PORT-OF-ENTRY ADVANCED SORTING SYSTEM (PASS) OPERATIONAL TEST

FINAL REPORT

SPR 393

by

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for

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16. Abstract

In 1992 the Oregon Department of Transportation undertook an operational test of the Port-of-Entry Advanced Sorting System (PASS), which uses a two-way communication automatic vehicle identification system, integrated with weigh-in-motion, automatic vehicle classification, and over-height detection tied into a heavy vehicle database. The purpose of this operational test was to demonstrate the feasibility of using this system to let trucks directly bypass the port and the static scale weighing process, thus resulting in significant benefits for both the carriers and the State. An additional purpose was to test the use of "double-threshold" bending plate type weigh-in-motion scales to improve the weighing accuracy as compared to single weigh-in-motion scales. In this Final Report, the authors describe the PASS system and present results obtained from three years of operation. Results from a survey of trucking firms are presented. Results from the testing of the double-threshold weigh-in-motion scales are also presented and discussed.

Some problems with the state-of-the-art PASS occurred, causing interruptions. Most were software problems, which were resolved. The survey indicated that truckers and trucking firms using the two-way transponders were pleased with the system. The project proved that the mainline sorting of heavy vehicles to bypass or enter a Port-of-Entry is workable with current technology.

The variability of weight measurements using the double-threshold weigh-in-motion scales was found to be less than the variability of measurements from the twin weigh-in-motion scales when taken separately. Unfortunately, the weights provided by the WIM scales appeared to be biased toward the mean in spite of careful calibration. Thus the value of double-threshold WIM scales remains unclear.

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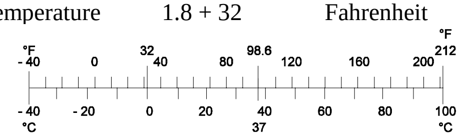
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	inches	25.4	millimeters	Mm
Ft	feet	0.305	meters	M
Yd	yards	0.914	meters	M
Mi	miles	1.61	kilometers	Km
		AREA		
In^2	square inches	645.2	millimeters squared	mm^2
Ft^2	square feet	0.093	meters squared	m^2
Yd^2	square yards	0.836	meters squared	m^2
Ac	acres	0.405	hectares	Ha
Mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
Fl oz	fluid ounces	29.57	milliliters	mL
Gal	gallons	3.785	liters	L
Ft^3	cubic feet	0.028	meters cubed	m^3
Yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
Oz	ounces	28.35	grams	g
Lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



***** SI is the symbol for the International System of Measurement

(4-7-94 jbp)

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DISCLAIMER

PORT-OF-ENTRY ADVANCED SORTING SYSTEM (PASS)
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1.0 INTRODUCTION

Truck weight and dimension measurements are usually performed at commercial vehicle inspection stations. At a Truck Inspection Station (TIS) an inspector checks a vehicle's weight, dimensions and physical condition with respect to safety. Other information is also verified, including operating credentials and driver logbooks. TIS facilities that do basic weight, dimension, and safety checks may be operated on a continuous or rotating shift basis.

In certain states, the State also performs an audit function of vehicle authority. These states have either mileage taxes or mileage-weight taxes. Mileage-weight taxes are referred to as weight-distance taxes. In these states, all trucks are required to report to the TIS to verify that they have the proper operating authority in that state. These facilities are referred to as Ports-of-Entry (POE), as they represent the first entry point to the state. The majority of POE operate on a continuous basis -- 24 hours per day, 365 days per year.

Currently truck weight, permit and registration verification procedures at weigh stations and POE are labor intensive. The diversion of trucks for verification requires a significant staffing effort and often causes long queues to form. To deal with this problem, the use of weight sorting, using weigh-in-motion (WIM) combined with automatic vehicle identification (AVI), has been successfully demonstrated at moderate speeds on entrance ramps to weigh stations (*Krukar 1986*). To maximize efficiency, however, it is more desirable to sort vehicles on the "main line" at highway speeds. In this way, backups and other safety problems may be avoided by decreasing the number of trucks passing through the weigh station.

1.1 RESEARCH OBJECTIVES

The Port-of-Entry Advanced Sorting System (PASS) Demonstration Project installation is located on Oregon Interstate 5 northbound: the WIM/AVI system is at milepost 12.4; and the Ashland Port-of-Entry (POE) is at milepost 17.5. The project began in 1992, with acceptance testing continuing into mid-1996.

The principle objective of this project was to demonstrate the feasibility of integrating state-of-the-art AVI, WIM, automatic vehicle classification (AVC), and on-board information systems to identify, weigh, classify and direct selected heavy vehicles in advance of weigh stations and Ports-of-Entry. This process was accomplished at highway speeds in two lanes without the use of message signs or lane restrictions. During this demonstration, drivers of legally operating trucks participating in the project were directed to bypass the POE and the static scale weighing process, resulting in significant benefits for both the State and trucking companies.

A secondary objective of the project was to test the use of "double-threshold" WIM scales as an economical method of improving WIM accuracy. Accuracy of highway-speed WIM scales has been a critical limiting factor in their utility. In theory, taking multiple "samples" of the forces applied to the highway by a moving truck could give a more accurate estimation of the truck's static weight. It may be possible to provide suitably accurate weight estimates by the use of multiple scales or sensors at less cost than by the use of expensive "deep pit" type WIM scales. The PASS installation incorporated twin "bending plate" scales in each of two lanes. Data from these scales provided a test of the improvement in accuracy from this double-threshold technology.

