, such as speed, delay and high level safety criteria that are essential for estimating long-range performance and conditions on the roadway system.

[1] http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.cfm

This report is the second part of a four part analysis where different performance indicators are evaluated. Part One evaluated the outputted base year speed characteristics from the model, as compared with observed data. The report also discussed the potential application of the outputted future year speed characteristic as indicators to inform on future system performance for given scenario conditions.

Part Two evaluates the various delay characteristics, as they relate to both base and future analysis years. The discussion continues further to evaluate ways to incorporate the HERS-ST delay predictions into reliability calculations.

Part Three will look at the analysis associated with safety elements within HERS-ST. The latest version of HERS-ST allows for greater flexibility in calibrating the crash rates to local conditions.

Part Four evaluates future performance on the system associated (with or without) proposed improvement projects. This report will identify and evaluate future conditions in light of the targets associated with the previous three reports.

These all are important elements in HERS-ST analysis because they contribute to the development of travel time and user cost for a given scenario.

Planning

There are a number of national goal areas being discussed under the Moving Ahead for Progress in the 21st Century (MAP-21) program, including safety, infrastructure, congestion, reliability and freight elements. The federal rulemaking process for the MAP-21program is still ongoing so there are many unknowns yet to be anticipated. There is considerable discussion and pro-action on these topics, both through the Strategic Highway Research Program (SHRP 2) and the 2010 Highway Capacity Manual (HCM2010). Numerous analytical procedures are being actively developed, including analysis and software procedures, but the data requirements are significantly large.

The HERS-ST model tool is a natural fit for the infrastructure and congestion elements of MAP-21. Depending on the formal adoption of the MAP-21 rules, some minor adjustments to the HERS-ST modeling process could enhance the model's ability to satisfy the congestion, safety, reliability, and/or freight elements.

The greatest contribution the HERS-ST model has to offer to the planning process is the tools ability to evaluate future performance conditions of the roadway system associated with or without proposed improvement projects. HERS-ST is an excellent tool choice for identifying and evaluating future performance conditions in light of the baseline and future targets defined through the long-range planning process. This is critical in light of the national push for performance-based planning and programming (PBPP). "PBPP attempts to ensure that transportation investment decisions are made - both in long-term

planning and short-term programming of projects - based on their ability to meet established goals[2]."

The HERS-ST model is an excellent tool for assessing base and future MAP-21 performance targets associated with pavement and congestion performance on a roadway system, and with some modifications could be applicable to safety, reliability, and freight elements. HERS-ST is also a natural choice for the scenario analysis and strategic planning expectations associated with PBPP.

The HERS-ST model is extremely useful for assessing long-range needs on a highway system and evaluating investment trade-offs. Some of the types of traditional questions HERS-ST is designed to address include:

- What level of capital expenditure is justified on benefit-cost grounds?
- What user cost level will result from a given stream of investment?
- What investment level is required to maintain user cost levels?
- What are the user cost and fiscal impacts of varying the investment stream (e.g., postponing improvement of backlog deficiencies)?
- What are the tradeoffs between capital investment and the performance of the highway system? If total investment is less than the economically efficient level, how much is lost in lower benefits?
- What is the cost, over 20 years, of correcting all existing and accruing highway deficiencies?
- Given a certain investment scenario, what percentage of the vehicle miles traveled (VMT) will be on roads with conditions below a minimum tolerable standard?
- What level of capital investment is needed to achieve or maintain the targets defined under MAP-21? Under constrained funding, how much of the system can achieve the target performance?
- For PBPP, how many resources should be allocated to achieve specific performance targets?

Reliability

There are a number of national performance areas being discussed under the MAP-21 program. This report will center on the elements associated with travel time reliability. Travel time reliability is simply a way to describe the variation of travel time encountered by a traveler on a roadway segment associated with both the expected and unexpected delay.

The FHWA has identified several primary causes that account for most delay on a roadway system[3]:

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[2] FHWA (US Department of Transportation, Performance Based Planning and Programming Guidebook, September 2013, https://www.fhwa.dot.gov/planning/performance_based_planning/pbpp_guidebook/

[3] http://www.ops.fhwa.dot.gov/aboutus/opstory.htm; these estimates are a composite of many past and ongoing congestion research studies and are rough approximations.

- Inadequate base capacity (40%)
- Incidents (25%)
- Weather (15%
- Work zones (10%)
- Special events (5%)
- Traffic control devices (5%)

The first bullet, inadequate base capacity, has traditionally been accounted for through the Congestion Management System (CMS[4]) approach, which tracks and evaluates congestion issues, such as bottlenecks. Congestion delay, also known as recurring delay, has historically been the primary focus for most transportation engineers, accounting for only 40% daily recurring delay encountered by travelers, particularly during peak travel periods.

The recurring delay is often taken into consideration by most travelers because they expect certain levels of traffic congestion at specific locations during various time periods throughout the day (i.e., bottleneck locations).

The remaining five bullets identify what is new with reliability analysis. These elements are considered "non-recurring delay" and account for 60% of the overall delay on the roadway system. The non-recurring delays are the unexpected elements that the traveler encounters by chance. Reliability analysis within MAP-21 is focused towards addressing the additional 60%.

Through MAP-21 there is much discussion on this topic and analytical procedures are being proposed. Though the exact rulemaking process has not been completed, there are a number of terms like Travel Time Index, Planning Time Index and Misery Index that are being discussed as ways to describe the reliability performance on a roadway system.

There could be three critical levels of analysis needed to be satisfied:

- Defining and setting performance targets.
- Measuring existing performance of the roadway system (i.e., what's on the ground today) with respect to the targets.
- Evaluating future performance conditions, in lieu of the performance targets.

Analysis Process

This is the second of a four part analysis process that investigates the relevance and potential application of the HERS-ST model in evaluating existing and forecasting future System Reliability Performance.

[4] The Transportation Equity Act for the 21st Century (TEA-21), enacted in 1998, required states to develop congestion management systems as a systematic process for managing congestion. https://www.fhwa.dot.gov/tea21/sumcov.htm

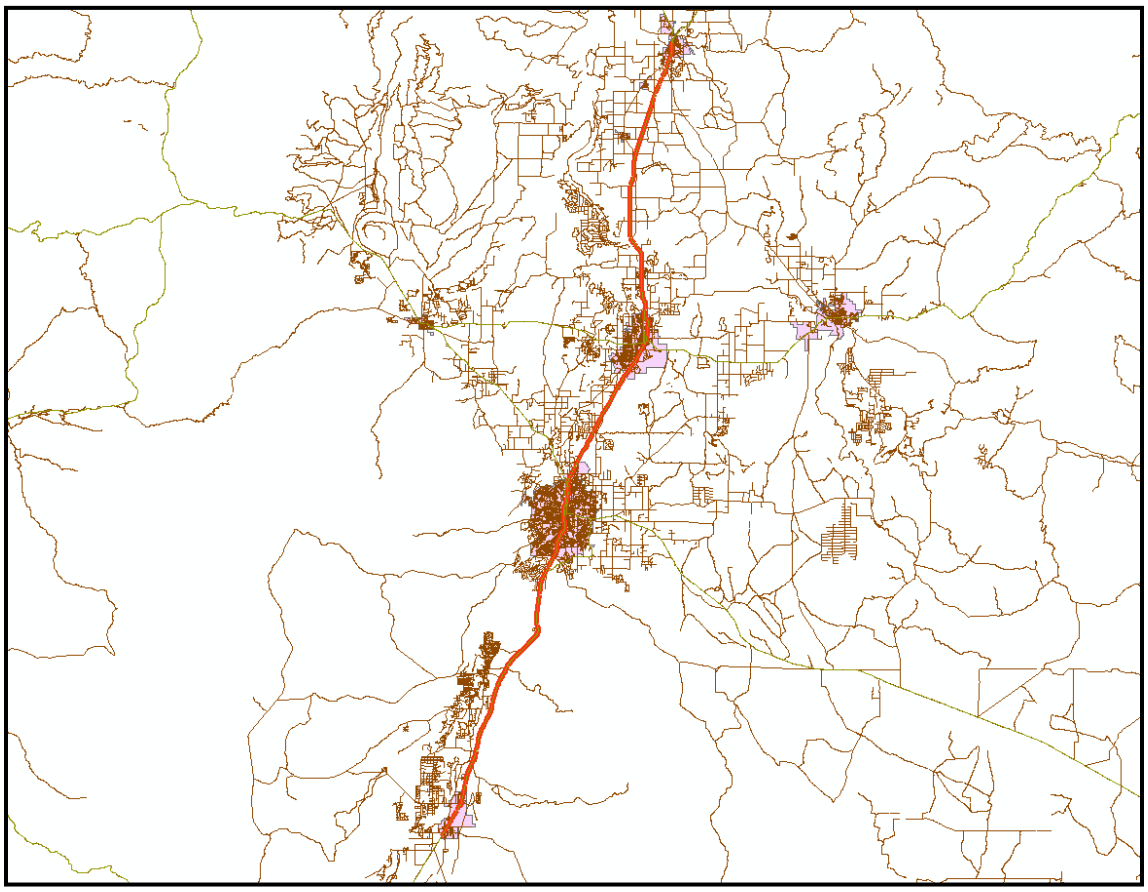
Phase Two evaluates the base and forecast future delay on the system, with the intention of exploring ways to examine potential future system conditions, and then relate the results back to MAP-21 targets.

This is a critical concept as there are limited ways to project future conditions in order to determine how the future improvement combinations align with MAP-21 targets set during a base year. The objective here is to develop a high level tool for forecasting delay associated with any number of future improvements.

The Corridor

The US-97 corridor is located in Central Oregon (see Figure 1), and extends south from the Jct. US-26 in Madras, Oregon to Jct. OR-31 south of La Pine, Oregon. The corridor spans a distance of 74 miles, and passes through four incorporated cities: Madras, Redmond, Bend and La Pine, as well as one unincorporated area known as Terrebonne. The two largest population centers are the cities of Bend and Redmond, with 2013 populations of 81,200 and 27,400, respectively. The two smaller urban areas are Madras and La Pine, with 2013 populations of 6,400 and 1,700, respectively.

Figure 1: US-97 Corridor through Central Oregon



The alignment is considered high desert with rolling hills and minor curves. The weather is generally dry, but does experience freezing conditions during winter months. In addition, the central Oregon area has significant recreational aspects which can result in large seasonal swings in the traffic demand on the roadway system throughout various weekends and much of the summer and winter months.

A summary of the section length and VMT for the various categories can be found in Table 1, which splits out the data into three general terms: the corridor as a whole; rural vs. urban; and eight individual segments defined by the urban boundaries. The table also provides a breakdown of the VMT growth between the 2014 and 2034 analysis years, and the percent change in VMT for the annual and 20-year timeframes.

Table 1: Corridor Length and VMT Summary (million VMT)

	Section Length		VMT - 2014		VMT - 2034		VMT % Change	
	Miles	%	VMT	%	VMT	%	20-Year	Annual
Corridor	73.72	- -	457	- -	614	- -	34	1.49
RURAL	50.04	68	264	58	364	59	38	1.61
URBAN	23.68	32	193	42	250	41	30	1.31
Madras	1.92	3	13	3	15	2	9	0.42
Rural01	22.10	30	95	21	131	21	39	1.65
Redmond	5.39	7	44	10	59	10	34	1.49
Rural02	7.78	11	78	17	105	17	35	1.51
Bend	10.54	14	113	25	149	24	32	1.40
Rural03	17.40	24	84	18	118	19	40	1.71
La Pine	5.83	8	22	5	27	4	21	0.96
Rural04	2.76	4	8	2	10	2	24	1.08

Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

The corridor carried 457 million VMT for the 2014 base year, and forecasts 614 million VMT for the 2034 future analysis year. The total corridor shows an average 20-year VMT growth of 34%, at an annual growth rate of 1.49%. Two-thirds of the corridor alignment is identified as rural, and caries 60% of the traffic. The split is roughly the same for both the 2014 base and 2034 analysis years. The VMT growth is higher in rural than in urban areas.

