Evaluation of Dynamic Weight Threshold Algorithm for WIM Operations using Simulation

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ABSTRACT

In the past decades, states have utilized weigh-in-motion (WIM) technology to reduce delay and increase enforcement of overweight vehicles. Usually a threshold value is used to filter and sort the trucks by weight. If the WIM reading of a truck is over the threshold, the truck would be sent to a static scale for further inspection. To fully utilize the WIM technology and enhance the operational efficiency at WIM sites, the authors devised a dynamic weight threshold (DWT) algorithm. The threshold value is increased when the queue at the weigh station is long so as to avoid the closure of the weigh station while still catch the worst weight limit offenders. The threshold value is lowered when the queue at the station is short to maximize the number of trucks inspected.

This paper focuses on the evaluation of the design and operations of the dynamic weight threshold algorithm. A microscopic simulation model based on a real-world ramp WIM weigh station site was first developed and calibrated. Subsequently the dynamic threshold adjustment strategy was modeled and tested. The results show that under a wide range of conditions DWT algorithm always outperforms the traditional static threshold operations. Under heavy demand conditions, DWT catches 16 times more overweight trucks than the static operations while keeping the average delay per truck at only 30% of the delay under static operations. In other words, DWT is both more effective in weight enforcement and more efficient for traffic flow.
INTRODUCTION

In the past twenty years Weigh-in-Motion (WIM) technology became widely used to reduce delay and increase enforcement efficiency. Weigh-in-Motion is defined by the American Society for Testing and Materials (ASTM) as the process of estimating a moving vehicle’s gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces [1]. Consequently, ASTM defines a WIM system as a set of sensors and supporting instruments, which measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates tire loads, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information.

A WIM could be deployed on the ramp to a weigh station or on the mainline. In either case the WIM typically sorts arriving trucks based on a preset weight threshold. Trucks with WIM readings not exceeding the preset weight threshold are directed by a signal to bypass. Such a bypass system has the potential to significantly improve the efficiency of commercial vehicle enforcement agencies that operate weigh stations as well as the truck carriers that deliver the goods.

Using automated vehicle identification systems and mainline WIM scales, bypass systems enable commercial trucks to be weighed and verified in seconds as they travel past a weigh station. Overweight trucks and those flagged for credential and/or safety problems are directed to the weigh station for thorough inspections. In the event of weigh station closure, weight data could still be collected continuously by the WIM unit if it is deployed on the mainline.

Ramp WIM weigh station is the main form weigh station in the United States [2]. One of the drawbacks of the system is a preset weight threshold lacks flexibility to respond to the varying demand. When truck traffic heavy, a low preset threshold may direct too many non-offending trucks to the static scale and cause unnecessarily queuing and delay. On the other hand, a high preset threshold may allow too many weight offenders to slip through the cracks. As such, this paper presents a different approach to address these issues.

LITERATURE OVERVIEW

In the past, only a limited number of studies were conducted to evaluate the design and operation of a weigh station. Benekohal [3] studied Williamsville weigh station in Springfield, Illinois and attempted to measure the delay and traffic conflicts experienced by trucks at the weigh station. He reported an average delay of 4.95 minutes per truck that ranged from 3.56 to 6.59 minutes per truck for the various recording intervals. The maximum delay for the recording intervals ranged from 8.69 to 137.62 minutes per truck. Some 30 percent of the trucks were not weighed simply because queues were too long and about to spill back onto the mainline. The study also demonstrated that in many instances trucks within legal weights experienced unnecessary delay when they were requested to enter the static scales.

Kamyab [4] designed two approaches to increase capacity with a WIM system: mainline electronic screening and physical expansion. After simulating the two approaches he concluded that physical expansion would solve the problems in a shorter amount of time, but electronic screening has the potential of permanently eliminating the inefficiency of WIM stations. Glassco [2] analyzed existing and alternate weigh station operation scenarios with Westa, a weigh station simulation model developed by ITS Joint Program Office (JPO) and FHWA with support from FHWA Office of Motor Carriers (OMC) Size and Weight team. He reported longer ramps did not produce significant improvements in any of the measures.
of effectiveness studied, greater percentages of transponder-equipped trucks yield greater benefits, and WIM scale is very effective in reducing the number of trucks that must be weighed at the static scale. Katz [5] developed a procedure by Integration simulation model to evaluate the accuracy of the WIM technology in terms of service time, system time, and delay incurred at the static scales and provided a methodology that can be used to determine the effects of truck demand, WIM accuracy, system threshold.

Gu et al. [6] evaluated weigh station design and operational strategies using simulation under different design strategies and the impact of weight threshold, accuracy level of WIM scale, and transponder instrumentation rate. They found that WIM technology can improve the efficiency of weigh station operations. The also reported that the efficiency may be diminished for a weigh station with WIM scale on the mainline if the percentage of trucks equipped with transponder is less than 30. They concluded that the accuracy of WIM scale is crucial to the efficient operations of a WIM scale weigh station; and suitable threshold values should be implemented for WIM operation under various truck demand conditions.

