A Feedback-based Metering Control for Electronic Commercial Vehicle Screening Systems

Jinwoo (Brian) LEE, Ph.D.
Lecturer
School of Urban Development
Faculty of Built Environments and Engineering
Queensland University of Technology
Brisbane, Queensland, Australia
Email: Brian.Lee@qut.edu.au

Garland CHOW, Ph.D.
Associate Professor
Sauder School of Business, University of British Columbia
7th Floor - 2053 Main Mall, Vancouver, BC, Canada V6T 1Z2
Email: Garland.Chow@Freightsecurity.ubc.ca

Abstract: This paper presents an adaptive truck metering control algorithm to enhance the electronic screening (e-screening) operation at truck weigh stations. This algorithm uses a feedback control mechanism to control the level of truck vehicles entering the weigh station. Under overflowing truck conditions, the proposed algorithm attempts to prevent the queue spillback problem by allowing more trucks to bypass the weigh station. Alternatively, the algorithm leads the e-screening system to adopt a stricter bypass condition to preclude overweight trucks from being bypassed due to the Weigh-In-Motion measurement error. The proposed control concept is demonstrated and evaluated in a simulation environment representing a low capacity weigh station. The simulation results demonstrate considerable benefits of the proposed algorithm in improving the overweight enforcement with minimal negative impacts on legal truck vehicles.

Key words: commercial vehicle operations, electronic screening, weight compliance, weigh-in-motion, intelligent transport systems, feedback-control

1. INTRODUCTION

Queue spillback is a challenging issue in operating commercial vehicle weigh stations. Truck volumes exceeding the weigh station capacity increase the queue size in the queuing area and often cause the queue spillback onto the highway mainline. To avoid safety problems, busy weigh stations stop the scaling and inspection operation and allow the queued vehicles to bypass the overcrowded station. As a result, the overweight enforcement can be seriously compromised.

Electronic screening (e-screening) systems provide weigh stations with an automatic enforcement mechanism. Using mainline Weigh-In-Motion (WIM) scales and Automated Vehicle Identification (AVI), e-screening systems can sort only apparent overweight trucks and divert them to weigh stations for further inspection. The benefit of e-screening has been demonstrated by a number of studies in the past (1,2,3). By participating in the e-screening program, legal and safe carriers can save significant time by bypassing the weigh station. E-screening also can improve the operation productivity of weigh stations by reducing the queue spillback as only selected vehicles are directed to the weigh station.
However, these e-screening benefits may quickly diminish if truck volumes continuously overflow the weigh station’s capacity. The problem may get worse for the weigh stations with limited space to accommodate waiting trucks. A previous study by the authors reported that the operation of a small sized weigh station can be interrupted more than 20% of the total operation time even with an e-screening system (4). Although it is evident that e-screening programs can effectively reduce the level of trucks pulled-in, the queue spillback problem may be inevitable under overflowing traffic conditions without an effective measure to control the truck demand in weigh stations.

Another important factor impacting on the e-screening operation is the WIM accuracy. For properly maintained and calibrated WIM scales, acceptable measurement errors range from $\pm 6\%$ to $\pm 15\%$ by the type of scale sensors (i.e., Piezoelectric, bending plate, and load cell); however, practical performance may further deteriorate depending on the operating environment, the level of maintenance and calibration work carried out, and the pavement condition (5). Erroneous WIM measurements may misdirect overweight trucks to be granted a bypass signal and consequently impair the enforcement effectiveness. When a weigh station is substantially underutilized (i.e., lower truck flows than the station capacity), this problem can be resolved by pulling in and inspect more possible overweight vehicles, which could have been bypassed due to inaccurate WIM measurements.