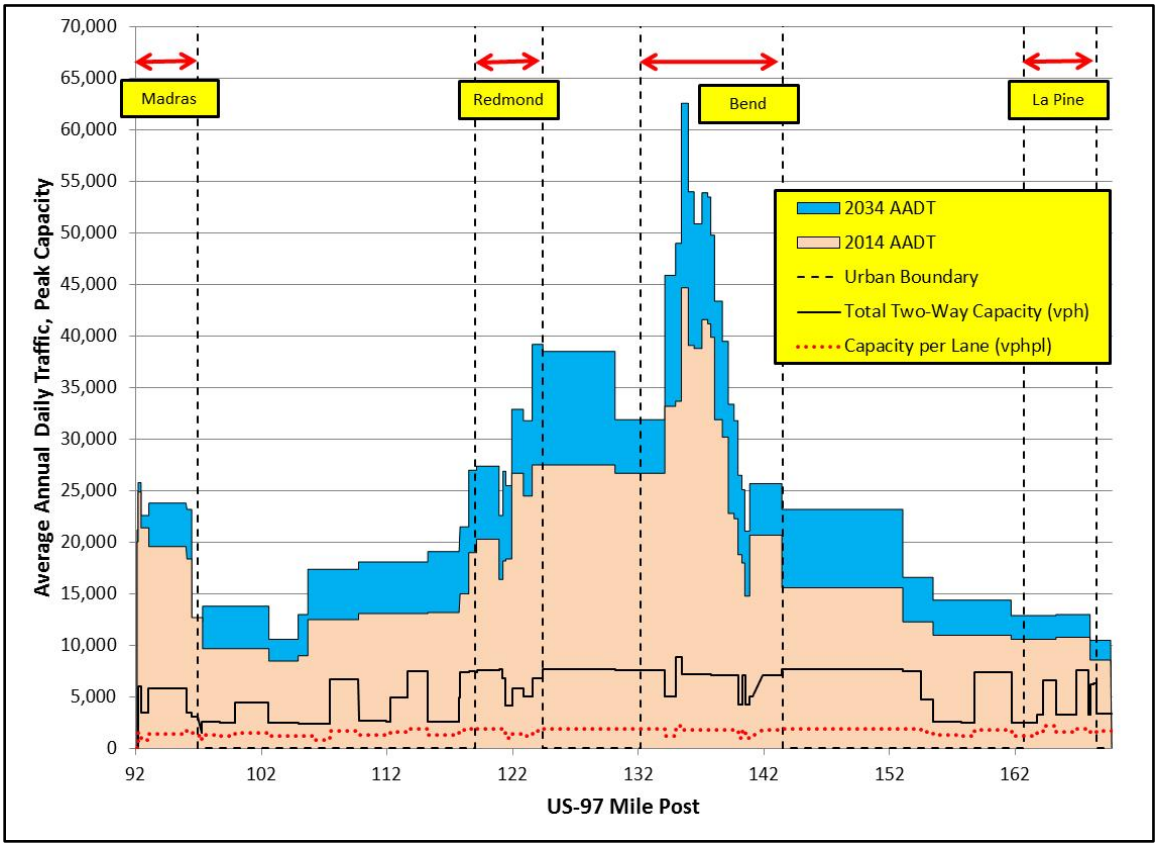
The Redmond and Bend urban areas and the rural area (Rural02) between the two, have an annual average growth that is similar to the total corridor's annual average. This area of the corridor makes up one third of the total corridor mileage, but carries half of the total VMT.

The rural segments between Madras and Redmond (Rural01) and between Bend and La Pine (Rural03) show a higher than average 20-year VMT growth, at 39% and 40%, respectively.

The roadway segment through the Madras area is designated a one-way couplet between mile posts 92 and 93.5. All analysis results for the two alignments have been aggregated together for this report. The 20-year VMT growth for Madras and La Pine is well below the 34% average VMT growth for the entire corridor, at 9% and 21%, respectively. Because the segments passing through these two urban areas are located at the outer edges of the total corridor area and only carry 10% of the total VMT, issues and changes to the roadway system within these areas should not significantly contribute to the overall travel within the corridor.

The comparison of 2014 and 2034 Annual Average Daily Traffic (AADT) along the US-97 corridor is shown in Figure 2. A summary of the total AADT growth between the two analysis years is defined as the area between the two curves.

Figure 2: Comparison of 2014 and 2034 AADT on US-97



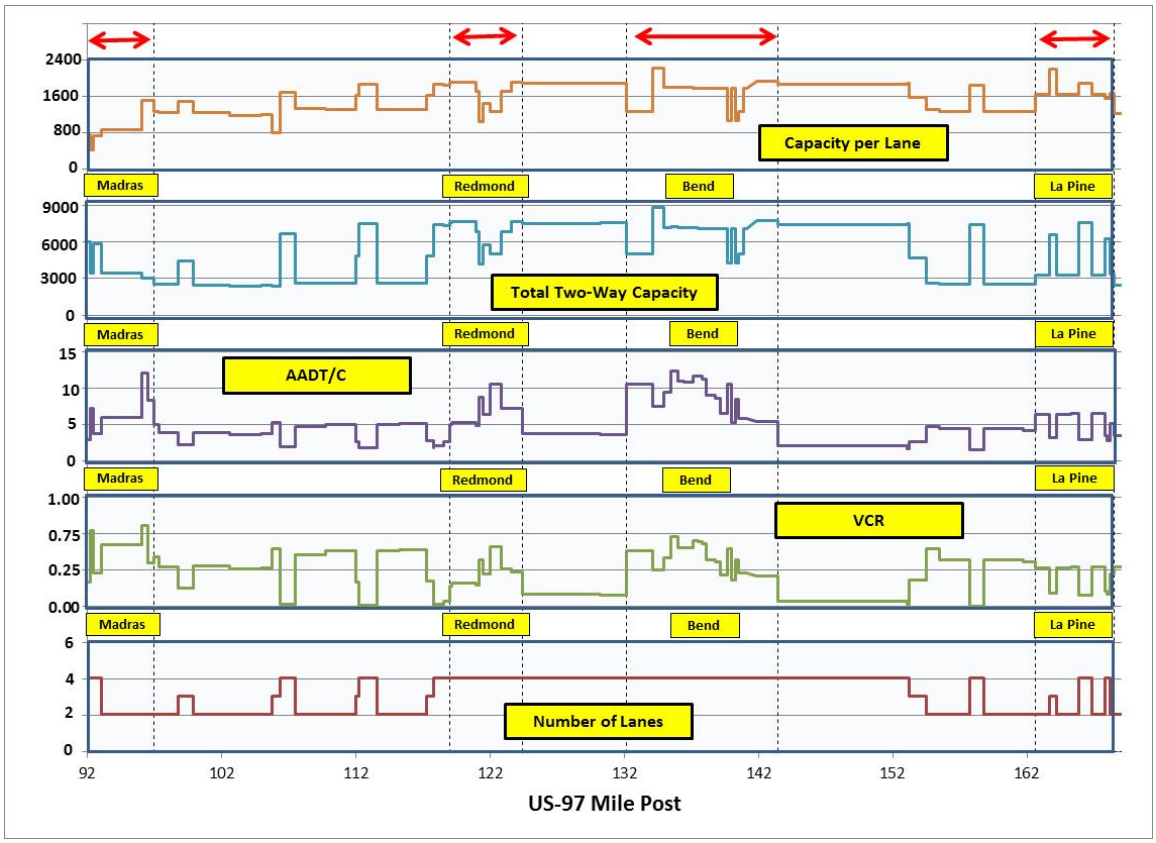
The total two-way capacity, and capacity per lane values, are also provided in Figure 2 as a point of reference; both are peak period capacities.

For rural segments HERS-ST calculates capacity as a two-way peak capacity, whereas for urban segments the capacity is a one-way (or by direction) peak capacity. To simplify the comparison between rural and urban areas, all capacities on urban segments are converted to a total two-way peak capacity (i.e., solid black line). The total two-way peak capacity varies from 1,530 to 8,860 vehicles per hour (vph). The capacity per lane

(i.e., dotted red line) serves as a quick double-check on the reasonability of the capacity calculations; the capacity per lane varies from 760 to 2,220 vehicles per hour per lane (vphpl).

The concept is expanded in Figure 3, which shows a quick comparison of the roadway characteristic profiles on US-97. The x axis represents the corridor alignment, identified by mile posting. The four urbanized segments are identified. The data elements include, in order from bottom up: the number of lanes, the volume-to-capacity (VCR), the annual average daily traffic to capacity ratio (AADT/C), the total two-way capacity and the capacity per lane. All data reflects the existing system condition as currently on the ground for the 2014 base year.

Figure 3: Comparison of 2014 Roadway Characteristic Profiles on US-97



As an example, Figure 3 can assist to quickly identify the location of the three passing lanes in the rural segment between the urban areas of Madras and Redmond (i.e., Rural01) and the corresponding VCR and AADT/C values for said locations.

The bottom graph in Figure 3 shows that nearly half of the US-97 corridor is four lanes, including the entire roadway segment through and between the Redmond and Bend areas, and half the rural segment down to La Pine.

HERS-ST Analysis

A full sample (100%) HPMS formatted dataset was developed for the US-97 corridor, where each data record represents a specific segment, with the expansion factor set to unity. The base year was defined as 2014, with a 20-year future analysis year of 2034. The model was run with four 5-year funding periods; however none of the interim years are reviewed for this report. The initial scenario for this analysis was defined as a "No Build" scenario, where only pavement improvements were allowed by the HERS-ST model. The widening feasibility was set to zero for both the user parameter settings and the HPMS input dataset in order to restrict HERS-ST from adding lanes during the 20-year analysis period.

The HERS-ST model utilizes the Capacity Model, based on the HCM2010 formulas, to analyze recurring delay by evaluating congestion issues and simulating roadway improvements to alleviate congestion bottlenecks. The state improvement file option adds a critical level of reality check to the needs analysis. The congestion analysis accounts for 40% of the causes of delay, as identified by the FHWA.

FHWA developed a report in 2013[5] that provides some basic guideline on adjustment factors that can be applied to free flow speed, capacity and demand elements to account for the probability of various conditions on the roadway system, such as weather, special events and work zone. HERS-ST does not have a direct process for evaluating the probabilities of changes in demand and capacity associated with incremental changes in weather conditions and the addition of special events. However, there is a feature that is available within HERS-ST that can assist for this type of analysis.

HERS-ST has a unique State Override feature that allows the user to supplement the highway data and to override the improvement decisions that HERS-ST makes on any given roadway section, which in turn can impact system performance conditions. The State Override switch was originally designed to allow the user to turn on/off HERS-ST improvements and add unique state specific improvements as alternatives. One of the user inputs into the state override file details the adjusted capacity of the roadway system associated with the override improvement. This feature will allow the user to perform the capacity adjustments discused in the 2013 FHWA report.

A batching process can be developed and utilized to run a number of probability scenarios that adjust the capacities within the state override file, reflecting the probability of different roadway capacity and demand probability.

The HERS-ST model performs a high level evaluation of the cost of work zone delay. As of this writing, ODOT has not performed any review or testing of this feature, but hopes to have more information soon on its added value to the performance analysis.

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[5] Federal Highway Administration. *"Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies,"* FHWA-HOP-13-042, Washington, D.C., June 2013.

The HERS-ST model contains a number of sub models, such as speed, safety and congestion that perform a large number of internal calculations in order to assess and evaluate current and future conditions and performance on a roadway system. Some of the results of the internal calculations are only used to feed other sub model calculations and the internal numbers are discarded at the end of the model run. Other results are reported out to the analyst.

One of the key sets of results useful for reliability analysis is the delay element set, which is also tied to the safety and congestion analysis. HERS-ST evaluates three types of delay: zero-volume delay, incident delay and congestion delay, which is reported out as "Hours of Delay per 1,000 VMT".

- Zero-volume delay is the delay associated with traffic control devices. This is the expected delay that a single vehicle would encounter even if it were the only vehicle on the road. Zero-volume delay only exists for sections controlled with stop signs or traffic signals and is not calculated for uncontrolled sections.
- Incident delay[6] is the delay associated with crashes. HERS-ST estimates delay due to crashes through a secondary (or inferred) process where the HERS-ST model estimates the delay cost of crashes and then back-calculates the delay estimates due to crash incidents from the cost calculations.
- Other congestion (or recurring) delay is the average delay due to non-incident congestion.

The HERS-ST model does a good job projecting and evaluating future conditions on a roadway system. Though the model is not designed to provide and evaluate travel-time or planning-time indexes that are used within reliability analysis, there are post processing methods that can be useful for this work.

Scenario Development

Looking at FHWA's list of six primary causes of delay, the HERS-ST analysis can reasonably account for the traffic control devices (zero volume delay), the incidents (incident delay), and the inadequate base capacity (other congestion delay) elements of delay. Though the contribution of the weather, work zone and special events delay can not be directly modeled through HERS-ST, there are ways to work around these minor limitations. The HERS-ST analysis can be enhanced by utilizing scripted batch processes to apply various probability adjustment factor to the capacity and demand elements, within the input data, to develop probabilistic scenarios to account for various weather, work zone and special event conditions.

Two capacity reduction scenarios were developed as examples for this report: an 8% reduction and a 15% reduction, reflecting medium rain and medium snow, respectively. A batching process was developed to run the files with adjusted capacities within the

[6] The HERS Incident Delay is a default input for FREEVAL-RL, being developed as part of SHRP 2 (http://www.trb.org/Main/Blurbs/169594.aspx)

state override file, reflecting the probability of different roadway capacity and demand probability. A batch processing discussion can be found in Appendix B.

Discussion

Zero-Volume Delay

Zero-volume delay is the delay associated with traffic control devices, which accounts for about 5% of the delay encountered by a traveler. This is the expected delay that a single vehicle would encounter even if it were the only vehicle on the road. Zero-volume delay is only associated with sections controlled with stop signs or traffic signals located within urbanized areas.