AUTOMATED THRESHOLD ADJUSTMENT

To address the issues of queue spillback and, hence, mass bypass due to a low weight threshold value and an increased probability of missing weight offenders due to a high weight threshold, a dynamic or self-adjusting weight threshold system was devised and tested using simulation. To this end, VISSIM was used for its ease geometric configuration and traffic characteristics coding and its VISVAP tool, which allows the design of user-defined traffic control logic (Figure 1, Figure 2).

As alluded to, a dynamic weight threshold scenario was simulated using VISSIM. By observing the graphical output, see the figure below, the initial case was verified as reasonable.

A dynamic weight threshold scheme, see below, was implemented via VISVAP for the simulation.

$$\theta_1 = \theta_0 + \Delta \theta \cdot \lambda$$

where:
- $\theta_1$ is the actual, or new, weight threshold value of the WIM sorter;
- $\theta_0$ is the original weight threshold value of the WIM sorter when truck arrival rate or demand is not considered;
- $\Delta \theta$ is weight threshold incremental value per additional truck in queue; and
- $\lambda$ is the number of trucks waiting in queue.

Note that a simple linear function was used for this paper even though a non-linear function based on negative exponential distribution may be more suitable in certain cases.

MEASUREMENTS OF EFFECTIVENESS

To gauge the performance of the floating weight threshold scheme, one has to examine several parameters resultant from the simulation runs and subsequent data analyses. These parameters include capture rate, $\gamma$, the percentage of overweight trucks caught over total number of trucks, or:

$$\gamma = \frac{\text{Overweight Trucks Caught}}{\text{Total Trucks}} \times 100\%$$
Obviously a higher $\gamma$ value means a more efficient system. The second parameter is overflow bypass rate, $\beta$, which is the ratio of the number of trucks that bypassed the weigh station due to queue spillback to the total number of trucks, or:

$$\beta = \frac{\text{Trucks Bypass Weigh Station due to Queue Overflow}}{\text{Total Trucks}} \times 100\%$$

For this case, the fewer trucks bypass, the better. Thirdly, we look at the amount of delay a legal weight truck spends in the system. This delay is denoted as $\tau$.

RESULTS

A floating weight threshold scenario was introduced to simulate the operation of a ramp WIM weigh station with the following parameters:

- Truck arrival rate: 250, 300, 350, 400, 450, 500, 550, 600, and 650 trucks per hour;
- Original weight threshold value, or $\theta_0$: 68,500 lbs; and
- $\Delta \theta$: 1,500 lbs per truck

The results are shown in the table below with the three resultant parameters from the base scenario and the dynamic threshold scenario tabulated side by side. Results from a total of 270 simulation runs are presented to cover the stochastic effect of microscopic simulations (Table 2).

It is obvious that the dynamic threshold algorithm does improve the operation of weigh station significantly. For all the simulated scenarios, the capture rate increased by 16.34%. The percentage of trucks turned away due to queue overflow just about totally eliminated, a near 100% reduction. The delay for legal-weight trucks spent in the weigh station reduced about 50%.

A $t$-test was performed and its result supports the findings that the dynamic strategy does improve the weigh station operation, especially for decreasing travel time and avoiding truck bypass due to overflow. At 95% significance level the values of $\gamma$, $\beta$, and $\tau$ all improved decidedly from the base scenario. (Table 3)

Further studies shows that if truck demand is less or equal 400 trucks per hour for this case, overflow bypass rate $\beta$ and the delay $\tau$ still show significant improvement by the dynamic algorithm while the capture rate $\gamma$ does not. If truck demand is greater than 400 trucks per hour, the dynamic algorithm improved the three MOES significantly. (Table 4, Table 5)

CONCLUSIONS

From the results it can be concluded that the dynamic weight threshold strategy is a better and smarter approach to improve the efficiency of weigh station operations, and can be applied to both low and high truck demand. The higher truck demand, the more effective. The implementation of such a strategy does not require costly capital hardware investment or lengthy construction or installation duration. The resultant savings in time and money should not be overlooked.