2.0 PORT-OF-ENTRY ADVANCED SORTING SYSTEM

2.1 BACKGROUND

The State of Oregon has been sorting heavy vehicles on ramps at several Ports-of-Entry since 1984 by use of WIM, AVI, and signal lights to direct vehicles (*Krukar 1986, 1988*). These on-ramp sorting systems have been successful, but there are still problems with queuing during peak periods, as well as confusion with signal lights. Much of the problem with queuing and signal operation has to do with land availability and the prohibitive cost of the construction of extension ramps. In high traffic areas, the ramps required for a medium speed ramp WIM sorting system need to be quite long. This construction is expensive, and in many cases the land is simply not available, due to urban encroachment around the interstate highway. The situation may arise where it is simply too dangerous to operate stations in this environment. Under these conditions, a backup of trucks onto the freeway is created when the stations are open, causing a serious safety concern.

Mainline sorting using WIM technology was developed in Quebec in the early 1980's. A typical system is shown in Figure 2.1. At that time prototype stations were successfully installed at two sites (*Bergeron and Robert 1985*). In 1991 Oregon installed three mainline sorting systems to study the viability of the technology. One system was installed at Umatilla on Interstate 84, and two systems were placed at Roseburg on Interstate 5. These systems utilized new fiber optic technology roadside signing. To date, these systems have operated satisfactorily.

The mainline WIM systems in Oregon at Umatilla and at Roseburg have saved truckers considerable time when they are given the ability to mainline clear the stations. The Umatilla facility operates as a POE; hence vehicles are required to stop for credential checks. The system uses AVI in conjunction with the mainline WIM system to collect vehicle information from transponder-equipped trucks. A bypassing vehicle saves as much as eleven minutes by not entering the facility. The estimated value of such a time saving ranges from $5 to $11.

The systems in operation at Roseburg are strictly weight and dimension check facilities to discourage overloading. At this facility, approximately 75% of all heavy vehicles get a mainline bypass using the mainline WIM. There is an estimated two-minute time saving to each truck allowed a mainline bypass at the Roseburg facility.

With current traffic volumes at each facility running 4,000 vehicles per day, the combined savings to the trucking industry from these two facilities is approximately $2.4 million per year. This creates a benefit to cost ratio of about 5 to 1 in the first year of operation.

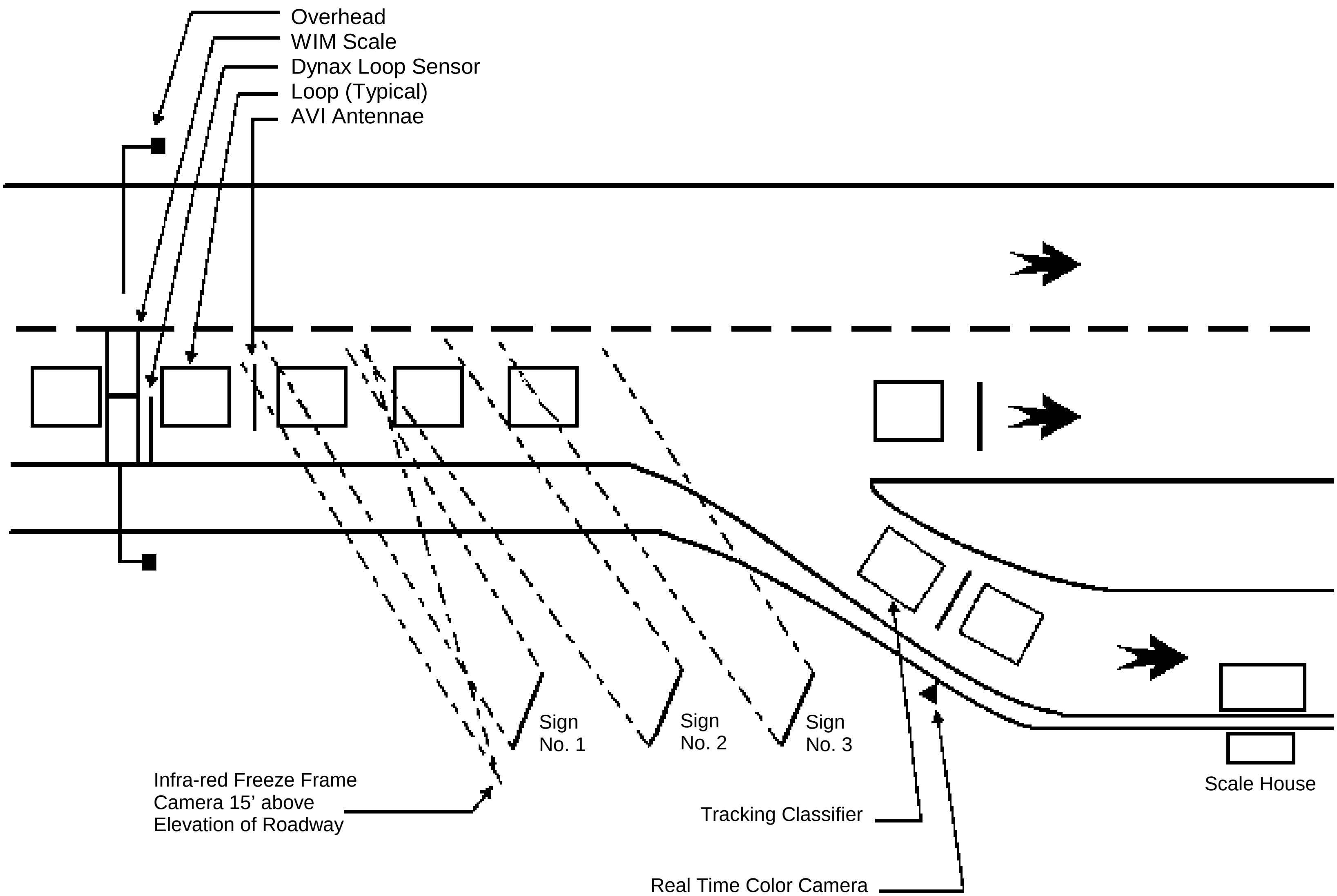

Figure 2.1: Conventional mainline sorting system

Although this conventional mainline sorting system works well, there have been problems with the variable message signs that are used to direct heavy vehicles. Specifically:

- Truckers still misread the signs.
- The signs also tend to confuse passenger car drivers.
- The signs require program modifications and are a constant maintenance concern.
- During inclement weather and on heavily traveled or multi-lane highways, variable message signs can prove ineffective.

The principle of mainline sorting, therefore, appears to be sound; but there is a need to improve the communication link with the driver of the truck.

2.2 PROJECT SCOPE

Current research in North America dealing with two-way communicating AVI (truck to AVI / AVI to truck) could lead to reduced roadside signing. The use of this transponder technology offers hope of direct communication with each truck driver, thereby reducing confusion, misread signs, and potential safety problems (*Little 1988*). AVI systems of this type are available and appear to be usable for mainline sorting; however, field testing of the system is needed. The Heavy Vehicle Electronic License Plate (HELP) and Crescent Demonstration projects are operating with two-way AVI transponders. Oregon's implementation of a two-way transponder demonstration project has been named the "Port-of-Entry Advanced Sorting System," or PASS.

This demonstration was carried out on Interstate 5 northbound at the Ashland POE to utilize an existing, two-lane WIM system approximately five miles in advance of the POE. As shown in Figure 2.2, the project consists of:

- WIM scales in each of the two lanes;
- Three two-lane AVI stations;
- A one-lane AVI station;
- Two Automatic Vehicle Classifiers (AVC); and
- Two hundred (200) two-way electronic vehicle transponders with on-board information interface systems[1].

A central supervisory system computer (SSC) located in the weigh station directs the system. The SSC contains in-depth data on all vehicles participating in the demonstration. Figure 2.3 shows the data flow for PASS.

[1] This quantity of transponders was used to provide statistical accuracy, and to create enough participation in the project to "spread the word" among trucking firms.