This study proposes a new approach to improving the e-screening productivity. We propose the use of an adaptive truck metering control algorithm that regulates the truck flow into weigh stations by varying the weight threshold used to determine whether a vehicle should be pulled into a weigh station or not. The idea of using a metering control concept for truck weigh stations has been rarely investigated in the past. To our best knowledge, a study by Gu and Han (6) is the only case that addressed this idea. Their study proposed a simple method to adjust the weight threshold proportionally to changes in the queue size in the inspection ramp. The test results showed significant improvement achieved in terms of the capturing overweight trucks compared to the test scenario using a preset weight threshold. Such a strategy, however, requires accurate measurement or estimation of the queue size in the inspection ramp in real-time, which is often implausible in reality. The size of truck queue in the queuing area may not properly represent the operation status (or truck demand status) of the weigh station when the demand is greater than the maximum queue that the inspection ramp can accommodate.

The proposed truck metering control algorithm is simple and easy to implement as it requires no estimation or prediction, but takes the system outputs as input parameters. The general framework of the algorithm was developed based on the well-known freeway ramp metering strategy, ALINEA, via suitable modification and selection of model parameters. The next section describes the details of the e-screening operation and identifies the factors affecting system degradation. The proposed algorithm is presented in the next section. A simulation study is carried out to verify the effectiveness of the proposed algorithm. The simulation results are presented with discussions on the algorithm performance in the next section. The last section concludes this study with further research opportunities.
2. ELECTRONIC COMMERCIAL VEHICLE SCREENING

2.1. Structure and Elements
E-screening systems are comprised of the elements illustrated in Figure 1. A WIM scale is typically deployed in the mainline highway together with a roadside transponder reader. The screening operation is initiated when a truck vehicle travels through the WIM scale. The transponder reader identifies the vehicle from a transponder installed in the vehicle, while the WIM scale measures the vehicle weight. The weight information collected is sent to the computer in the weigh station along with the identification of the vehicle from the transponder through a wired or wireless communication link. The weigh station grants a “green light” via the vehicle transponder or a variable message sign, if all the bypass conditions are satisfied. Otherwise, the truck must exit the highway and enter to the weigh station for further inspection.

![Figure 1 Electronic screening system](image)

2.2. Screening Decision Making
Several criteria can be used to make the bypass/pull-in decision. Figure 2 shows an example of the decision making process with typical criteria.

![Figure 2 Decision making process and criteria](image)

The weigh station status (i.e., open or closed) condition must be defined first. No vehicle needs to pull-in if the weigh station is temporarily closed or outside of scheduled operating time. Note that the screening decision is made and all the required communications are completed during the instance vehicles’ passing the WIM scale. Once a truck received a “pull-in” signal, it must do
so even the station status has changed (to close) during the vehicle is traveling to the weigh station.

The registration status is the next condition to be examined. In order for a truck to be able to take advantage of e-screening, the vehicle must be registered in the program and equip with a vehicle transponder. The truck registration rate, also referred to as the truck participation rate, is the single most important factor affecting the bypass/pull-in decision for the majority of trucks. Since non-registered vehicles are simply “invisible” from the e-screening system, by regulation they must pull-in for the station inspection regardless of the WIM reading. The overall performance of e-screening systems is largely dependent on the participation level of truck carriers in the program as demonstrated by other study results.

The final screening decision is made based on the measured vehicle weight. WIM determines a potentially “overweight” condition if the WIM reading exceeds the weight threshold. The weight threshold indicates the maximum allowable truck weight at which the e-screening system determines overweight vehicles. E-screening systems often employ a lower weight threshold than the legal limit to prevent overweight trucks from being bypassed due to WIM measurement errors. A lower weight threshold implies adopting a stricter standard, which will divert more vehicles including both legal and illegal into the weigh station.

3. ADAPTIVE TRUCK METERING CONTROL ALGORITHM

Traffic metering is a traffic management strategy to control the amount of vehicles entering a downstream segment or a transportation facility such that the entering flows do not exceed the maximum capacity. Freeway ramp metering is a good example. Ramp metering strategies release vehicles from entry ramps using a traffic signal placed at the end of the entry ramp aiming at preventing flow breakdown (7). Traffic metering also has been applied for the dynamic traffic control in urban corridors, work-zones, and toll plazas (8, 9).

