Abstract—This paper presents an adaptive metering 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. The basic operation of the algorithm allows more trucks to be inspected when the weigh station is underutilized by adjusting the weight threshold lower. Alternatively, the algorithm restricts the number of trucks to inspect when the station is over-utilized to prevent queue spillover. The proposed control concept is demonstrated and evaluated in a simulation environment. The simulation results demonstrate considerable benefits of the proposed algorithm in improving the overweight enforcement with minimal negative impacts on non-overweighed trucks. The test results also reveal that the effectiveness of the algorithm improves with higher truck participation rates in the e-screening program.

Index Terms—Commercial Vehicle Operations, Truck Weight, Electronic Screening, Weigh Station, Traffic Control

I. INTRODUCTION

INTELLIGENT Transportation Systems (ITS) technologies for Commercial Vehicle Operations (CVO) have been mainly focused on government regulation activities for enhancing the operation of such regulation facilities and ensuring the safety of motor carriers. Electronic truck screening (e-screening) is a key ITS-CVO application for enhanced regulation of overweight commercial vehicles. Traditional truck weigh stations require all commercial vehicles to stop for weight and safety inspection which incurs significant and unnecessary delay. E-screening utilizes Automated Vehicle Identification (AVI) and Weigh-In-Motion (WIM) that enable selective inspection of only highly probable overweighed trucks and thus reducing the number of vehicles to serve by weigh stations and improving the operation efficiency of weigh stations.

A typical e-screening system is illustrated in Figure 1. A WIM operates in the highway mainline together with a roadside transponder reader. The screening operation initiates when a truck travels onto the WIM scale. The transponder reader identifies the vehicle identification from an in-vehicle transponder, while the WIM weigh the vehicle. The measured truck weight and the vehicle identification information are sent to the processing computer in the weigh station. A “green light” is granted to the truck via the in-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.

Fig. 1. Electronic truck screening

The benefit of e-screening has been demonstrated in various aspects. The most significant benefit would be the time savings of trucks. Legal trucks registered in the e-screening program can save significant time by bypassing the time-consuming in-station inspection. Ismail et al. [1] developed a discrete event-based simulation model for the benefit analysis of an e-screening system in British Columbia, Canada. The study reported significant time and emission saving benefits (up to $8.8 million for 5 years). Kamyab [2] reported that the e-screening operation achieved an average of 2.3 minutes of travel time saving per truck. A similar study by Gu and Han [3] reported that e-screening could decrease the travel times of commercial vehicles more than 80%. Time spent in queue for an inspection also decreases as the result of decreased truck volumes diverted into weigh stations for an inspection. Lee and Chow [4] demonstrated this type of time saving benefit could range between 2 and 10 minutes per truck depending on the percentage of participating trucks in the e-screening program.

II. PROBLEM STATEMENT

Although e-screening has been widely and successfully implemented [5-9], a few challenging issues still exist. The
queue spillover is one of those. Truck inflows exceeding the weigh station capacity increase the queue size and eventually spill over onto the highway mainline. To prevent potential conflicts with the mainline traffic, overcrowded weigh stations inevitably stop the inspection operation and allow the queued trucks to bypass the inspection, which quickly diminishes the benefit of e-screening. The queue occurs more frequently and severely at smaller-sized weigh stations which have limited space to accommodate waiting trucks. A previous study by the authors found that the normal operation of such small sized weigh stations can be interrupted more than 20% of the total operation time even with an e-screening system [10]. The queue spillover problem cannot be effectively prevented for those weigh stations without a measure to control the truck inflow.

The WIM accuracy is another important factor. In general, acceptable error limits of WIM range from ±6% to ±15% by the type of technologies [11]. However, the practical performance may substantially deteriorate depending on the operating environment, the level of maintenance and calibration work carried out, and the pavement condition [12,13,14]. To prevent overweight trucks from being bypassed due to WIM errors, typical weigh stations operate a weight threshold value lower than the legal limit. The weight threshold indicates the maximum allowable truck weight at which the e-screening system determines overweight vehicles. A lowered weight threshold implies adopting a stricter standard, which will divert more trucks including legally weighted and thus increase the travel times of those vehicles.