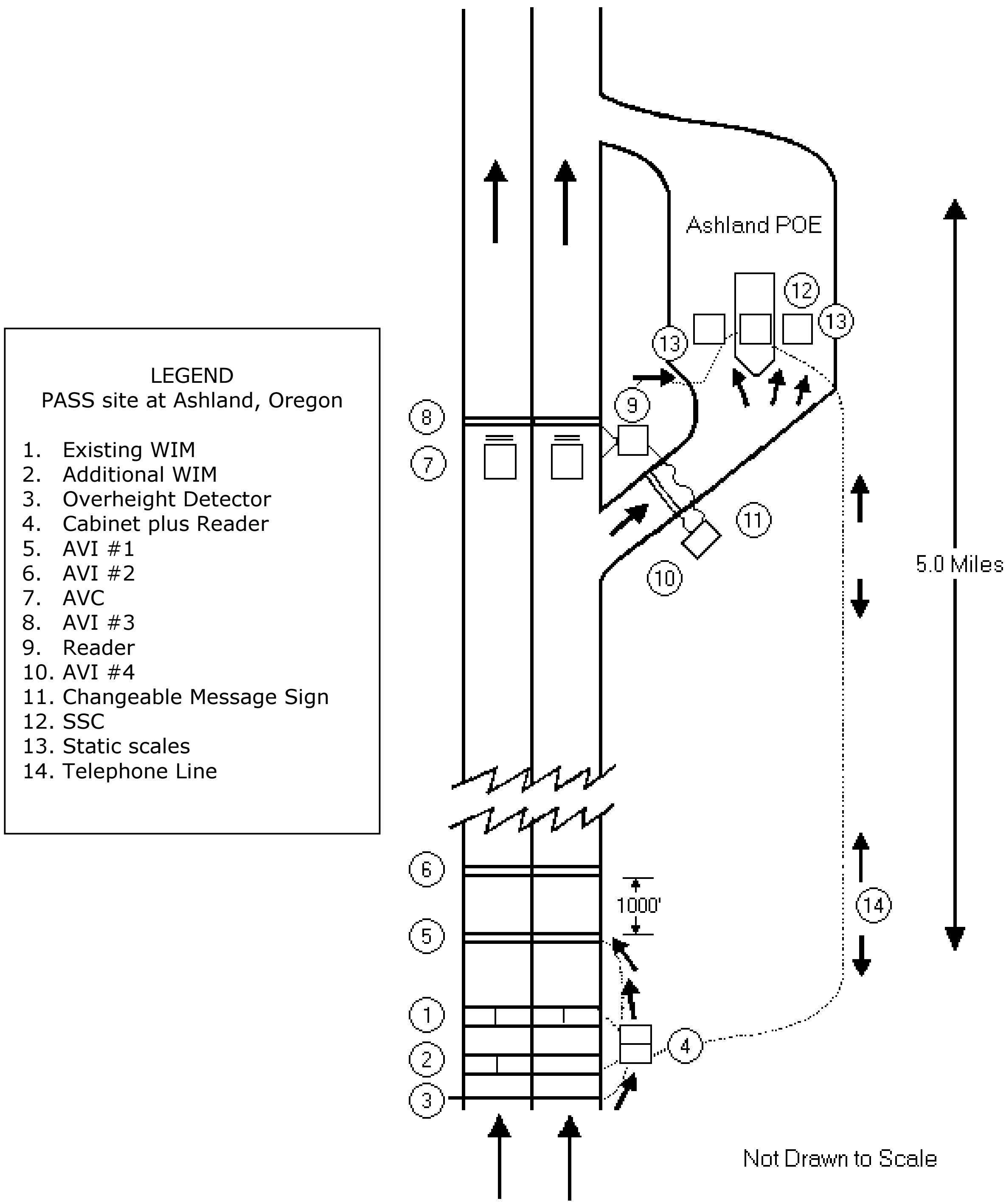

Figure 2.2: Port-of-Entry Advanced Sorting System

The sequence of events for PASS is as follows:

1. A heavy vehicle approaching the POE passes over the mainline WIM scales and is weighed. The WIM information is stored internally by the WIM computer. Vehicles in both lanes may be weighed simultaneously.
2. At AVI #1, the vehicle ID is read from the electronic tag on the truck (if equipped) and data from both the AVI and WIM are sent to the SSC via a telephone line.
3. The SSC checks the status of licenses, registrations, permits, safety data, tax data, and other operating credentials to determine if the vehicle is operating legally. The system also checks the WIM weights against the vehicle's allowable weights to determine if the vehicle is within weight tolerances. The SSC sends either a "bypass" or "report" message to AVI #2. The POE operator has the ability to override the SSC manually.
4. At AVI #2, the electronic tag information is again read and matched to the message from the SSC. The bypass/report message is then relayed to the in-cab instructional lighting system that lights green if the truck is allowed to bypass or red if it must report. AVI #2 is located 1000 feet after AVI #1 to allow for transmission and processing of the data.
5. At AVI #4 on the weigh station ramp, the vehicle is again identified and its WIM and PUC information is displayed to the weighmaster at the static scale. The vehicle is then weighed at the static scale and/or sent to the PUC office for appropriate handling.
6. The AVC and AVI #3 are located on the main line just after the highway exit to the POE. These units work in tandem to identify vehicles bypassing the POE. Heavy vehicles bypassing without clearance trigger an alarm in the POE so that appropriate action may be taken.

2.3 SYSTEM IMPLEMENTATION PROBLEMS

The PASS project began in June of 1992, and was originally scheduled for completion in November of 1995. Problems with integration of the various components of PASS delayed the start of operational testing until the summer of 1995. The major delays included:

- The need for a new communication protocol design on the "Type III" transponders, which required FCC approval.
- Repeated supervisory computer software re-designs to integrate revised components.
- Traffic control restrictions on holiday travel periods.
- The need for replacement of the existing bending-plate scales due to structural failure.
- Adjustments to the sensitivity of the over-height detector.
- Cable replacements and design changes needed for the mainline AVI system.

All of these delays were of the type that may be expected when integrating new systems and in no way reflected inherent problems with the system itself.