An adaptive truck metering control algorithm is presented in this paper. The operation goal is to improve the overweight enforcement while minimizing the negative impact of the algorithm’s operation on legal trucks. The proposed algorithm attempts to achieve this goal by: increasing the utilization of the available weigh station capacity when the capacity is underutilized; and, restricting the truck flow entering the weigh station when the capacity is over-utilized. The term “utilization” in this study indicates the required capacity to accommodate a certain level of truck demand.

A feedback control system measures the actual system outputs, which are then compared with the desired system set points. An error signal is produced to indicate the difference between the desired operating point and the actual system operating status. This feedback process provides the controller with the information at what status the system is actually operating and the direction and magnitude to modify the control parameters for the subsequent time interval.

The proposed algorithm uses feedback control to drive the capacity utilisation level, \( u \), appropriately for the current system status. An appropriate level of the capacity utilisation is
defined as \( u_o \). Suppose \( u_o \) is the ideal status point of the e-screening system, the algorithm adjusts \( \theta \) to achieve the condition \( u = u_o \) based on the following equation:

\[
\theta(t) = \theta(t-1) - K_\theta [u_o - u(t-1)]
\]

(1)

Where, \( \theta(t) \) = weight threshold (kgs) to be implemented during the new time period \( t \)

\( \theta(t-1) \) = weight threshold that has implemented during the \( t-1 \) interval

\( K_\theta \) = regulator parameter

\( u_o \) = target utilization rate (%)

\( u(t-1) \) = measured utilization rate during \( t-1 \)

Feedback control initiates at the end of every time period \( t \) by receiving the real-time measurements \( f_s(t-1) \) and \( \sum_{k=1}^{k(t)} (\delta_k^s + \delta_k^c) \) to calculate \( u(t-1) \). A positive error signal is generated when the weigh station is underutilized at less than the desired level (\( u_o > u(t-1) \)). As a result, \( \theta(t) \) will be adjusted lower than \( \theta(t-1) \) and more trucks including overweight vehicles will be pulled in and inspected at the weigh station. On the other hand, negative error signals lead the algorithm to adjust \( \theta(t) \) higher than \( \theta(t-1) \) that allows more trucks including possibly overweight vehicles to receive a bypass signal. Although overweight trucks may escape being pulled in, this operation is beneficial, because by preventing the queue spillback, the weigh station is not closed and will continue to pull in vehicles using a higher weight threshold. The above described operation is repeated every update cycle, \( \Delta t \). Including \( \Delta t \), the algorithm has two additional parameters \( u_o \) and \( K_\theta \) to have a constant value. Figure 3 illustrates the algorithm operation based on feedback control.

\[ [u_o, K_\theta, \Delta t] \]

4. SIMULATION STUDY

In this section, the proposed metering control algorithm is implemented and evaluated in a simulation environment to demonstrate the algorithm’s operation and performance. The Port Mann weigh station, located in British Columbia, Canada, was selected for the simulation study.
This weigh station with the e-screening operation was modeled using the microsimulation program VISSIM by the use of the COM programming interface.

The e-screening program at the Port Mann station initially launched as a pilot program in 2007. The truck participation rate has increased rapidly since the program’s inception and it reached over 10% at the end of 2008. In order to further increase the participation rate, British Columbia Ministry of Transportation (BC MoT) has been working in collaboration with Transport Canada to facilitate incentives programs for participating carriers.

Currently, the Port Mann weigh station is suffering from frequently occurring queue spillback due to heavy truck volumes as well as relatively short queuing area (180 meters). The queue spillback may seriously compromise the operation of this weigh station. Due to the heavy traffic volumes in the two-lane highway section, the weigh station operators inevitably allow even the waiting trucks in the queuing area to bypass the weigh station when the queue spillback occurs in order to avoid the safety problems in the highway mainline. Physical expansion of the station is not a feasible option to solve the problem as the weigh station is located closely between two highway ramps. In authors’ opinion, using operational strategies such as the truck metering control is a viable solution to improve the productivity of the weigh station.