This study proposes an adaptive truck metering algorithm for the control of truck inflows into weigh station. When the likelihood of oversaturation continues to grow, the proposed algorithm attempts to reduce the truck inflow in order to prevent or delay the onset of queue spillover. On the other hand, when the weigh station is considerably under-utilized, the algorithm increases the truck inflow including possible overweight trucks for inspection and thus improving the overweight enforcement. The truck inflow is controlled by adjusting the weight threshold value. The weight threshold indicates the maximum allowable truck weight at which the e-screening system determines overweight vehicles.

The literature indicates only one study by Gu and Han [3] addressed this issue. This study suggested a simple method to adjust the weight threshold proportionally to the changes in the queue size in the weigh station. Although positive results were observed from a simulation study, the strategy requires accurate measurement or estimation of the queue size in weigh stations, which is often implausible in reality. Furthermore, the size of truck queue in the inspection area may not properly represent the future demand for the weigh station, which is in fact determined predominantly by the truck volumes on the highway mainline.

The proposed strategy is distinct from the work by Gu and Han in two ways. Firstly, the strategy is developed in the framework of the feedback control. Secondly, the weigh station status is measured in terms of the utilization rate (see Section II) that incorporates the current queue in the weigh station and additional trucks in the mainline which have received a pull-in signal and to enter the weigh station shortly. The later component represents the short-term future demand for the weigh station.

### III. E-SCREENING AND WEIGHT STATION

The truck inflow into a weigh station is determined on the basis of the e-screening criteria displayed in Figure 2.

Several criteria can be used, but those three are the most commonly used ones: the weigh station status (i.e., opened or closed), the vehicle registration status, and the weight compliance of the vehicle. No vehicle needs an inspection if the weigh station is temporarily closed or outside of scheduled operating time. In order 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 [15,16].

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 weight threshold that is lower 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.

#### A. E-screening and Weigh Station Capacity

The mainline truck flow, denoted as $f_m$, splits into the pull-in truck flow $f_s$ and the bypass flow $f_p$ based on the e-screening
results and the weigh station operation status. Define \( \hat{f}_s(t) \) as the total number of trucks that require a station inspection (i.e., sum of non-registered trucks and overweighted trucks) during a time interval \( t \). In other words, \( f_s(t) \) is the demand for the weigh station and can be expressed as the following:

\[
\hat{f}_s(t) = f_m(t) \cdot g(t) + f_m(t) \cdot (1 - p(t)) - f_m(t) \cdot [g(t) \cdot (1 - p(t))]
\]

\[
= f_m(t) \cdot [1 - p(t) + g(t) \cdot p(t)]
\]

(1)

Where, \( t \) is the discrete time period index; \( f_m(t) \) is the mainline truck flow rate during \( t \); \( p(t) \) is the proportion of registered trucks (%) during \( t \), \( p(t) \in \overline{p} \); \( \overline{p} \) is the average proportion of registered trucks on the highway segment; \( g(t) \) is the proportion of overweighted trucks (%) during \( t \), \( g(t) \in \overline{g} \); \( \overline{g} \) is the average proportion of overweighted trucks on the highway segment. Note that \( \hat{f}_s(t) \neq f_s(t) \), because of: (i) station closure caused by queue spillover; (ii) WIM errors; and, (iii) actual weight threshold settings different from the legal limit.

When \( \hat{f}_s(t) \) is greater than the weigh station capacity, \( q_{cap}(t) \), a waiting queue forms from the upstream of the station scale in the queuing area. Continuous overflowing \( \hat{f}_s(t) \) \(( > q_{cap}) \) eventually causes queue spillover onto the highway mainline. Then, the weigh station must allow mainline trucks to bypass the weigh station (\( f_p = f_m \) and \( f_s = 0 \)) until the queue vanishes. Therefore, the actual pull-in truck flow, \( f_s \), can be expressed as the following equation using the demand, \( \hat{f}_s(t) \), and another term denoting the station closure event as follow:

\[
f_s(t) = \hat{f}_s(t) - \sum_k^{K(t)} (\delta_k^o + \delta_k^u)
\]

(2)

Where, \( \hat{f}_s(t) \) is the truck demand for the station inspection during the time period \( t \); \( \delta_k^o \) is the unauthorized bypass of overweighted trucks during the \( k^{th} \) station closure event; \( \delta_k^u \) is the unauthorized bypass of non-registered (and legal) trucks during the \( k^{th} \) station closure event; \( K \) is the total station closure events during the time period \( t \).