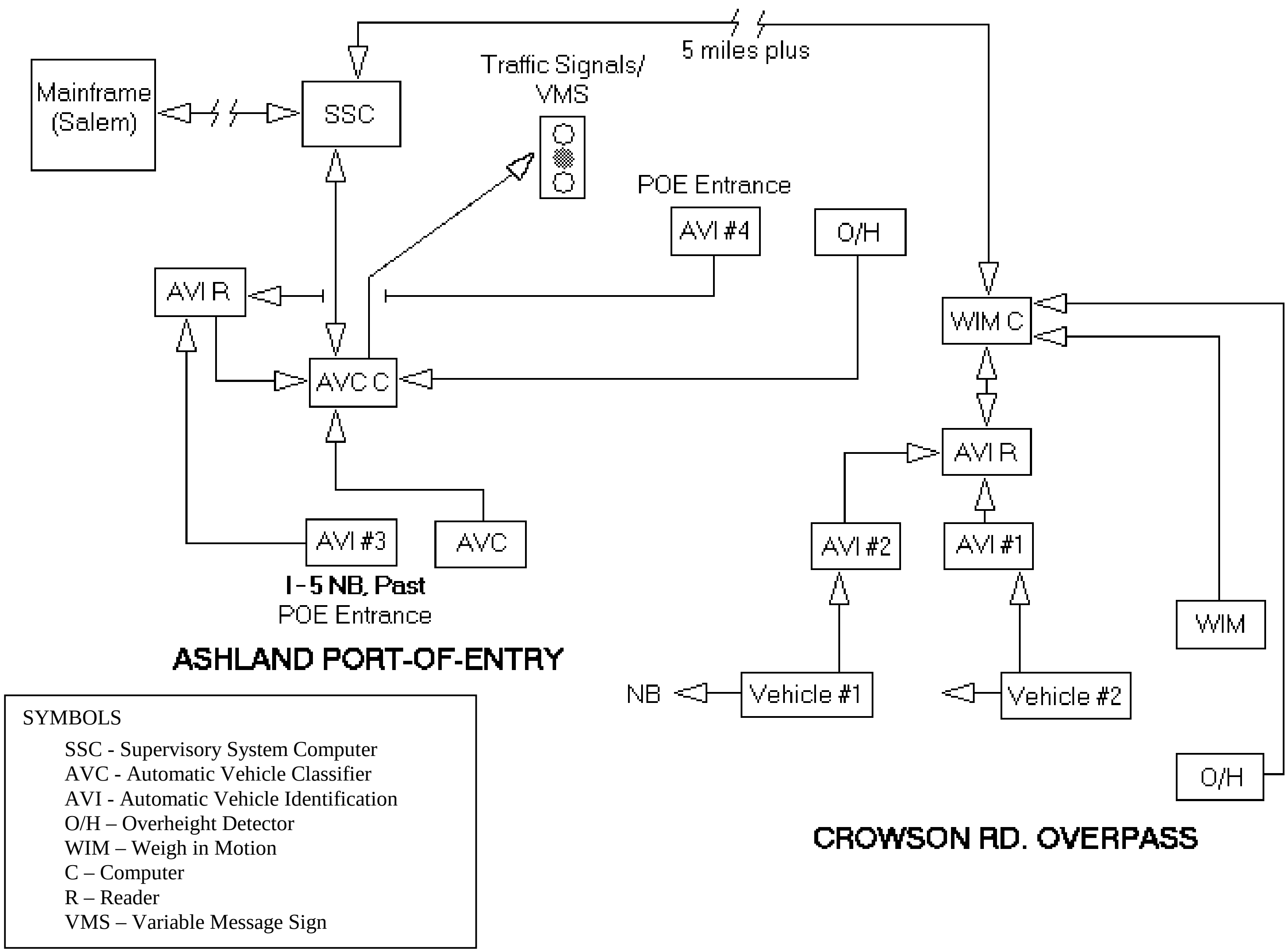

Figure 2.3: Data Flow for PASS

2.4 SYSTEM BENEFITS

A number of benefits were expected for both the State and commercial vehicle operators from operation of a PASS type system. Within the scope of the demonstration program, these benefits proved themselves to be achievable and worthwhile. These benefits included:

- Improved weigh station personnel productivity and increased enforcement revenues.
- An automatic and continuous check on weights, licenses, registrations, permits, safety, and tax payments.
- Significant time and operating expense savings for legally operating motor carriers who are pre-cleared.
- Decline in large truck queues, thereby improving weigh station safety.
- Elimination of confusing variable message signs and complex signal timing on the main line.
- Utilization of existing weigh stations without massive reconstruction or costly real estate acquisitions to handle increased truck volumes.
- Focusing of static weight enforcement and safety inspections on trucks most likely to be in violation of weight or operation regulations.
- Discouraging unlawfully operating carriers through increased enforcement and time delays, thereby achieving a higher degree of truck compliance and highway safety.
- Acquiring continuous traffic volume, classification, and weight data for highway planning and maintenance.

There could be substantial economic benefits from the PASS system for both the state and private industry. For example, the Ashland POE weighs 1,400 heavy vehicles on an average day. If 75% of the traffic were to bypass, the existing crew could be reduced by two people, saving $78,200 annually. Additionally, there would be yearly savings in data entry and tax collection expense of $10,000 and $11,500, respectively. Experience from the Ashland demonstration project indicates that a 75% bypass rate is very conservative.

Private industry would save at least two minutes per truck if allowed to bypass the port. Savings to the trucking industry would conservatively amount to more than $600,000 annually. A summary of estimated savings is provided in Table 2.1.

Table 2.1: Estimated Annual Savings from PASS

Weighmaster crew reduction thru automation:	$78,200	
PUC data entry savings:	$10,000	
PUC tax collection savings:	$11,500	
Estimated State savings total:		$99,700
Trucking industry time savings: 12,775 hours @ $50/hour – includes labor and operating costs (*Reed 1994*)	$638,750	
Estimated private industry total:		$638,750
Total estimated annual savings:		$738,450

The cost of the PASS as installed at the Ashland POE is $420,000. The total estimated savings by the state and private industry for one year would more than offset the initial investment in PASS. The estimated savings to the state alone would pay for the system in just over four years.

2.5 WEIGHMASTER AND TRUCK FIRM SURVEY

In August 1996, the Oregon Department of Transportation (ODOT) conducted a survey of all of the firms to whom two-way AVI transponders had been distributed. The transponders had been distributed at no cost to the trucking companies in 1995. Eleven companies responded to the survey, representing 63% of the transponders distributed for the demonstration. The survey form is included in Appendix A. The topics addressed by the survey and the findings are summarized as follows:

- Installation time required. The time required to install the transponder varied from 20 to 90 minutes. The average time reported was 60 minutes. One firm reported having to re-install the transponder in order to obtain a reliable signal.
- Cost of installation. Estimates of installation costs ranged from $20 to $60. The average cost was $32.50. Most companies did the installations themselves.
- Estimates of time saved. The estimates of time required to go through the port varied considerably, from a low of 2 minutes to a high of 12 minutes. The average estimate of time lost at the port was 6.7 minutes. The average number of trips through the port, per truck per week, was 6.0. Multiplying the average port time by the average number of trips per week resulted in an average time saving of 40.2 minutes per truck per week.
- Estimates of truck cost savings. Only three of the eleven respondents chose to offer any estimate of the cost savings provided by the program. Based on these estimates of cost savings, the average value of an hour's timesaving was $14. Estimates ranged from $6 to $20 per hour.