Figure 4 identifies the magnitude and location of the zero-volume delay on the US-97 corridor alignment.

This analysis is based on existing system conditions on the ground in 2014. It does not include the new signalized intersections added on US-97 within the City of La Pine. In addition, the analysis does not include the future intersection improvement projects scheduled within the Bend and Madras areas. Several of the Bend improvements will replace existing signals with interchange connections. The removal of signals will have significant reduction of future zero-volume delay on the system.

The scenario assumes that all future traffic signal configurations, such as type of signals, percent green time and turning lanes, remains the same in the future analysis year, as that defined in the base year. The zero-volume delay values could change in the future, depending on alternative scenarios that include potential signal upgrades or timing improvements.

Because the analysis assumes no changes to the signalized roadway system the future zero-volume delay rate should be identical to the base year zero-volume delay rate. The difference between the areas in Figure 4 is directly due to the increased AADT.

Figure 4: Zero-Volume Delay Profile – Base and Future Analysis Years

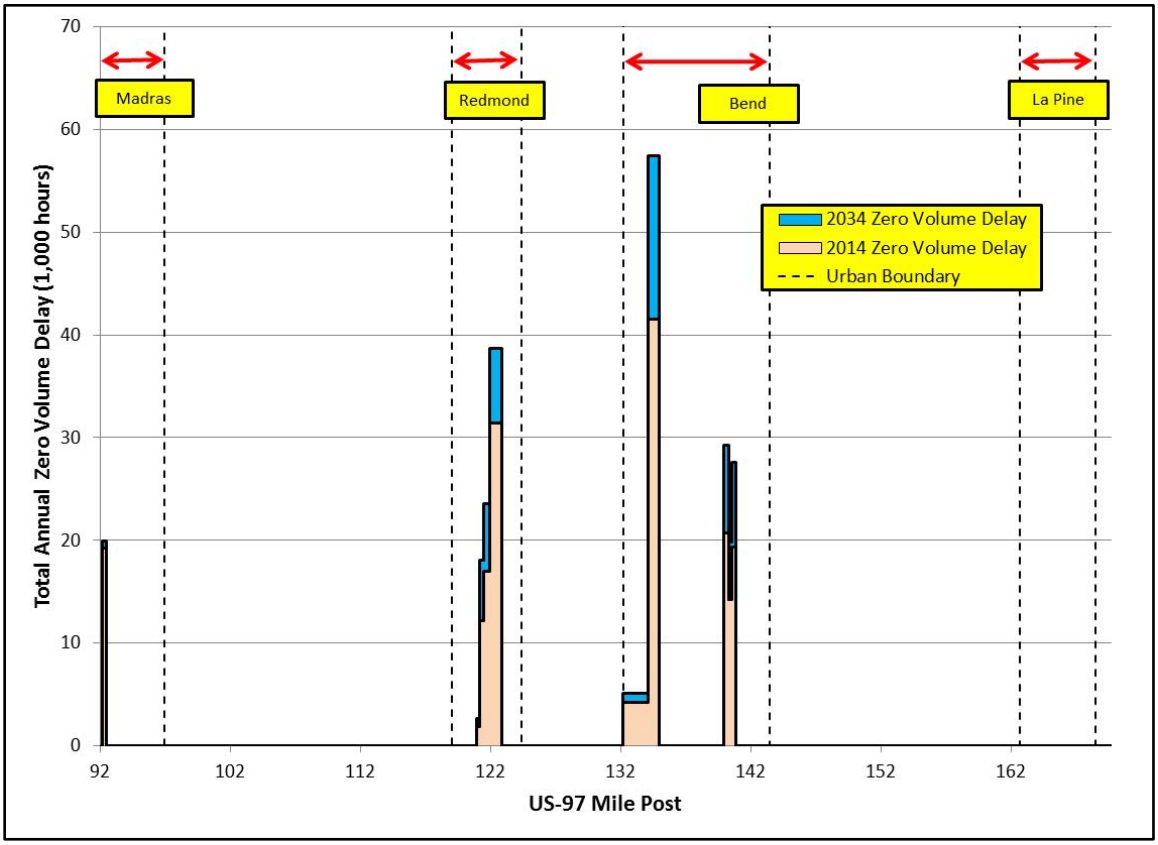


Table 2: Zero-Volume Delay Percent Difference (1,000 hours)

	2014		2034		20-Year	
	TOTAL	%	TOTAL	%	DIFF	%Diff
Corridor	184.5	--	247.8	--	63.4	34
RURAL						
URBAN	184.5	100	247.8	100	63.4	34
Madras	21.8	12	22.8	9	1.0	5
Rural01						
Redmond	62.5	34	84.8	34	22.3	36
Rural02						
Bend	100.1	54	140.2	57	40.1	40
Rural03						
La Pine						
Rural04						

Where:

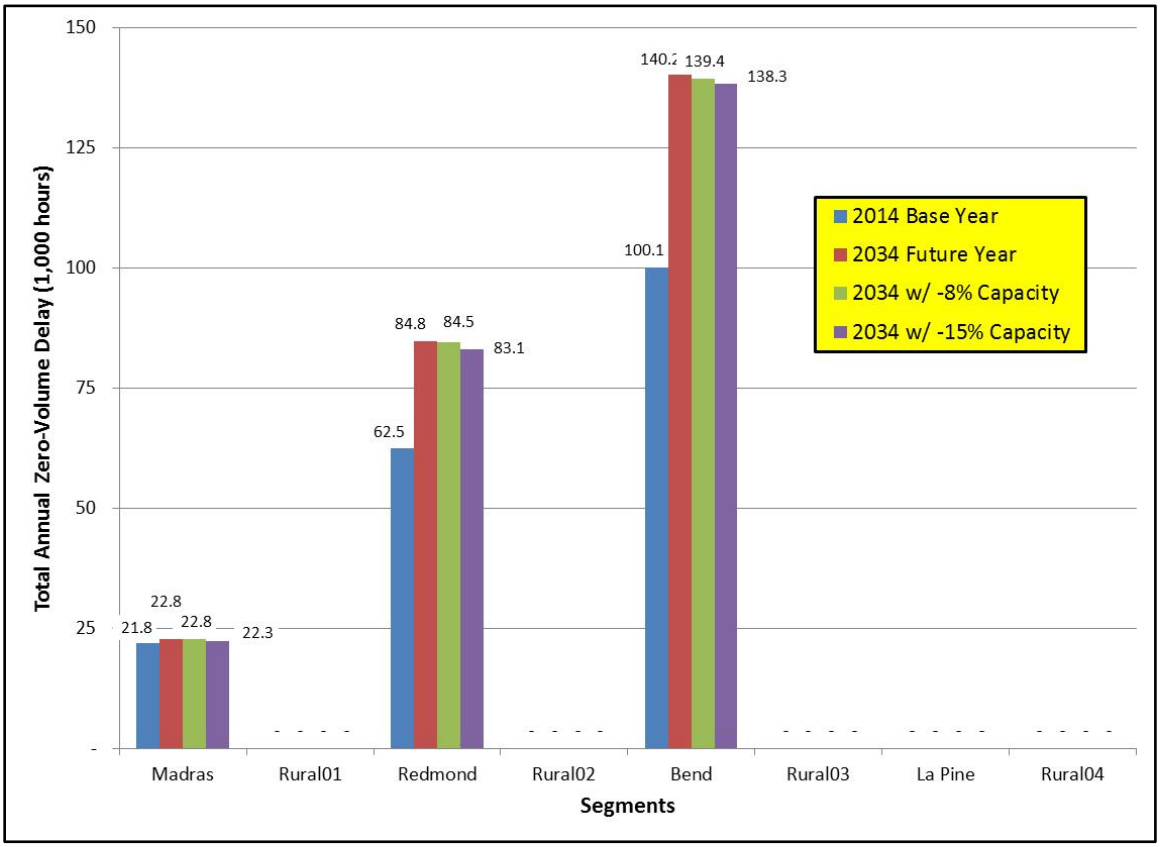
Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

The summary of the zero-volume delay for the various segments of the corridor are shown in Table 2. Over one-half of the delay is within the Bend area, which carries one-fourth of the total VMT for the corridor (see Table 1). One-third of the delay is found in

the Redmond area (with 10% VMT), and half again is found in the Madras area (with 3% VMT). These delay percentages appear to be reasonable when considering the proportional VMT within each of the three areas (see Table 1). The 20-year growth seems to be closely associated with the 20 year increase in VMT; as an example, the Redmond area shows a 34% 20-year growth in VMT area and a 36% growth in zero-volume delay over the same period of time.

Results of the two capacity reduction scenario, as shown in Figure 5, indicates minor reduction in the hours of delay at the different locations. The analysis only looks at capacity reduction for the future year condition, whereas similar type results could be expected had the capacity reduction been applied to the base year.

Figure 5: Zero-Volume Delay – Comparison with Capacity Reduction Scenarios



Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

Incident Delay

Incident delay is the delay associated with crashes. HERS-ST estimates delay due to crashes through a secondary (or inferred) process where the HERS-ST model estimates the cost of crashes and then back-calculates the delay estimates associated with crash incidents from the cost calculations.

Figure 6: Incident Delay Profile – Base and Future Analysis Years

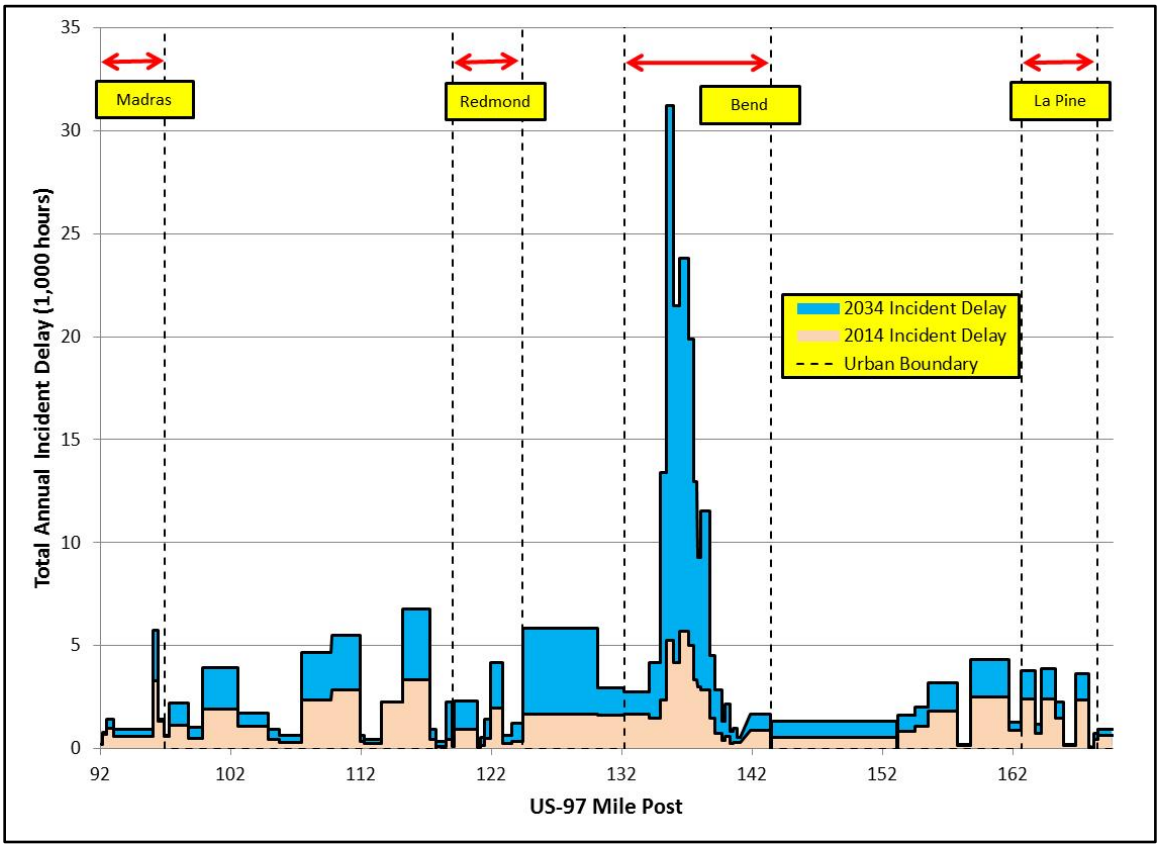


Figure 6 shows the profile of the average incident delay for the 2014 base and 2034 future analysis years, plotted along the corridor alignment. The largest increase in incident delay is located within the Bend urban boundaries, where the future incident delay is three times higher than the incident delay during the base year.

The summation of the total difference in the incident delay between the two analysis years on the roadway corridor is the area between the two curves.

The future capacity improvements feature was turned off for this analysis and not included in these results. This is a key point because this measure is directly associated with the predictive roadway safety, which is more indirectly associated with roadway geometry and capacity issues, such that future capacity improvements would alter the results of this study.