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<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geometric</td>
<td>The sketch of Westbound Weigh Station located at I-40, Knoxville, TN</td>
</tr>
</tbody>
</table>
| 2  | Weight distribution| • Gross Weights are used  
• Normal distribution  
• Mean: 60,000lbs  
• And Standard Deviation: 8,800lbs. |
| 3  | Static Scale Service time | • Normal distribution.  
• For an overweight truck  
  o Mean: 50 seconds,  
  o Standard Deviation: 20 seconds;  
• For a non-overweight truck  
  o Mean: 20 seconds  
  o Standard Deviation: 10 seconds. |
<p>| 4  | Accuracy of WIM scale | • Standard Deviation: 10% of real weight                                    |
| 5  | Threshold          | • 68,500 pounds                                                            |
| 6  | Weight Limit       | • 80,000 pounds                                                            |</p>
<table>
<thead>
<tr>
<th>Truck demand Trucks/Hour</th>
<th>Base Scenario (Fixed Threshold)</th>
<th>Dynamic Scenario (Dynamic Threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>γ</td>
<td>β</td>
</tr>
<tr>
<td>250</td>
<td>1.29%</td>
<td>0.00%</td>
</tr>
<tr>
<td>300</td>
<td>1.21%</td>
<td>0.00%</td>
</tr>
<tr>
<td>350</td>
<td>1.26%</td>
<td>0.00%</td>
</tr>
<tr>
<td>400</td>
<td>1.20%</td>
<td>0.11%</td>
</tr>
<tr>
<td>450</td>
<td>1.21%</td>
<td>0.00%</td>
</tr>
<tr>
<td>500</td>
<td>1.04%</td>
<td>0.00%</td>
</tr>
<tr>
<td>550</td>
<td>0.93%</td>
<td>0.19%</td>
</tr>
<tr>
<td>600</td>
<td>0.83%</td>
<td>0.56%</td>
</tr>
<tr>
<td>650</td>
<td>0.85%</td>
<td>2.02%</td>
</tr>
<tr>
<td>Total</td>
<td>1.05%</td>
<td>0.44%</td>
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</table>
Table 3 T-Test Results for Comparing Basic and Dynamic Threshold Adjustment Scenarios (All the Cases)

Paired Samples Test

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capture Rate (Dynamic) - Capture Rate (Basic)</td>
<td>.0013651</td>
<td>.0021789</td>
<td>.0001875</td>
<td>.0009941 - .0017360</td>
<td>7.279</td>
<td>134</td>
<td>.000</td>
</tr>
<tr>
<td>2</td>
<td>Overflow Bypass Rate (Dynamic) - Overflow Bypass Rate (Basic)</td>
<td>-.1214</td>
<td>.1335</td>
<td>.0115</td>
<td>-.1442 - -.0987</td>
<td>-.10.569</td>
<td>134</td>
<td>.000</td>
</tr>
<tr>
<td>3</td>
<td>Delay (Dynamic) - Delay (Basic)</td>
<td>-43.6674</td>
<td>37.0864</td>
<td>3.1919</td>
<td>-49.9804 - -37.3544</td>
<td>-13.681</td>
<td>134</td>
<td>.000</td>
</tr>
</tbody>
</table>
Table 4 T-Test Results for Comparing Basic and Dynamic Threshold Adjustment Scenarios
(Truck Demand <=400 trucks per hour)

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>Mean</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>Capture Rate (Dynamic) - Capture Rate (Basic)</td>
<td>.0002595</td>
<td>.0011238</td>
<td>.0001451</td>
<td>-.0000308</td>
<td>.0005498</td>
<td>1.789</td>
<td>59</td>
<td>.079</td>
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<tr>
<td>Pair 2</td>
<td>Overflow Bypass Rate (Dynamic) - Overflow Bypass Rate (Basic)</td>
<td>-.0070</td>
<td>.0186</td>
<td>.0024</td>
<td>-.0118</td>
<td>-.0022</td>
<td>-2.924</td>
<td>59</td>
<td>.005</td>
</tr>
<tr>
<td>Pair 3</td>
<td>Delay (Dynamic) - Delay (Basic)</td>
<td>-9.3150</td>
<td>11.5862</td>
<td>1.4958</td>
<td>-12.3080</td>
<td>-6.3220</td>
<td>-6.228</td>
<td>59</td>
<td>.000</td>
</tr>
</tbody>
</table>
Table 5 T- Test Results for Comparing Basic and Dynamic Threshold Adjustment Scenarios
(Truck Demand > 400 trucks per hour)

**Paired Samples Test**

<table>
<thead>
<tr>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 Capture Rate (Dynamic) - Capture Rate (Basic)</td>
<td>.0022495</td>
<td>.0024097</td>
<td>.0002782</td>
<td>.0016951 - .0028039</td>
<td>8.085</td>
<td>74</td>
<td>.000</td>
</tr>
<tr>
<td>Pair 2 Overflow Bypass Rate (Dynamic) - Overflow Bypass Rate (Basic)</td>
<td>-.2130</td>
<td>.1135</td>
<td>.0131</td>
<td>-.2391 - -.1868</td>
<td>-16.244</td>
<td>74</td>
<td>.000</td>
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<tr>
<td>Pair 3 Delay (Dynamic) - Delay (Basic)</td>
<td>-71.1493</td>
<td>25.7153</td>
<td>2.9693</td>
<td>-77.0659 - -65.2328</td>
<td>-23.961</td>
<td>74</td>
<td>.000</td>
</tr>
</tbody>
</table>
Figure 1 Graph of Simulation Model
Figure 2  Graph of VISSIM
Figure 3 Graph of Capture Rate
Figure 4 Graph of Overflow Bypass Rate
Figure 5 Graph of Truck Delay