  The perception of savings appears to be low. ODOT estimates the value of truck travel time to be about $23.08 per hour. This figure does not include operating costs of the truck itself, but does include the employer's cost of the truck driver (wages and benefits) and depreciation of inventory.
- Perceived advantages of the system. The most commonly mentioned advantage of the system was time saved in bypassing the port. Other advantages mentioned included safety, reduced pollution, and "less hassle."
- Perceived problems with the system. By far, the most commonly reported problem with the system was the number of "false red" signals received by the transponder. The transponder shows a green light when the truck is cleared to bypass the port and a red light when the truck must enter the port. The display of a red light causes the driver to think he/she may be running overweight or have some other violation. Eight of the eleven respondents reported too high a number of such "red light scares" that turned out

to be nothing. Most of the "false red" signals were caused by early system problems which have since been corrected.

- Recommendation to other truckers. The response was unanimous: all eleven respondents to the survey said they would recommend participation in the program to other truckers.

2.6 IMPLEMENTATION POTENTIAL

In addition to the operations noted previously, a fully implemented PASS intrastate system could also include random safety checks and inspections, static scale transaction processing, violation logging and processing, and in-cab road information and weather warnings. The SSC could also track data from portable WIM and AVC systems on alternate or bypass routes to determine bypass frequencies for unlawful and overloaded trucks.

A valuable tool for commercial truck operations would be the ability for truck operators to track their vehicles between weigh stations and the POE. The PASS system has the potential to provide such a tool. In addition, the system could allow carriers to send messages to their drivers advising them to contact the dispatcher for important information.

3.0 DOUBLE-THRESHOLD WIM SCALE EVALUATION

3.1 OVERVIEW

A significant issue in mainline sorting is the accuracy of high-speed WIM scales: they are required to allow trucks at legal weight to bypass the static scales and still reliably detect overweight trucks. The previously discussed WIM system at the Ashland POE has an average error of approximately five percent on gross vehicle weight (GVW). To obtain a 95% confidence level that trucks operating just above the legal load limit would be detected, all trucks with a WIM scale reading within ten percent of the legal weight limit would need to be diverted to the static scale. Unfortunately, most heavy vehicles operate above 90 percent of their maximum legal load. Under the current WIM accuracy, many of these legally operating trucks would be diverted to the static scales along with the unlawfully loaded vehicles. To prevent unnecessary diversion of heavy but legally loaded trucks, WIM accuracy must be improved.

3.2 SOURCES OF WIM ERROR

WIM systems provide a measurement of the instantaneous axle or wheel load as the vehicle crosses the WIM scale. From this information we attempt to infer the weight of the vehicle, as it would be measured on the static scale. Three factors contribute to difficulty in inferring static weight from instantaneous load:

- WIM scale measurement error;
- Static scale measurement error; and
- Vehicle dynamic loading.

Scale measurement errors can be reduced by careful calibration, but vehicle dynamic loads are more complex and less well understood. Dynamic loading errors appear to be dependent on a number of factors including:

- Vehicle type;
- Vehicle speed;
- Road conditions;
- Suspension type; and
- Acceleration and braking.

3.3 THE DOUBLE-THRESHOLD WIM CONCEPT

In contrast to static scale measurements, a WIM scale takes an instantaneous reading of a fluctuating or oscillating force. The concept of a "double-threshold" WIM originates with the belief that averaging the readings from two bending-plate WIM scales would provide a more accurate estimate of the results of static weighing than a single WIM scale. Theoretical advantages of such a system include:

- Similar accuracy to more expensive types of WIM systems;
- Redundant scales ensure use of the system if one scale fails; and
- Possibility to retrofit existing single-scale systems at low cost.

The advantage of a double-threshold system comes from the increased number of "samples" of the dynamic weight exerted by the wheel system on the road surface. Assuming that the instantaneous dynamic forces exerted on the road surface by a wheel follow a normal distribution, having two samples of this instantaneous force rather than a single sample would reduce the sampling error component of the estimate of the true average force by:

$$\left(1 - \frac{1}{\sqrt{2}}\right) 100 = 29\ \% \qquad \textbf{(3-1)}$$

Note that this is a theoretical improvement in accuracy for a group of weight estimates, and that an individual weight estimate may or may not be improved by use of the double-threshold measurement technique. Also, the improvement in accuracy is dependent on the "independence" of the two samples -- which, in the case of a double-threshold WIM, prohibits interaction between the scales and requires fully independent calibration of the scales.

The actual improvement in the estimation of axle and vehicle weights is further complicated by sources of error other than the variability of the sensors. As discussed in the Section 3.2 above, a number of dynamic forces act on the moving vehicle, which modify the force placed on the scales. The effects of these dynamic forces may vary with the nature of the force.

Some of these dynamic forces may produce a consistent deviation of the "weight" of a specific axle or axle group for the entire period the vehicle is passing over the WIM scales. The error induced by this type of force will not be reduced by a multiple threshold WIM scale system. Examples of this type of dynamic force interaction could include aerodynamic lift or down force, and braking or acceleration.

Other dynamic factors may cause the axle weights to vary in either periodic or random patterns around the true weight of the axle. These forces may include harmonic oscillation of the vehicle suspension components and reaction of the suspension to road irregularities. Because of the variation in axle loading over time (and therefore, over distance), multiple threshold weighing may improve the estimate of the static weight of axles under these conditions.

3.4 WIM TECHNOLOGY

The accuracy of a WIM system tends to increase more or less proportionately with the cost of the system. Differing technologies are used by existing WIM systems, each offering a different level of performance at a different level of cost. Table 3.1 compares the differences in performance of various WIM technologies in relation to their initial and life cycle costs (*Taylor and Bergan 1993*).