A summary of incident delay for the various categories is shown in Table 3. For the 2014 base year 67% of the incident delay is found in the urban area, which increases slightly to 77% for the future analysis period. The urban incident delay is double the rural incident delay in the 2014 base year, and three times as large in the 2034 future year. The urban area with the highest base year incident delay is the Bend area at 43% and 63% for the 2013 and 2034 analysis years, respectively. This would be expected because the Bend

area has both significantly higher VMT and more corridor mileage than the other urban areas.

The Madras and La Pine areas have about the same amount of incident delay for both the base year and the future analysis year. There is twice as much incident delay in the Madras and La Pine areas, as compared with the Redmond area. The major factor contributing to this difference is probably associated with the alignment characteristics because the Redmond area employs considerably stronger access control elements which significantly reduce the incident.

Table 3: Incident Delay Percent Difference (1.000 hours)

	2014		2034		20-Year	
	TOTAL	%	TOTAL	%	DIFF	%Diff
Corridor	92.1	--	267.0	--	174.9	190
RURAL	30.5	33	62.0	23	31.5	103
URBAN	61.5	67	205.0	77	143.4	233
Madras	7.3	8	10.7	4	3.3	45
Rural01	18.7	20	37.3	14	18.5	99
Redmond	4.3	5	11.0	4	6.7	157
Rural02	3.3	4	9.0	3	5.8	175
Bend	39.8	43	167.2	63	127.4	320
Rural03	7.9	8	14.8	5	6.9	87
La Pine	10.1	11	16.1	6	6.0	60
Rural04	0.6	1	1.0	0	0.3	55

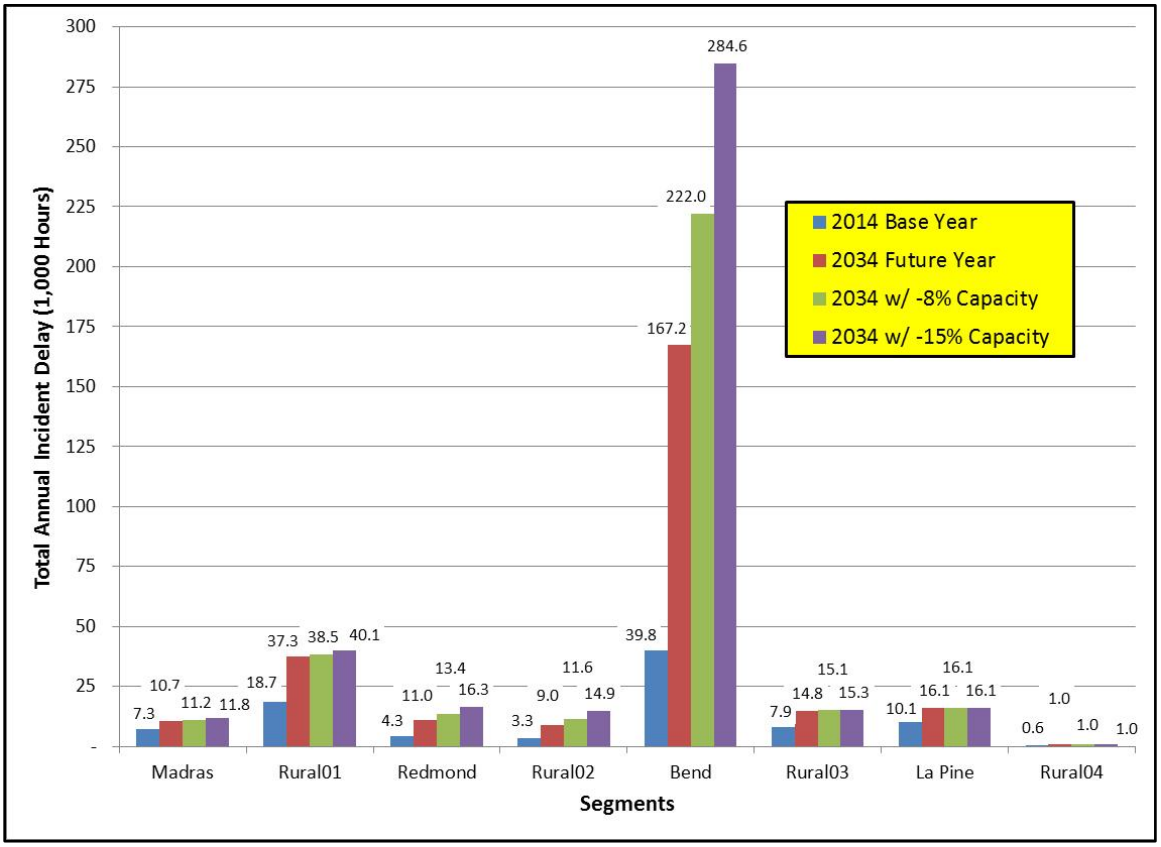
Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

The 20-year percent difference (%DIFF) represents the magnitude of the change over the 20-year analysis period. A doubling of a value is equivalent to a 100% increase for said value. The average incident delay for the overall corridor almost triples (increases 190%) over the 20-year analysis period. Most of this is due to the changes in the Bend area. This is an interesting point when considering the VMT growth is only 34% (see Table 1) for the same 20-year period of time. Evaluating the corridor by rural and urban area categories shows the average incident delay doubles in the rural areas, while increasing by three and a half times for urban areas.

This is seen in Figure 7, which shows the values for the difference analysis years stacked side by side. The annual total incident delay for the Bend area is substantially greater than any other area.

Figure 7: Incident Delay – Comparison with Capacity Reduction Scenarios



Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

Table 4: Corridor Incident Delay Summary, with/without Bend Area (1,000 hours)

Annual Total Incident Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	92.1	267.0	328.9	400.1
wo/ Bend	52.2	99.8	106.8	115.5
Annual Average Incident Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	11.5	33.4	41.1	50.0
wo/ Bend	7.5	14.3	15.3	16.5

Table 4 shows a summary of the annual total and annual average incident delay for the entire corridor, with and without the inclusion of the Bend area. The annual total incident delay is 92.1 and 267 (x 1,000) hours for the 2014 and 2034 analysis periods, respectively. However, if the Bend area is removed from the analysis, the annual total incident delay is reduced by almost half for the 2014 base year and by a third for the 2034

future year. This suggests that incident delay within the Bend area plays a major role in the total incident delay analysis for the corridor.

A similar evaluation of the annual average incident delay reveals much of the same. The annual average values are 11.5 and 33.4 (x 1,000) hours; the numbers are about halved when the Bend area is removed. In general, most all areas seem to have values near the level of the annual average without Bend, with the exception of the rural segment between Madras and Redmond (Rural01), which is well over twice the annual average without Bend.

Incident delay outside of the Bend area does not seem to change significantly when the reduced capacity scenarios are added to the analysis. A future year capacity reduction of 8%, which is similar to medium rain, increases the annual total incident delay by 7% when the Bend area is omitted from the analysis, but the increase is 23% when the Bend area is included. Similarly, the future year capacity reduction of 15%, which is similar to medium snow, increases the annual total incident delay by 15% when the Bend area is omitted from the analysis, but the increase is 50% when the Bend area is included. The contribution from the reduced capacity scenarios on the incident delay element plays out most significantly within the Bend area than anywhere else on the US-97 corridor.

NOTE: The reduced capacity scenarios are run as examples of the batch analysis process. The next steps would be to define all potential incident events, assign probabilities of occurrence to said events, run additional analysis and summarize results.

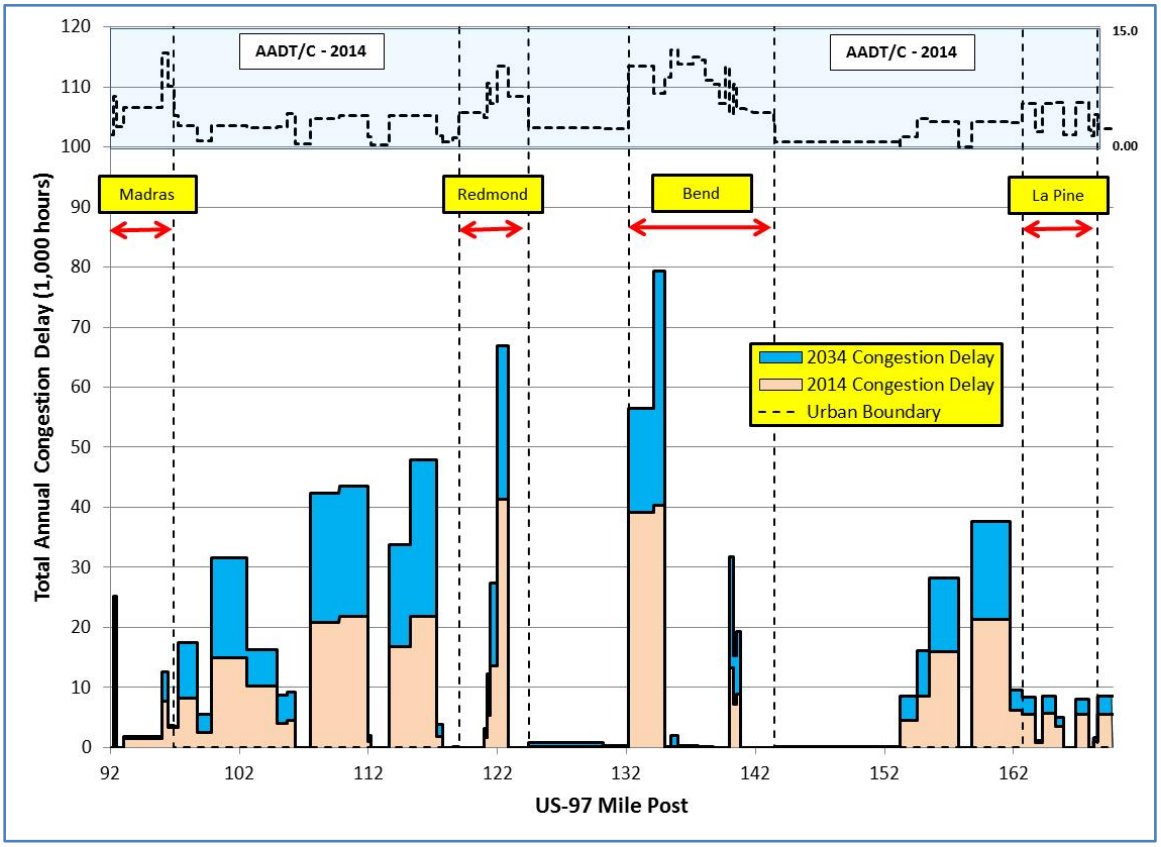
Other Delay

Other delay, also known as congestion or recurring delay, is the average delay due to non-incident congestion. HERS-ST evaluates average daily delay per 1,000 VMT as a function of the ratio of AADT/C.

The HERS-ST future capacity improvements option was turned off for this analysis and not included in these results. This is a key point because this measure is directly associated with the roadway capacity such that future capacity improvements would alter the results of this study.

Figure 8 shows the profile of the average other congestion delay for the base and future years, plotted along the corridor alignment. In addition, the 2014 AADT/C profile is inserted for reference purpose to give a better understanding on how congestion delay aligns with the volumes and capacity of the roadway system. The summation of the total congestion delay on the roadway corridor between the two analysis years is the area between the two curves.

Figure 8: Other (Congestion) Delay Profile – Base and Future Analysis Years



Because the congestion delay is defined as a function of AADT/C, an increase in capacity will result in a substantial decrease in delay. The decline of congestion delay within the rural segments (i.e., the valleys) is directly associated with the location of the multi-lane segments, known as passing lanes.

Table 5 shows the summary of the other congestion delay for the various categories. The percentage split between rural and urban is 46-54% for the 2014 base year, and almost 50-50 for the 2034 future year. The corridor alignment percentage split between rural and urban is 67-33% (see Table 1). The average (unweighted) AADT/C for the 2014 base year is 3.4 and 7.2 for the rural and urban areas, respectively.

The average other congestion delay increases 80% over the 20-year analysis period for the overall corridor.

The two areas with the largest congestion delay are the rural area between Madras and Redmond (Rural01) and the urban Bend area. Rural01 appears to have 20% more congestion delay for the 2014 base year then what is found in the Bend area, and 34% more in the 2034 future year. The average (unweighted) AADT/C for the 2014 base year is 3.5 and 8.7 for these two areas, rural and urban, respectively. The average AADT/C for Bend is over twice that for Rural01. The biggest factors to explain the reason why the congestion delay for rural Rural01 is higher than the urban Bend are the geometric

alignment and segment lengths. Rural01 is rolling terrain with the segment length twice that for Bend; Bend is a fairly flat terrain.

The two urban areas with the highest congestion delay are the cities of Bend and Redmond, at 109 and 62 (x 1,000) hours, respectively. The future year congestion appears to increase by 50% for the Redmond area, while doubling for the Bend area.

Though the rural area between Redmond and Bend (Rural02) increases by 196%, the actual value is so low that it should be considered insignificant.