4.1. Test Environments
For the modeling of the Port Mann weigh station and the e-screening operation, truck encounter data (at the mainline WIM) was collected for five days from February 5, 2007 to February 9, 2007 during the station operation time from 8:00 am to 4:00 pm. This dataset includes: date and time of truck detection, truck speed, truck class, truck length, Gross Vehicle Weight (GVW), Equivalent Single Axle Loads (ESAL), axle weight (up to 14 axles), and axle spaces.

**Truck Arrival Pattern**
Figure 6 shows the averaged truck arrivals in every 30 minute interval obtained from the encounter dataset.
The observed pattern shows the truck arrival rate gradually increases throughout the station operation time with the peak period from 14:00 to 14:30. The highest variation by time-of-day is 56 trucks between the least congested period (from 8:00 am and 8:30pm) and the most congested period (from 14:00 pm and 14:30 pm).

**Truck Type and Length**

BC MoT classifies truck vehicles into 20 categories by gross vehicle weight, axle weight, number of axles, and distances between axles. For simplicity, all trucks are modeled as a single type as having a uniform vehicle length (11 meters) in this study. The average vehicle length was found from the encounter dataset.

### 4.2. Simulation Study Results

The proposed algorithm is evaluated in two test scenarios employing truck participation rates of 15% and 30%. The 15% participation level denotes the status quo scenario. The 30% participation rate scenario represents a future scenario where more truck carriers are participating in the program assuming incentive programs have been effective. Numerical results are averages from 10 simulation runs for each test scenario. Table 1 provides a summary of the simulation study.

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<th>Table 1 Simulation Results</th>
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<td>Overweight enforcement rate</td>
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<td>Impact on legal and registered trucks</td>
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<td>Average travel time</td>
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<td>Station closure event</td>
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<td>Percentage closure time over total simulation period</td>
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The simulation results indicate that the proposed algorithm performs reasonably well in both test scenarios, but greater benefits are observed with 30% participation rate. At the 30% participation rate, the overall enforcement rate improved from 81.9% to 89.2% with the operation of the proposed algorithm. The station closures reduced by 36% from 21 times to 13 times. The proposed algorithm also effectively improved the overweight enforcement during non-peak periods by applying stricter weight threshold values.

The observed benefit was relatively insignificant with the 15% participation rate. The overweight enforcement improved from 74.8% to 76.6%, mainly resulting from the reductions in the queue spillback. With the proposed algorithm, the observed station closures decreased by 8.8% (i.e.,
34.1 times to 31.0 times) and by 10.1% in terms of the percentage station closure time (i.e., 16.9% to 15.2%).

In summary, the proposed algorithm demonstrated reasonably good performances in improving the overweight enforcement with minimal impact of its operation on the legal and registered trucks. The algorithm’s operation was more effective when it gained more controllability. However, with a lower level of participation rate, the algorithm’s operation to prevent the queue spillback was relatively ineffective compared to the 30% participation rate scenario.

5. CONCLUSIONS

An adaptive truck metering control algorithm is presented in this paper. This algorithm uses a feedback mechanism to control the level of truck traffic in weigh stations. The basic operation of the algorithm is simple. It adjusts the weight threshold lower when the station status is underutilized in order to inspect more potentially overweight trucks. Alternatively, the algorithm increases the weight threshold when the station status is over-utilized, restricting the incoming truck flow to prevent the queue spillback without closing the weigh station. This control concept was evaluated in a simulation environment representing a low capacity weigh station with considerable benefits demonstrated. It was also revealed that the effectiveness of the proposed algorithm may be relatively insignificant without sufficient truck participation in the e-screening program due to lack of controllability. The importance of the participation rate and its impact on the controllability of the adaptive metering control was demonstrated by the significantly different results of the 15% and 30% participation rates. It should be noted that the numerical testing was conducted on a relatively small weigh station with limited capacity. The simulation can be expanded to test whether these results can be generalized to a broader range of volume and participation scenarios.
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