Table 3.1: WIM Technology – Performance, Capital Costs, and Life Cycle Costs

Scale Type Typical Performance	(+/- % Error on GVW) Total Installed	Cost Per Lane	Annual Cost per Lane (12 year life)
Piezo Sensor Based	10%	$ 9,500	$4,224
Bending Strain	5%	$18,900	$4,990
Double-threshold Bending Strain	3% to 5%	$35,700	$7,709
Deep Pit Load Cell	3%	$52,550	$7,296

New WIM sensor technologies are being introduced on a regular basis. Of note are the quartz crystal and fiber optic sensors being developed in Europe and Australia, respectively. Both of these new technologies claim increased accuracy at much lower initial and ongoing cost, compared to existing scales.

The quartz crystal sensors claim accuracy similar to bending plate scales at a price comparable to piezo-electric sensors. Long-term precision is assured by the nature of the material itself, and temperature extremes do not affect accuracy.

Fiber-optic sensors are a very new development that has not yet been implemented in actual field use. There is hope that this technology may allow very high accuracy at prices below any existing sensor-based system. In time, this technology may make other systems obsolete.

3.5 PREVIOUS RESEARCH ON DOUBLE-THRESHOLD WIM SCALES

Very little research has been done on the use of the "double-threshold" WIM as a means of increasing accuracy of the WIM system. Only four works pertaining to multiple sensor WIM systems exist.

> <u>Bending Plate Scales:</u> WIM manufacturers such as PAT, Streeter-Richardson, and International Road Dynamics have recommended use of at least two WIM scales for sorting applications, claiming this will improve accuracy. PAT engineers claim the 95th percentile error in measurement of GVW may be reduced from 8% with a single scale down to 5% with a dual installation. PAT also claims the 67th percentile error in

measurement of axle weights may be reduced from 11% with a single scale down to 5% with dual installation. PAT has provided no supporting data.

A study by the California Department of Transportation (Caltrans) investigated potential accuracy improvement using "double-threshold" bending strain scales. "Double-threshold" scale WIM systems were installed in two lanes, and a single-scale WIM system in a third lane. The results of the study were inconclusive (*Translab 1986*).

Piezoelectric sensors: A study in Oregon used multiple piezoelectric sensors (*Henion, et al 1990, Krukar and Evert 1994*). The test involved a set of four sensors installed in one lane of Interstate 5. The study found that the overall accuracy of the system improved compared to the error rates of single sensors. Using two sensors, the standard deviation of the mean was reduced by as much as 30%. Use of additional sensors beyond two produced progressively less improvement. A previous study in France using multiple piezoelectric sensors indicated error reduction of as much as 50% (*Siffert 1986*).

Piezoelectric sensors as WIM scale devices have some drawbacks. Rather than measuring only the vertical component of applied force, piezoelectric sensors will measure the total energy imparted to the pavement. In particular, acceleration and deceleration forces affect the total force applied to the sensor, and they provide an additional source of error when attempting to use the measurements as an analog of weight.

Other sensor types: Further studies in France on WIM capacitance strips showed that three or more evenly spaced sensors increase accuracy beyond the level provided by two sensor strips (*Cebon 1989, Cebon and Winkler 1991*). The researchers recommended three sensors as a reasonable design choice and developed a model for optimal spacing of the sensor strips based on vehicle speed and suspension oscillation frequency.

Variability in vehicle speed, suspension type and loading, however, would all effect the optimal spacing of the sensors. A true optimum spacing for all vehicles thus appears to be unobtainable.

Although theory suggests increased accuracy is possible by use of double-threshold WIM systems, the only positive results have been obtained in studies using piezoelectric or capacitance sensors. Factors such as pavement condition and vehicle characteristics may be important in obtaining improved results from double-threshold WIM systems. Additional research is merited.

3.6 DESCRIPTION OF THE PASS DOUBLE-THRESHOLD SCALES

The PASS double-threshold mainline weighing system was initially tested for acceptance in January 1996. Raw dynamic weight data on trucks, along with corresponding Public Utility Commission (PUC) plate numbers, were collected at the WIM site. Static weights of axle groups, along with the PUC plate numbers, were also collected at the nearby POE. The associated weights from the WIM and static scales were matched by PUC number.

The WIM scales were pre-set to output weights that averaged approximately 10% below the associated static weights. This was done to compensate for the expected higher variability associated with WIM weighing. This compensation was made to help assure that trucks within the legal weight limits would not be called to the static scale unnecessarily.

In a standard single-threshold arrangement, axle weights are calculated from the output of two independent bending plate weighing systems, one in each wheel path. For this paper, each individual weighing device is referred to as a "plate." Axle group weights are determined by measuring the wheel weights in the group and adding them.

The double-threshold system was made up of four independent bending plates, two in each wheel path. Two estimates of the weight of each wheel were obtained with this arrangement. Axle group weights were determined by adding the measurements of wheel weights in the group and dividing by two, effectively averaging the weight estimates of each wheel.

3.7 RESULTS OF PASS DOUBLE-THRESHOLD WIM TESTING

As shown in Table 3.2, the weight measurements made by use of the double-threshold WIM did achieve a reduction in variability, compared to the averaged variability of the measurements of the two component scales. This variability reduction was achieved in the weighing of steering axles, drive axles, trailer axles, and for the gross vehicle weight. The average level of variability reduction provided by the double-threshold WIM compared to the average of the single scales was 7.4% -- well short of the 29% theoretical improvement.