Table 5: Other (Congestion) Delay Percent Difference (1,000 hour)

	2014		2034		20-Year Diff	
	TOTAL	%	TOTAL	%	DIFF	%Diff
Corridor	426	--	767	--	341	80
RURAL	195	46	376	49	182	93
URBAN	232	54	391	51	159	69
Madras	38	9	42	5	4	10
Rural01	132	31	266	35	134	101
Redmond	62	15	110	14	48	77
Rural02	0	0	1	0	1	196
Bend	109	26	206	27	97	88
Rural03	57	13	100	13	44	78
La Pine	22	5	33	4	11	49
Rural04	6	1	9	1	3	53

Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

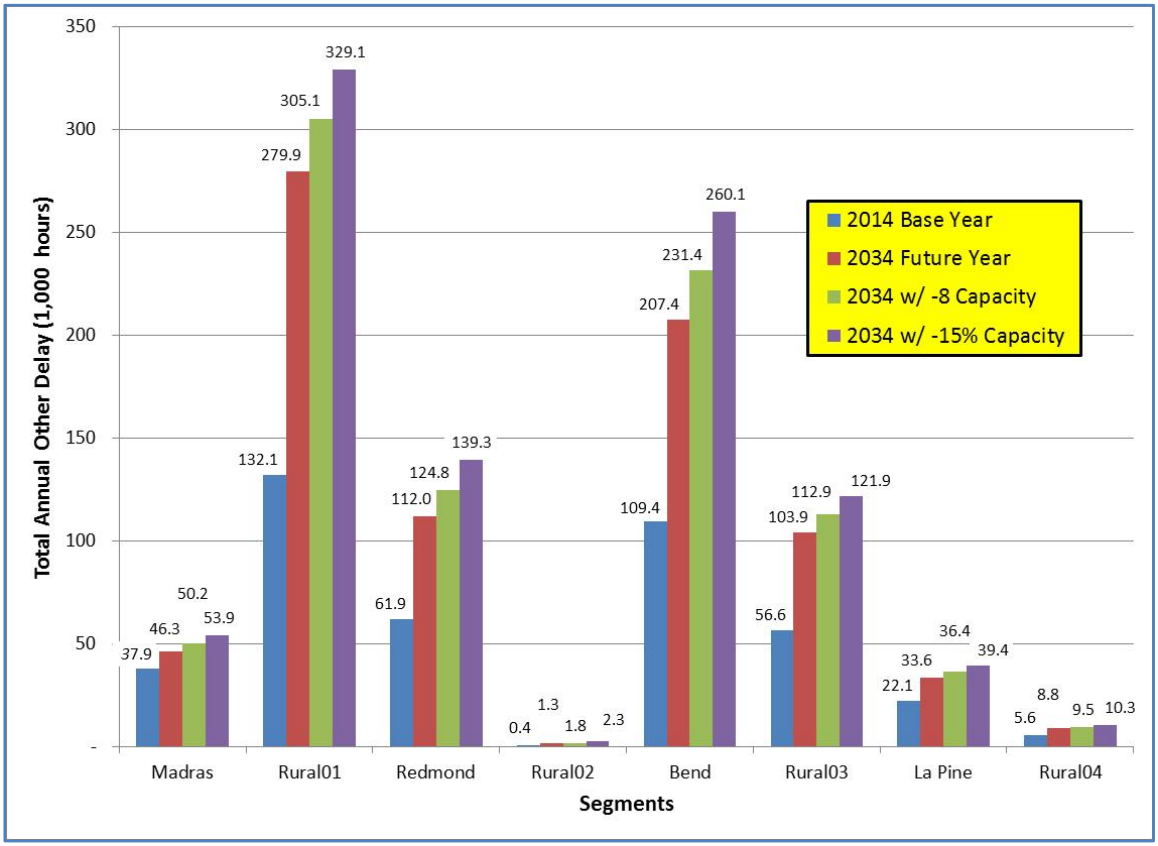
Table 6: Corridor Congestion Delay Summary, with/without Bend Area (1,000 hours)

Annual Total Congestion Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	426.1	793.0	872.2	956.3
wo/ Bend	316.6	585.7	640.8	696.3
Annual Average Congestion Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	53.3	99.1	109.0	119.5
wo/ Bend	45.2	83.7	91.5	99.5

Table 6 shows a summary of the annual total and annual average congestion delay for the entire corridor, with and without the inclusion of the Bend area. The annual total congestion delay is 426.1 and 793.0 (x 1,000) hours for the 2014 and 2034 analysis periods, respectively. However, if the Bend area is removed from the analysis, the annual total congestion delay is reduced by a quarter for both the 2014 base year and the 2034 future year. This suggests that congestion delay within the Bend area only plays a minor role in the total congestion delay analysis within the overall corridor.

A similar evaluation of the annual average congestion delay reveals much of the same. The annual average values are 53.3 and 99.1 (x 1,000) hours; the numbers are 15% lower when the Bend area is removed.

Figure 9: Other (Congestion) Delay – Comparison with Capacity Reduction Scenarios



Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

Congestion delay outside of the Bend area does not seem to change significantly when the reduced capacity scenarios are added to the analysis. A future year capacity reduction of 8% (i.e., medium rain) increases the annual total congestion delay by 10%, with or without inclusion of the Bend area. Similarly, the future year capacity reduction of 15% (i.e., medium snow) increases the annual total congestion delay by 20%, with or without inclusion of the Bend area. The contribution from the reduced capacity scenarios on the congestion delay element does not appear to be any more significant within the Bend area than anywhere else on the US-97 corridor.

Figure 9 shows the base and future year values for the congestion delay stacked together.

Total Delay

Total Delay is the summation of the three individual delay elements: zero-volume, incident and other congestion.

Figure 10: Total Delay Profile – Base and Future Analysis Years

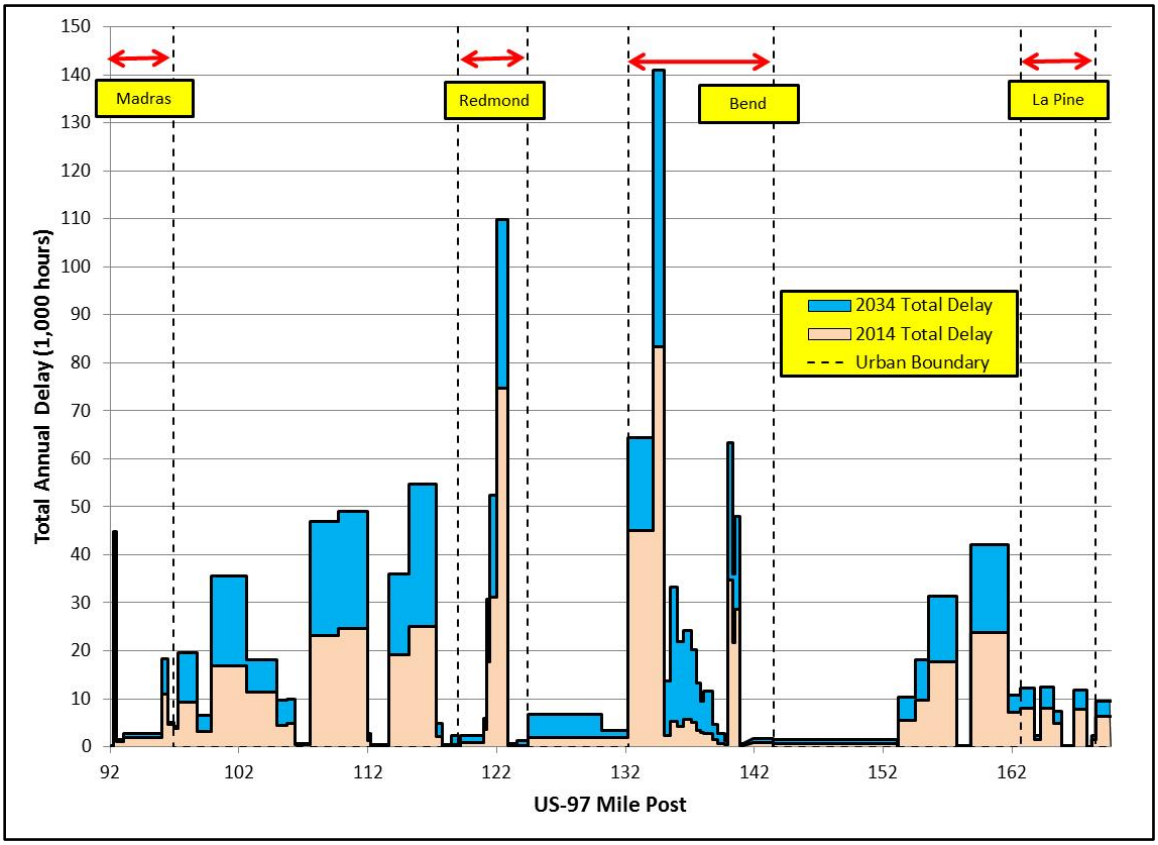


Figure 10 shows the profile of the average total delay for the base and future years, plotted along the corridor alignment. The summation of total delay between the two analysis years on the roadway corridor is the area between the two curves.

Table 7 shows the summary of total delay for the various categories. Two thirds of the total delay is found in the urban area, which seems fairly consistent across the 20-year analysis period.

For the 2014 base year, the Bend area shows the most total delay, at 249.4 (x 1,000) hours, which is about twice that for the Redmond area, at 128.7 (x 1,000) hours, and four times that for the Madras area. The trend is similar for the 2034 future year, with some slight exaggeration in the percentages.

Table 7: Total Delay Percent Difference (1,000 hour)

	2014		2034		20-Year Diff	
	TOTAL	%	TOTAL	%	DIFF	%Diff
Corridor	702.6	--	1,308.0	--	605.4	86
RURAL	225.2	32	455.9	35	230.7	102
URBAN	477.3	68	852.1	65	374.7	79
Madras	67.1	10	79.7	6	12.6	19
Rural01	150.9	21	317.1	24	166.2	110
Redmond	128.7	18	207.8	16	79.2	62
Rural02	3.7	1	10.4	1	6.7	182
Bend	249.4	35	514.8	39	265.5	106
Rural03	64.5	9	118.7	9	54.2	84
La Pine	32.2	5	49.7	4	17.5	54
Rural04	6.2	1	9.7	1	3.5	57

Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

For the overall corridor, the total delay almost doubles (i.e., 86%) over the 20-year analysis period. The average percent difference for the urban areas is 79%, with the Bend area being highest at 106%, while the Madras area is lowest at 19%. The average percent difference for the rural areas is 102%, with the Rural02 being highest at 182%, while the Rural04 is lowest at 57%. The actual values for Rural02 and Rural04 are low and considered insignificant for the corridor analysis.

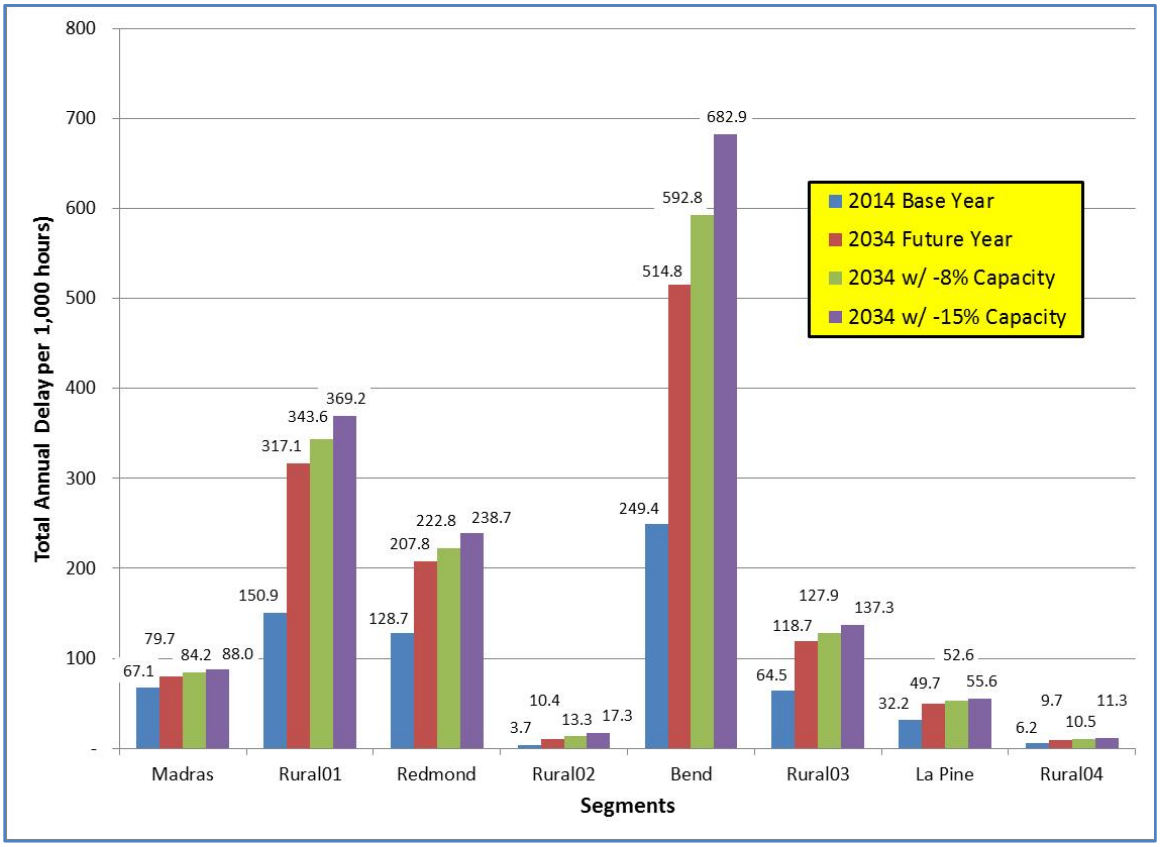
Table 8: Corridor Total Delay Summary, with/without Bend Area (1,000 hours)

Annual Total Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	702.6	1,308.0	1,447.7	1,600.3
wo/ Bend	453.2	793.1	854.9	917.3
Annual Average Total Delay				
	2014	2034	2034 w/ -8% Capacity	2034 w/-15% Capacity
w/ Bend	87.8	163.5	181.0	200.0
wo/ Bend	64.7	113.3	122.1	131

Table 8 shows a summary of the annual total and annual average total delay for the entire corridor, with and without the inclusion of the Bend area. The annual total delay is 702.6 and 1,308 (x 1,000) hours for the 2014 and 2034 analysis periods, respectively. However, if the Bend area is removed from the analysis, the annual total delay is reduced by a third for both the 2014 base year and 2034 future year. This suggests that total delay within the Bend area only plays a minor role in the total delay analysis within the overall corridor.