The screening decision error is another factor that must be considered. A decision error may be caused either by an erroneous WIM measurement or operating the weight threshold \( \theta \) different from the legal weight limit \( W \).

\[
f_s(t) = \hat{f}_s(t) - \sum_k^{K(t)} (\delta_k^o + \delta_k^u) + (e_\alpha(t) - e_\beta(t))
\]

(3)

Where, \( e_\alpha \) is the legal trucks pulled-in due to the type I decision error \( \alpha \); \( e_\beta \) is the overweighted trucks bypassed due to type II decision error \( \beta \). The type I error in (3) indicates a false screening decision for a legal vehicle. This type of errors may occur when the weigh station operates a \( \theta \) lower than \( W \), or when the WIM scale overestimates truck weights. The type II error grants a wrong bypass signal to an overweighted truck. This type of errors can be caused by operating a \( \theta \) higher than \( W \) or by underestimated weight measurements by WIM.

IV. ADAPTIVE TRUCK METERING ALGORITHM

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 [17,18,23]. Traffic metering also has been applied for the dynamic traffic control in urban corridors, work-zones, and toll plazas [19, 20, 22].

An adaptive truck metering algorithm presented in this paper aims at improving the overweight enforcement while minimizing the negative impact of the e-screening operation on legal trucks. The algorithm attempts to achieve this goal by:

- Increasing the utilization of the available weigh station capacity when the station is underutilized. This operation attempts to increase the in-station examination of possible overweighted trucks;
- Restricting the truck flow entering the weigh station when the capacity is over-utilized. This operation attempts to prevent or reduce the queue spillover event.

A. Feedback Control

The algorithm employs a feedback control mechanism via suitable modifications and selection of control parameters. 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 \( u \) to \( u_o \), a pre-defined target utilization level. Suppose \( u_o \) is the ideal status, the algorithm adjusts \( \theta \) to achieve the condition \( u = u_o \) based on the following equation:

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

(4)

Where, \( \theta(t) \) is the weight threshold (kgs) to be implemented
at the e-screening system during the next time period \(t\); \(\theta(t-1)\) is the weight threshold that has implemented during the \(t-1\) period; \(K_\theta\) is the regulator parameter; \(u_o\) is the target utilization rate (%); \(u(t-1)\) is the measured utilization rate during \(t-1\).

The target utilization rate \(u_o\) must be determined in consideration of the actual weigh station capacity that could be measured from a field study.

The capacity utilization rate is defined as the number of trucks requires an in-station examination over the estimated capacity. In this context, “utilization rate” can be expressed using the following equation:

\[
u(t) = \left( f_s(t) + \sum_k^{K(t)} \left( \delta_k^o + \delta_k^n \right) \right) / q_{\text{cap}}(t)
\]

Where, \(u(t)\) is the weigh station capacity utilization rate (%) during the time period \(t\); \(f_s(t)\) is the actual pull-in truck flow (veh/\(\Delta t\)) during the time period \(t\); \(q_{\text{cap}}(t)\) is the station capacity flow rate (veh/\(\Delta t\)) during the time period \(t\). The component, \(\sum_k^{K(t)} \left( \delta_k^o + \delta_k^n \right)\), in (5) denotes the number of trucks that could have been pulled-in, but bypassed because of the station closure events occurred during \(t\).

Feedback control initiates at the end of every time period \(t\) by receiving the real-time measurements \(f_s(t-1)\) and \(\sum_k^{K(t)} \left( \delta_k^o + \delta_k^n \right)\) to calculate \(u(t-1)\). A positive error signal is generated when the weigh station is underutilized, \((u_o > u(t-1))\). The weight threshold setting for the next time period, \(\theta(t)\), will be adjusted lower than the current weight threshold, \(\theta(t-1)\), and as a result, more trucks including possible overweighted vehicles will be examined at the weigh station. On the other hand, negative error signals lead the algorithm to increase \(\theta(t)\) from \(\theta(t-1)\) that allows more trucks including possibly overweighted vehicles to bypass the weigh station. A few overweight trucks may bypass the station examination during this operation; however, this operation could effectively prevent the queue spillover.