The full presentation of the collected PASS data indicated some unexpected patterns in variance between the two scales in each of the two lanes (*Krukar, et al 1996*):

- In most situations, and in each of the two lanes, the variance in the first ("leading") scale was lower than that of the second scale.
- In most situations, and in each of the two lanes, the variance of the leading scale was lower than that of the static scale.

It was expected that the variance of both WIM scales in both lanes would be similar, and that the WIM scales would have greater variance than the static scale. The results indicated that, compared to the static scale, measurements from the WIM scales at PASS were biased toward the mean: i.e. weights below the mean were measured too high, and weights above the mean were measured too low. This may have been caused by inherent scale error, or by unexplained dynamic loading phenomena.

The value of the double-threshold WIM compared to the added expense has not been proven by this demonstration project. The nature of dynamic forces acting on trucks at highway speeds and their effects on weighing heavy vehicles in motion need to be better understood before recommendations can be made toward multiple sensors or scales to improve precision and accuracy for WIM systems.

Table 3.2: Variance in Axle Weights by Axle Type -- PASS Operational Test[2]

Highway Lane #1	Static Scale	WIM Scale 1	WIM Scale 2	WIM 1&2 Average	Double-threshold	Variance Reduction
Steering Axle	.70	.60	.98	.79	.74	6.3%
Drive Axles	50.6	45.0	52.6	48.8	48.1	1.4%
Trailer Axles	58.9	58.1	42.0	50.05	44.8	10.5%
Gross Vehicle Weight	162	199	153	176	132	25.0%

Highway Lane #2	Static Scale	WIM Scale 1	WIM Scale 2	WIM 1&2 Average	Double-threshold	Variance Reduction
Steering Axle	1.26	.39	.69	.54	.50	7.4%
Drive Axles	47.4	28.0	46.5	37.25	36.0	3.4%
Trailer Axles	79.1	52.7	70.1	61.4	60.0	2.3%
Gross Vehicle Weight	172	102	173	137.5	133	3.3%

[2] Sample variance is used here as a measure of variability to be consistent with the calculations in the double-threshold WIM theory section of the paper. The more familiar standard deviation measure is the square root of variance.

4.0 CONCLUSION

The principle objective of this project was to demonstrate the feasibility of integrating state-of-the-art automatic vehicle identification (AVI), weigh-in-motion (WIM), automatic vehicle classification (AVC) and on-board information systems to identify, weigh, classify and direct selected heavy vehicles at highway speeds in advance of weigh stations and Ports of Entry. The PASS demonstration project clearly demonstrated that these technologies can work together in a real-world situation to provide substantial savings to both the State and the trucking industry.

A secondary objective of the project was to test the use of "double-threshold" WIM scales as an economical method of improving WIM accuracy. In theory, taking multiple "samples" of the forces applied to the highway by a moving truck could give a more accurate estimation of the truck's static weight. Data from the twin bending-plate scales at the PASS installation provided a test of the improvement in accuracy from this double-threshold arrangement. The results from the PASS implementation did not show a substantial benefit from the double-threshold arrangement. The complex dynamic forces at work on moving heavy vehicles require more study, and the new sensor-based WIM technologies may soon exceed the accuracy and precision goals of the PASS double-threshold bending-plate system at reduced cost.

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APPENDIX A

TRUCKING COMPANY SURVEY

Trucking Company Survey

Date: ________________________

1. Name of Trucking Company: ____
2. Number of Trucks: ______________________
3. Trucks with Transponders:________________
4. How much time spent installing the transponder and readout system: ___________________
5. Estimated Installation Costs: ____
6. Number of times a truck goes by the Ashland POE:________ times per Day/Week (underline correct time period)
7. Estimated time to go through the port (from leaving freeway to re-entering the freeway):____________
8. Estimated Truck Time Savings:_____________
9. Estimated Truck Costs Savings:_____________
10. How do you rate the system -- 1 to 5 with 1 being the worst and 5 the best:

Please circle the appropriate number.

A. Efficiency:	1	2	3	4	5
B. Costs:	1	2	3	4	5
C. Convenience:	1	2	3	4	5
D. Reliability:	1	2	3	4	5

1. What are the advantages of the PASS system? _____________________________________
____
____
2. What are the disadvantages (problems)? ____
____
____
3. Would you recommend the system to other truckers?: Yes____ No____
4. Name of Interviewee: ____
5. Title: ____

APPENDIX B

ASTM STANDARDS FOR WIM SYSTEMS

ASTM STANDARDS FOR WIM SYSTEMS

The ASTM E1318-92 specification entitled "A Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Method" is the first attempt at a North American specification for WIM systems. It defines four types of WIM systems:

- Type I - high accuracy data collection systems (typically bending plate scale type WIM);
- Type II - lower cost data collection systems (typically piezoelectric scale type WIM);
- Type III - systems for use in a sorting application at weigh station entrance ramps (bending plate or deep pit load cell type WIM) at speeds from 15 to 50 mph.;
- Type IV - low-speed WIM.

Table B-1 shows the ASTM performance standards for each WIM type. Note that no type specification exists for high-speed sorting applications, and that no general performance specification exists for low-speed WIM systems.

Table B-1: ASTM Standards for WIM Systems -Maximum Error at 95% Confidence Level

WIM Type	Single Axle	Axle Group	Gross Vehicle Weight
I	20%	15%	10%
II	30%	20%	15%
III	15%	10%	6%
IV	No Specification	No Specification	No Specification