A similar evaluation of the annual average total delay reveals much of the same. The annual average values are 87.7 and 163.5 (x 1,000) hours. The numbers are about 25% lower when the Bend area is removed.

Figure 11: Total Delay – Comparison with Capacity Reduction Scenarios



Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

Total delay outside of the Bend area does not seem to change significantly when the reduced capacity scenarios are added to the analysis. A future year capacity reduction of 8% (i.e., medium rain) increases the annual total delay by 10%, with or without inclusion of the Bend area. Similarly, the future year capacity reduction of 15% (i.e., medium snow) increases the annual total delay by 20%, with or without inclusion of the Bend area. The contribution from the reduced capacity scenarios on the total delay element does not appear to be any more significant within the Bend area than anywhere else on the US-97 corridor.

Figure 11 shows the base and future year values for the congestion delay stacked together.

The future capacity improvements feature was turned off for this analysis and not included in these results. This is a key point because this measure is directly associated with the projected roadway safety and capacity, such that future capacity improvements would alter the results of this report. This serves as a reference in the case of no further capacity enhancement.

Predictive Tool

HERS-ST can be used as a predictive tool to evaluate the future performance indicators for delay on the roadway system. Based on a no build scenario, total delay on the corridor is expected to increase by 86% over the 20-year analysis period (see Table 7), which represents a 3.16% annual growth in total delay. However, because the corridor has many different segments, some with more rural characteristics, and others with more urban type, it makes more sense to evaluate the corridor at the eight unique segment levels identified throughout all tables in this report.

Madras

The Madras area segment shows a 19% increase in total delay over the 20-year analysis period, which represents a 0.87% annual growth in total delay. Eight to 10% of the total delay for the total corridor is associated with the Madras area. The proportional split for the three delay categories is 33%, 11%, 57% for base year, and 29%, 13%, 58% for future analysis year, for zero-volume, incident and other congestion, respectively. This suggests that about one third of the delay in Madras is associated with the signals, 60% is associated with congestion and 12% is tied to incidents.

Rural01

The segment between Madras and Redmond (Rural01) shows a 110% increase in total delay over the 20-year analysis period, which represents a 3.78% annual growth in total delay. Twenty one to 24% of the total delay for the total corridor is associated with the Rural01 area. Because this is a rural section, there is no zero-volume delay. The proportional split for the two remaining delay categories is 12% and 88% for both base year and future analysis year, for incident and other congestion, respectively. Though the percent splits seem consistent across the different analysis periods, the congestion delay seems high for the area. Similar proportional splits are found in Rural03 and Rural04.

Redmond

The Redmond area segment shows a 62% increase in total delay over the 20-year analysis period, which represents a 2.43% annual growth in total delay. Sixteen to 18% of the total delay for the total corridor is associated with the Redmond area. The proportional split for the three delay categories are 49%, 3%, 48% for base year, and 41%, 5%, 54% for future analysis year, for zero-volume, incident and other congestion, respectively. This suggests that just under half of the delay in Redmond is associated with the signals, and half is associated with congestion, leaving a small sliver of delay tied to incidents.

Rural02

The segment between Redmond and Bend (Rural02) is a major commuting route between housing in Redmond and employment in Bend. The roadway is multilane and functions more like an expressway rather than a principal arterial. One percent of the total delay for the total corridor is associated with the Rural04 area. Because this is a rural section, there is no zero-volume delay. The proportional split for the two remaining delay categories is 88% and 12% for both base year and future analysis year, for incident and

other congestion, respectively. It is interesting to note these proportional splits are directly opposite of what is seen in Rural01, Rural03 and Rural04.

Bend

The Bend area segment shows a 106% increase in total delay over the 20-year analysis period, which represents a 3.69% annual growth in total delay. Thirty five to 39% of the total delay for the total corridor is associated with the Bend area. The proportional split for the three delay categories is 40%, 16%, 44% for base year, and 27%, 32%, 40% for future analysis year, for zero-volume, incident and other congestion, respectively. The signal delay decreases about the same amount the incident delay increases. Only the congestion delay appears consistent across the 20-year analysis period. The signal and incident delay decreases/increases about the same 15%, respectively.

Rural03

The segment between Bend and La Pine (Rural03) shows an 84% increase in total delay over the 20-year analysis period, which represents a 3.10% annual growth in total delay. Nine percent of the total delay for the total corridor is associated with the Rural03 area. Because this is a rural section, there is no zero-volume delay. The proportional split for the two remaining delay categories is 12% and 88% for both base year and future analysis year, for incident and other congestion, respectively. Though the percent splits seem consistent across the different time periods, the congestion delay seems high for the area. Similar proportional splits are found in Rural01 and Rural04.

La Pine

The La Pine area segment shows a 54% increase in total delay over the 20-year analysis period, which represents a 2.19% annual growth in total delay. Four to 5% of the total delay for the total corridor is associated with the La Pine area. Because there are no signals within the La Pine area, there is no zero-volume delay. The proportional split for the two remaining delay categories is 31% and 69% for base year, and 32% and 68% for future analysis year, for incident and other congestion, respectively. The proportional splits are consistent across the time periods, and suggests that about one third of the delay in La Pine is associated with incidents, while two thirds of the delay is attributed to congestion.

NOTE: At the time of the analysis there were no signalized intersections located on US-97 within the La Pine area. Since that time a signal has been installed at the intersection of US-97 and 1st Street.

Rural04

The segment between La Pine and OR-30 (Rural04) shows a 57% increase in total delay over the 20-year analysis period, which represents a 2.27% annual growth in total delay. One percent of the total delay for the total corridor is associated with the Rural04 area. Because this is a rural section, there is no zero-volume delay. The proportional split for the two remaining delay categories is 10% and 90% for base year and future analysis year, for incident and other congestion, respectively. Though the percent splits seem

consistent across the different time periods, similar proportional splits are found in Rural03 and Rural04.

Reliability

Travel time reliability is an attempt to quantify the uncertainty in travel times that a traveler might experience from day to day, across different times of day. Travel times can vary considerably by time of day (TOD), day of the week (DOW) and month of the year (MOY) simply because of changes in traffic demand and/or capacity associated with congestion, incident, weather and work zones. Everyday congestion is common and most travelers expect and plan for some level of delay based on when and where they are going. However, the unexpected delay encountered by a traveler due to such things as weather, incidents and work zones can have a significant impact on the effectiveness of the transportation system. Travel time reliability measures attempt to account for the unexpected elements that an average travel time cannot capture.

A sketch planning method approach is highlighted in the Technical Reference for The Second Strategic Highway Research Program (SHRP 2) Project L05 *Incorporating Reliability Performance Measures into the Transportation Planning Program Process*[7]. This technical reference in Chapter 2 provides an overview of what travel time reliability is and why it is important. A discussion on the tools and methods for estimating reliability are presented in Chapters 3 and 4 and includes the application of sketch-planning tools and other approaches utilizing simulation. The methodical process for development reliability analysis is discussed in Chapter 5. The previous discussion on using HERS-ST as a tool for evaluating delay should be used as a replacement for Chapters 3 and 4 in the SHRP 2 Project L05 report.

The SHRP 2 Project *C11: Reliability Analysis Tool: Technical Document*[8] is an enhancement of the SHRP 2 L05 Project. The C11 report provides guidance on the application of the data-poor reliability prediction equations initially described in the SHRP 2 L05 report. A review of the data elements listed on page 10 of the C11 technical document suggests that a standard HPMS dataset would suffice for analysis. HERS-ST is a complex modeling tool that utilizes the HPMS dataset format.

The application of HERS-ST as a predictive tool for evaluating existing and future delay on a roadway system has been discussed in the previous sections. Reliability introduces the element of variation in travel time that is encountered daily on the roadway system; i.e., variation due to weather, incidents or work zone. There are a number of proposed

[7] Cambridge Systematics, Inc. *SHRP 2 Project L05: Incorporating Reliability Performance Measures into the Transportation Planning and Programming Process, Technical Reference*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, 2014. http://www.trb.org/Main/Blurbs/168856.aspx

[8] Cambridge Systematics, Inc., Weris, Inc., and Economic Development Research Group, Inc. *SHRP 2 Project C11: Reliability Analysis Tool: Technical Documentation*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, January 2013

performance measures being discussed at the national audience level, and the MAP-21 guidelines are due to be released in the next few months.

Performance Measures

This section will focus on three specific performance measures: Travel Time Index (TTI), Planning Time Index (PTI), and the Buffer Index (BI).

TRAVEL TIME INDEX

TTI measures the travel time mobility of the roadway system during the peak period. TTI is a rough indicator of the severity of congestion, and is defined as the ratio of the average travel time during the peak period to the free-flow travel time, where free-flow is an off-peak period of unobstructed traffic flow.

$$TTI = \frac{\text{Peak Average Travel Time}}{\text{Free} - \text{Flow Travel Time}}$$

A TTI of unity indicate the average peak travel time is the same as the free flow travel time mean that there is no delay on the system. A TTI of 1.25 indicated that the average peak travel time is 125% of the free-flow travel time. This suggests that it should take 25% longer to travel the roadway segment during the peak period than it would under uncongested conditions. As an example, a trip that would normally take 8 minutes during the off-peak period would take 10 minutes during the peak period.

The average peak travel time is typically used for the TTI calculations, but occasionally the same term will be used to represent various percentile travel time measures, such as the 80th or 95th percentiles. For such cases there should be a clear indication of the differences, such as TTI_{50} for the 50th percentile TTI, TTI_{80} is the 80th percentile TTI and TTI_{95} is the 95th percentile TTI.

The Overall Mean Travel Time Index (TTI_m) equation was developed for the SHRP 2 Project to incorporate both the congestion (recurring) and incident delay. These delay elements have been previously discussed in this report. The following equations from the SHRP 2 Project C11 report have been utilized in this analysis:

$$TTI_m = 1 + FFS * (RecurringDelayRate + IncidentDelayRate)$$

Where:

RecurringDelayRate – Aggregated Other Congestion Delay Rate from HERS-ST sectional output
IncidentDelayRate – Aggregated Incident Delay Rate from HERS-ST sectional output

$$TTI_{50} = 4.01224/\{(1 + e^{(1.7417 - 0.93677 * TTIm)})^{(1/0.82741)}\};\ TTI_{50} >= 1.0$$

$$TTI_{80} = 5.3746/\{(1 + e^{(-1.5782- 0.85867 * TTIm)})^{(1/0.04953)}\};\ TTI_{80} >= 1.0$$

PLANNING TIME INDEX

PTI is a measure for travel time reliability and is an indicator of the variability in the average peak travel time. It is a special case of TTI in that it is typically computed as the 95th percentile of TTI. It reflects the near-worst case travel time and is an indicator of how much total time a traveler should allow to ensure their arrival on-time 95% of the time. As an example, for a commuter it is the total travel time needed to ensure an on-time arrival to work 19 days out of 20; this would allow a commuter to be late to work one day out of the month. PTI is also referred to as TTI_{95}.

$$PTI = \frac{\text{95th Percentile Peak Travel Time}}{\text{Free} - \text{Flow Travel Time}}$$

As an example, a PTI of 2.50 indicated that the average peak travel time is 250% of the free-flow travel time. Using this PTI, if a commuter can only be late to work one day a month they need to plan for a 20 minute travel time during the peak period for a trip that would normally take 8 minutes during the off-peak period, in order to ensure they arrive to work on time 19 out of 20 days.