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’s control flow.

![Fig. 3. Feedback-based weight threshold control flow](image)

**B. Algorithm Controllability**

A main difference of the proposed algorithm from other metering applications is that the weight threshold control affects only a certain portion among total trucks. The algorithm’s controllability of determining the pull-in and bypass vehicles is largely dependent on the truck participation rate. Also, the control range of the weight threshold (to be discussed in the following section) influences the controllability. Assuming the truck weights follow a normal distribution \(N(\mu_w, \sigma^2_w)\), the algorithm’s controllability can be illustrated as in Figure 4.

![Fig. 4. Algorithm Controllability](image)

From the left side figure, the shaded area A shows the proportion of trucks with weights between the minimum adjustment limit, \(\theta_{\text{min}}\), and the maximum adjustment limit, \(\theta_{\text{max}}\). Applying the truck participation rate, \(g\), reduces the proportion of trucks affected by the algorithm to the area B in the right side figure. The total area (B+C+D) indicates the proportion of participating vehicles or \(g\). The area C is the proportion of trucks that always bypass the weigh station when operating \(\theta\) between \(\theta_{\text{min}}\) and \(\theta_{\text{max}}\). The area D shows the proportion of excessively overweighted trucks that are always pulled in regardless of the \(\theta\) setting when the weigh station is in operation. Therefore, the controllability of the algorithm can be expressed as an equation as follows:

\[
x = g \cdot \left[ P(X < \theta_{\text{max}}) - P(X < \theta_{\text{min}}) \right] = g \cdot \left[ \Phi \left( \frac{\theta_{\text{max}} - \mu_w}{\sigma_w} \right) - \Phi \left( \frac{\theta_{\text{min}} - \mu_w}{\sigma_w} \right) \right]
\]

Where, \(x\) is the proportion of controllable trucks; \(P(X < \theta_{\text{max}})\) is the proportion of trucks with their weights are
less than $\theta_{\text{max}}$; $P(X < \theta_{\text{min}})$ is the proportion of trucks with their weights are less than $\theta_{\text{min}}$. From (6), the algorithm will gain more controllability as $g$ increases or by defining a wider control range of $\theta$.

C. Weight Threshold Control Range

(4) accumulates the error signal, $u_\epsilon - u(t-1)$, if $u$ consistently stays or changes in only one direction (positive or negative) over a number of time periods. For example, if $f_\epsilon < q_{\text{cap}}$ holds for a long period (e.g., during off-peak periods), the condition $u > u_\epsilon$ cannot be fulfilled due to lack of demand, and the feedback term in the algorithm persistently produces a positive error signal, which drives $\theta$ to overshoot to an extremely low level.

When $u$ eventually exceeds $u_\epsilon$ (e.g., at the start of the peak period), the error signal changes to negative and will gradually adjust $\theta$ higher. This condition ($u > u_\epsilon$) must be maintained consistently to restore the normal operation range of $\theta$; however, it may be practically infeasible because $u_\epsilon$ is typically set at a value close to (but not exceeding) 1.0 to maximize the capacity utilization.

This “wind-up” effect is a typical limitation of any feedback control and can be avoided by establishing the maximum and minimum control range, $\theta_{\text{max}}$ and $\theta_{\text{min}}$ [21]. With this setting, any value of $\theta(t)$ either greater than $\theta_{\text{max}}$ or less than $\theta_{\text{min}}$ is disregarded when changing $\theta$. Selection of the threshold control range $[\theta_{\text{min}}, \theta_{\text{max}}]$ must be wide enough to allow the flexible operation of the proposed algorithm. However, this range also should not be too large, because the relative effectiveness of the $\theta$ control actions becomes incrementally insignificant as $\theta$ approaches both negative and positive end regimes.

V. SIMULATION STUDY

This section demonstrates the operation and performance of the proposed algorithm in microsimulation environments. The Port Mann weigh station, located in British Columbia, Canada, was modeled in VISSIM for a case study. An e-screening system launched at Port Mann weigh station as a pilot program in 2007 and the truck participation reached over 15% at the end of the year 2008. This weigh station is currently suffering from frequently queue spillover due to heavy truck volumes and relatively short truck waiting lane (180 meters).