The following equation from the SHRP 2 Project C11 report has been utilized in this analysis:

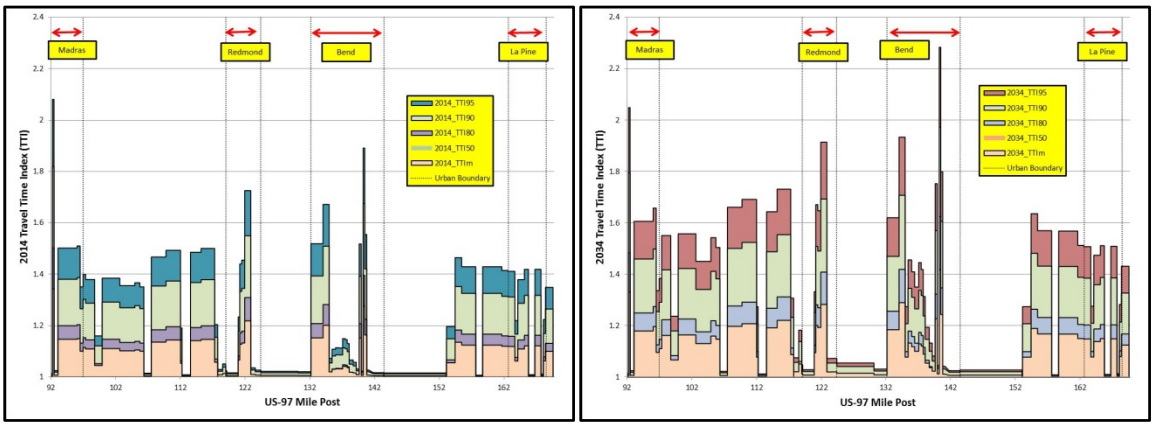
$$TTI_{95} = 1 + 3.6700 * \ln(TTI_m)$$

NOTE: The TTI_m and TTI_{95} were originally proposed in SHRP 2 L03 "Data Poor" Equations, whereas TI_{80} and TTI_{50} were developed specifically for SHRP 2 C11.

The Travel Time Index profiles for the different percentile, for the 2014 and 2034 analysis periods, are provided in Figure 12. The two graphs are plotted at the same vertical scale to simplify the comparison.

All two-lane rural segments and signalized urban segments show the largest amount of variation in travel time, regardless of the percentile levels evaluated.

Figure 12: Travel Time Index Profile on US-97
(a) 2014 **(b) 2034**



Utilizing the various equations from the C11 report, the daily TTI's for the mean, 50%, 80%, and 95% are calculated and provided in Table 9. The typical TTI calculations are a comparison of peak-period travel time to free-flow travel time. The analysis in the report is associated with daily TTI, not peak period TTI.

The TTI_{95} (also known as PTI) corridor level values are 1.21 and 1.31 for base and future years, respectively. However, with a corridor length of 74 miles, the reference travel time to traverse the entire corridor is almost an hour and half (i.e., ninety minutes). Because the corridor passes through different rural and urban roadway characteristics, an evaluation of the various performance measures will have limited meaning at this level of analysis. It is more practical to look at the value for the individual area.

Table 9: Travel Time Index Summary – Mean, 50%, 80% and 95%

	2014				2034			
	TTI_m	TTI_{50}	TTI_{80}	TTI_{95}	TTI_m	TTI_{50}	TTI_{80}	TTI_{95}
Corridor	1.06	1.03	1.12	1.21	1.09	1.05	1.18	1.31
Madras	1.11	1.07	1.08	1.38	1.13	1.08	1.25	1.43
Rural01	1.10	1.05	1.13	1.33	1.14	1.08	1.28	1.47
Redmond	1.06	1.04	1.08	1.21	1.09	1.05	1.17	1.29
Rural02	1.01	1.00	1.00	1.02	1.01	1.00	1.03	1.05
Bend	1.07	1.03	1.09	1.24	1.12	1.07	1.24	1.41
Rural03	1.04	1.02	1.06	1.15	1.06	1.03	1.11	1.20
La Pine	1.08	1.04	1.11	1.29	1.10	1.06	1.21	1.36
Rural04	1.09	1.04	1.12	1.32	1.12	1.06	1.24	1.41

The TTI_{95} for all segments for both base and future years is provided in Table 10. The reference travel time is the travel time at the poste speed. The travel time based on the TTI_{95} is TT_{95} and Added Time is the difference in travel time between TT_{95} and the reference travel time.

Table 10: Planning Time Index Summary – 2014 & 2034

	Length	Reference	2014			2034		
	(miles)	Travel Time (min)	TTI_{95}	Travel Time @ TTI_{95} (min)	Added Time (min)	TTI_{95}	Travel Time @ TTI_{95} (min)	Added Time (min)
Corridor	73.72	88.8	1.21	111.9	18.6	1.31	120.8	27.1
Madras	1.92	6.5	1.38	9.6	2.5	1.43	9.9	2.8
Rural01	22.10	24.7	1.33	32.9	8.2	1.47	36.3	11.7
Redmond	5.39	6.4	1.21	8.8	1.4	1.29	9.3	1.8
Rural02	7.78	8.5	1.02	8.7	0.2	1.05	8.9	0.4
Bend	10.54	13.4	1.24	18.2	3.2	1.41	20.5	5.6
Rural03	17.40	20.9	1.15	24.1	3.2	1.20	25.1	4.1
La Pine	5.83	8.2	1.29	10.5	2.4	1.36	11.1	3.0
Rural04	2.76	0.2	1.32	0.3	0.1	1.41	0.3	0.1

Using the Bend area as an example in Table 10, the US-97 alignment through Bend is 10.54 miles in length. Assuming that a traveler maintains the speed limit along the entire length (i.e., not needing to slow down or stop at the signalized intersections) they should normally be able to traverse the segment in 13.4 minutes. The PTI (i.e., TTI_{95}) for the Bend area is 1.24 and 1.41 for the 2014 and 2034 analysis years, respectively. Using PTI to account for the variability in the travel time, the traveler should allow an additional 3.2 minutes @ $TTI_{95} = 1.24$ to ensure traversing the entire Bend area 95% of the time for the 2014 base year. The additional time surges to 5.6 minutes for the 2034 future analysis year with $TTI_{95} = 1.41$. A traveler in 2034 should expect to take an additional 2.5 minutes (i.e., 75% increase in the additional travel time) to achieve the same 95th percentile travel time as observed in 2014.

NOTE: These values only cover travel on US-97 and do not include potential delay on other streets off US-97.

BUFFER INDEX

BI is closely related to the PTI. It is typically considered the percentage of extra time that a traveler needs to add to a trip to ensure a 95% on time arrival. It is the cushion of travel time that reasonably accounts for the worst travel conditions due to the varying congestion and delay issues on the transportation system.

$$BI = \frac{\text{95th Percentile Peak Travel Time} - \text{Average Travel Time}}{\text{Average Travel Time}}$$

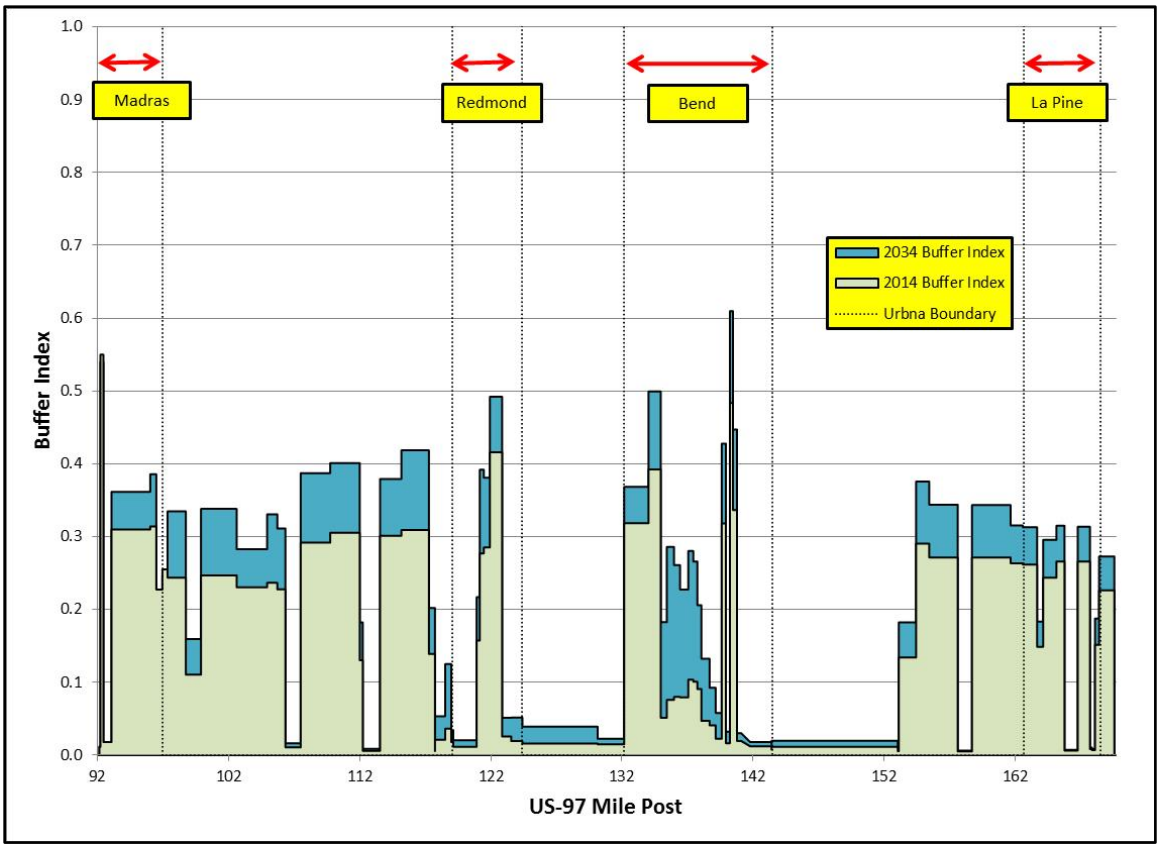
The BI is a percent factor that provides the buffer time when applied to the average travel time. Using the numbers from the PTI example, with a 95th percentile peak travel time of 20 minutes and an average travel time of 8 minutes, the BI is 1.5. The extra cushion of time is the BI times the average travel time (1.5*8), or 12 minutes.

The following equation from the SHRP 2 Project L05 report has been utilized in this analysis:

$$\text{Buffer Index} = (TTI_{95} - TTI_m) / TTI_m$$

The buffer index profile is provided in Figure 13 as a quick way to evalaute the locations that show the greatest variation in travel time on the corridor alignment for the 2014 and 2034 analysis periods.

Figure 13: Buffer Index Profile on US-97



The difference in BI between the 2014 and 2034 analysis periods is the area under the 2034 curve in Figure 13, minus the area under the 2014 curve. A summary of the average BI for each analysis year, weighted by VMT, and the percent difference between the analysis years are provided by area in Table 11.

Table 11: Buffer Index Summary* – 2014 & 2034

	2014 (%)	2034 (%)	%Diff
Corridor	13	18	40
Madras	22	25	13
Rural01	21	28	34
Redmond	13	17	28
Rural02	2	4	128
Bend	15	25	68
Rural03	10	12	22
La Pine	19	22	20
Rural04	21	26	22

* Weighted by VMT

Where:

Rural01 – Segment between Madras and Redmond
Rural02 – Segment between Redmond and Bend
Rural03 – Segment between Bend and La Pine
Rural04 – Segment between La Pine and Jct. OR-31

Using Rural02 as an example, the average BI is 128% higher in 2034 than in 2014. A quick look at Figure 13 reveals that the percent difference is uniformally spread across three quarters of the Rural02 alignment, however, the overall averages are small indicating that there is little variation in travel time through this area.

The average BI for the Bend area is 68% higher in 2034 than in 2014. A quick look at Figure 13 reveals that the percent difference is not uniformally spread across the Bend area; this is a simple approach to highlight the segments on the corridor alignment with the greatest varation in 2014 and 2034.

Conclusion

The HERS-ST model is an excellent tool for evaluating base and future year performance criteria, such as delay. The tool is a good choice for assessing base and future MAP-21 performance targets associated with pavement and congestion, and also demonstrates exceptional potential for reliability applications. HERS-ST is also a good choice for the scenario analysis and strategic planning expectations associated with PBPP.

HERS-ST can provide reasonable analysis for inadequate base capacity (40%), incidents (25%), and traffic control devices (5%), which make up 70% of the causes of delay on most roadway systems. The effects of weather, work zones, and special events can be evaluated by adjusting the capacity and/or demand input data. The probabilities and impacts from the various delay events can be modeled through an automated batching process that can run numerous scenarios associated with the likelihood that different combinations of delay events occur.

Though HERS-ST does not directly calculate performance measures associated with reliability analysis, such as Travel Time Index (TTI) and Planning Time Index (PTI), the delay elements from HERS-ST outputs can be used in post-processing analysis to develop TTI and PTI values.

There are proposed intersection improvements for US-97. A signalized intersection added in La Pine, and two signalized intersections in Bend were to be replaced with interchanges. Since the completion of the project analysis the signal has been added in La Pine. The proposed intersection changes in Bend have not been completed. These improvements would influence the 2034 analysis.

References

Cambridge Systematics, Inc. *SHRP 2 Project L05: Incorporating Reliability Performance Measures into the Transportation Planning and Programming Process, Technical Reference*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, 2014. http://www.trb.org/Main/Blurbs/168856.aspx

Cambridge Systematics, Inc., Weris, Inc., and Economic Development Research Group, Inc.. *SHRP 2 Project C11: Reliability Analysis Tool: Technical Documentation*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, January 2013

Federal Highway Administration. *"Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies,"* FHWA-HOP-13-042, Washington, D.C., June 2013.

Federal Highway Administration. "*HERS-STv5: Highway Economic Requirements System – State Version: User Guide,"* Washington, D.C.: US DOT/FHWA, September 2014

Federal Highway Administration. 2006. "*Highway Economic Requirements System – State Version: Technical Report,"* Washington, D.C.: US DOT/FHWA, August 2005

APPENDIX A – General HERS-ST Analysis Concepts[9].

Average Speed

The speed procedure within HERS-ST is based on a simplified version of the Aggregate Probabilistic Limiting Velocity Model (APLVM) and covers two distinct processes, free-flow speed (FFS) and average effective speed (AES). The FFS estimation is developed to reflect the average unconstrained speed that exists on the highway system in the absence of any other traffic or geometric influences. The FFS estimates are then adjusted to account for the effects of grades, congestion delay and traffic control devices to produce the AES for each roadway segment.

Several key data elements affect speed, including vehicle type, curves, grades, pavement surface quality, speed limits, congestion and traffic control devices. There are three controlling factors in the APLVM that potentially limit the free speed on a roadway section: curves, pavement roughness and posted speed limit. All of these factors have the potential of lowering the sectional speed estimate.

A vehicle traveling through a curved roadway section is subject to a centrifugal force that acts against the vehicle, forcing it to leave the curved path of the roadway. The higher the vehicular speed entering the curve, the heavier the vehicle, and the sharper the curvature of the road, the greater the external force acting upon the vehicle. This results in a reduced FFS for the roadway section.

When the pavement is smooth and the curvature is low (below two degrees) the average speed is governed by the posted speed limits. This model does not explicitly consider enforcement.

HERS-ST evaluates speed individually for each of the seven vehicle types, per direction of travel, than aggregates the individual speeds to calculate operating and travel time costs.

HERS-ST evaluates delay based on six types of highway characteristics associated with number of lanes and the type and presence of traffic control devices:

- Sections with stop signs, covering urban arterials with unsignalized intersections.
- Sections with traffic signals, covering urban arterials with signalized intersections.
- Sections with stop signs and traffic signals, covering both urban arterials with unsignalized intersections and urban arterials with signalized intersections.
- Free-flow sections, one lane per direction, covering two-lane rural sections
- Free-flow sections, three-lane two-way, covering two-lane rural sections and modified freeways and multilane rural highways.
- Free-flow sections. Two or more lanes per direction, covering freeways and multilane rural highways.

[9] HERS-ST model uses six internal models: Fleet Composite Model, Widen Feasibility Model, Capacity Model, Pavement Deterioration Model, Speed Model and Travel Forecast Model

Average Delay

There are three kinds of delays estimated in HERS-ST:

- Zero-volume delay is the delay associated with traffic control devices. This is the expected delay that a single vehicle would encounter even if it were the only vehicle on the road. Zero-volume delay only exists for sections controlled with stop signs or traffic signals and is not calculated for uncontrolled sections.
- Incident delay is the delay associated with crashes. HERS-ST estimates delay due to crashes through a secondary (or inferred) process where the HERS-ST model estimates the delay cost of crashes and then back-calculates the delay estimates due to crash incidents from the cost calculations.
- Other congestion (or recurring) delay is the average delay due to non-incident congestion.

Total daily traffic is broken into three phases, or demand periods, for all delay and speed analysis:

- Peak period analysis in the peak direction.
- Peak period analysis in the counter-peak direction.
- Off peak analysis in both directions.

Capacity

HERS-ST calculates peak capacity as a two-way capacity for rural roadway segments with fewer than four lanes. The peak capacity is a one-way (peak direction) capacity for urban and rural multi lane roadway segments.

The general capacity analysis is based on the "Procedures for Estimating Highway Capacity" found in Appendix N of the HPMS Field Manual[10], updated to incorporate algorithms from the 2000 Highway Capacity Manual (HCM2000).

Volume-to-Capacity Ratio (VCR)

HERS-ST incorporates revised HCM2000 equations to calculate peak-hour capacity for each roadway segment, for each travel direction. The model then estimates a VCR for the peak and counter-peak directions separately for signalized arterials or for free-flow sections with two or more lanes per direction.

Total peak traffic is broken into two phases for all VCR calculations:

- Peak period analysis in the peak direction.
- Peak period analysis in the counter-peak direction.

[10] http://www.fhwa.dot.gov/ohim/hpmsmanl/appn.htm.

APPENDIX B – HERS-ST Batching Process

There are two types of output provided by HERS-ST, Section Condition analysis and System Condition analysis. It is important to distinguish between the two because there are significantly different delay analysis elements available to the analyst based on which type of output is selected.

The Section Condition output provides detailed analysis of the highway system at the dataset record level (i.e., for each section of input data) for each funding period (generally 5 years). The output provides a section-by-section description of numerous data elements such as type of deficiencies evaluated, and type and cost of improvements simulated. The total daily traffic is broken into three demand periods for all capacity, speed and delay analysis: peak period in the peak direction, peak period in the counter-peak (opposite) direction and off-peak. However, the peak/off-peak analysis is only available for multilane roadways (2 lanes or more per direction). Only the average speed, capacity and delay are available for standard two-lane, two-way highways.

The System Conditions output aggregates the detailed record level data (section data) identified in the Section Condition data to a level, aggregated by functional classification and funding period. The System Condition analysis provides an aggregated analysis for the entire system (be it a corridor system or a representation of some type of district or region boundary area) for the entire analysis period (generally 20 years). The output table describes the system information or statistics such as the total vehicle miles of travel, total cost of improvements, simulated pavement conditions, and the total amount of delay on the system.

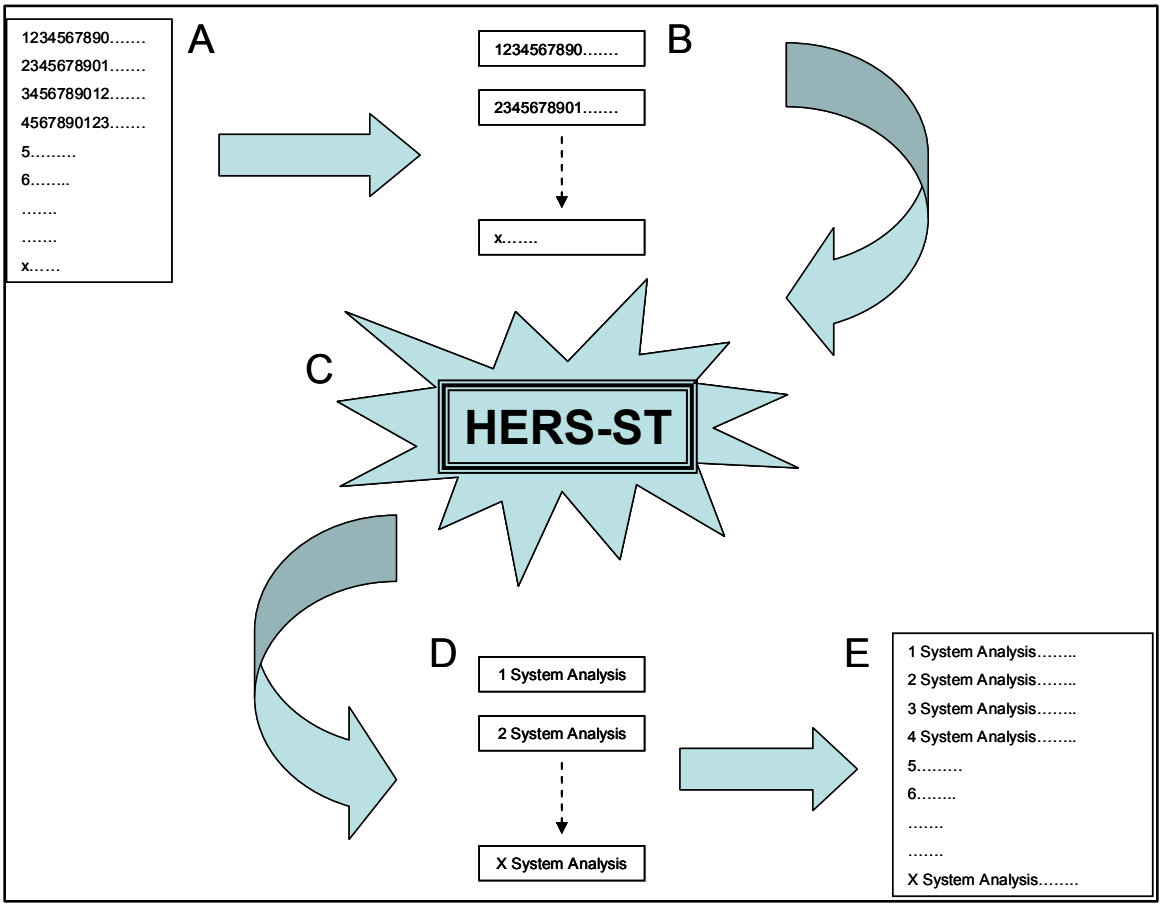
For CMS, the most important set of data elements produced from the System Conditions are associated with delay. There are three kinds of delay estimated in HERS-ST: zero, incident, and congestion. Zero-volume delay is the delay associated with traffic control devices (stop signs and traffic signals). Zero-volume is the expected delay that a single vehicle would encounter even if it were the only vehicle on the road. Zero-volume delay only exists for sections controlled with stop signs or traffic signals, and is not calculated for uncontrolled sections. Incident delay is the delay associated with crashes. HERS-ST estimates delay due to crashes through a secondary (or inferred) process, where first HERS-ST model estimates the delay cost of crashes, and then back-calculates the delay estimates due to crash incidents from the cost calculations. Congestion (or recurring) delay is the average delay due to non-incident congestion.

There are two delay procedures used within HERS-ST. The first process is used for all freeways, sections with traffic signals (no stop signs), and other multi-lane sections where there are two or more lanes per direction of traffic flow. These delay procedures generated delay estimates for incident delay (and the "NonIncident Travel Rate", which is the inverse of speed) during the three demand periods; peak, counter-peak and off-peak at the sectional level (i.e., Section Condition output). The second process is used to generate separate estimates of zero-volume delay, incident delay and recurring congestion delay at the system level for all other roadway configurations, which are predominately two-lane, two-way highways (i.e., System Condition output).

NOTE: The zero volume, incident and congestion delay elements can only be gathered from the System Condition output.

A number of data elements required for the performance measure calculations are automatically outputted in the sectional condition data files. However, several key delay data elements are only available at the aggregated system condition level. In order to capture the key delay information at the individual disaggregated record level, each record must be analyzed as a pseudo dataset using HERS-ST. In order to accomplish this, the initial HPMS formatted dataset must be parsed out to a number of single record HPMS datasets, each containing a single row of data.

Figure B-1: HPMS Dataset Parsing Analysis Process



ODOT developed a parsing process, using R-script, to:

- disaggregate the original HPMS dataset into individual datasets,
- run a batch program for HERS-ST analysis and
- (re)aggregate the individual System Condition output back into a dataset that can be linked back to the original HPMS dataset.

This parsing or disaggregated process can be seen in Figure B-1, and will be quickly described below.

The process begins with a standard HPMS dataset, identified as A, (see Figure B-1).

As an example, if there were 500 records in the original HPMS dataset, this process would parse out the data into 500 separate HPMS datasets, each dataset containing one single record (i.e., row of data), shown as B. Each individual HPMS dataset is then run through HERS-ST (see C) to develop the delay elements identified in the System Condition output (see D**).** In this example, the HERS-ST batch process evaluates 500 datasets and creates 500 separate outputs; the R-script joins (or aggregates) the individual HPMS datasets back to a single dataset level to match the original HPMS dataset; and the 500 individual files are aggregated back into a single file containing 500 records (see E**)**. At this point the redeveloped dataset contains the delay elements for each record, which are only available at the higher system level. Each individual record is treated as if they were an entire system unto themselves.