A. Test Environments and Simulation Model Design

Truck encounter data (mainline WIM) was collected for five days from February 5, 2007 to February 9, 2007 during the normal operation time from 8:00 am to 4:00 pm. This dataset includes: date and time of truck detection, speed, length, truck class, 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 arrival in every 30 minute interval obtained from the encounter dataset. The observed pattern shows that the truck arrival gradually increases throughout the station operation time with the peak period from 14:00 to 14:30.

![Average Truck Flow Rate (veh/30min)](image)

**Fig. 5. Average Truck Flow Rate (veh/30min)**

**Truck Type and Length**

British Columbia Ministry of Transportation 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.

**Truck Weight and Legal Weight Limit**

Weigh stations typically determine overweight based on the maximum allowable gross vehicle weight and axle weight. In this study, the simulation model uses only the gross vehicle weight rule. The followings were collected from the encounter dataset: mean vehicle weight, $\mu_m = 20,500\text{kg}$, the standard deviation, $\sigma_m = 4,400\text{kg}$, percentage overweight trucks, $p = 15\%$, and the legal weight limit, $W = 25,000\text{kg}$. Truck weights are assumed to follow a normal distribution, $N(\mu_m, \sigma_m)$, and we programmed the VISSIM model to generate vehicle weights to follow the target mean and standard deviation at $\mu_m$ and $\sigma_m$, respectively.

**WIM measurement accuracy**

The Port Mann e-screening system utilizes a load cell type WIM scale. A properly calibrated load cell WIM must be able to measure gross vehicle weights within $\pm6\%$ of the actual weight for $95\%$ of the total trucks measured [11]. Considering the frequency of calibration works and in consultation with the station officers, the WIM scale in the simulation model was modeled to measure the truck weigh with $\pm10\%$ accuracy for $90\%$ of the total trucks measured.

**Maximum Station Capacity**

Estimating the weigh station capacity is important to understand and to determine an appropriate level of the target capacity utilization rate, $u_\epsilon$. From a field study, it was
observed that trucks managed their speeds approximately at 5 km/hour when they pass the weigh station scale. A uniform service time was assumed for both illegal and legal trucks in this study. Although additional check-up and processes must follow the weight inspection for illegal trucks, those activities typically occur in a designate area separated from the waiting lane and thus it would not affect the weigh station capacity.

Using this measurement, we designed the simulated trucks to select their speeds between 4 km/hour and 6 km/hour when traveling over the station scale. The weigh station capacity with this setting is between 380 and 400 vehicles per hour. We selected 380 as the station capacity, $q_{cap}$, for this study.

B. Algorithm Parameters Setting

The algorithm’s parameters including $u_\theta$, $K_\theta$, $\Delta t$, and $[\theta_{min}, \theta_{max}]$ determine the stability, response time, and amplitude of the algorithm’s reactions for feedback signals. Selection of the set point $u_\theta$ plays an important role affecting both the direction (i.e., positive or negative) and the amplification of $\theta$ adjustment actions. The $u_\theta$ parameter is set at 0.95 in this study. This setting implies that the proposed algorithm considers the 95% utilization rate as the system’s maximum capacity, so it will attempt to bypass additional truck demands beyond this level.

The regulator parameter $K_\theta$ determines the amplification of the $\theta$ adjustment action. A greater $K_\theta$ will make a greater adjustment of $\theta$ for a certain change in $u$. $K_\theta$ must be selected in combination with the update cycle (or update frequency) $\Delta t$. $\Delta t$ decides the algorithm’s time-delay response for the changes in $u$. Frequent update of the weigh threshold enhances the algorithm’s adaptability for quickly changing traffic conditions, but the measured $u$ may not able to denote the overall traffic patterns during the period. In general, $\Delta t$ must be short enough to reflect the changes in the truck arrival pattern, but it also must be long enough to produce representative values. We selected the parameter set ($\Delta t : 600s$, $K_\theta : 0.10W$) that demonstrated better and consistent performances in terms of the overall overweight enforcement rate.

The minimum control range, $\theta_{min}$, is set at 23750kgs, which is 95% of $W$. With this setting, the e-screening can capture 90% of the overweight trucks that could have been bypassed due to the WIM measurement errors if operating $\theta = W$ assuming the truck weights follow $N(20500, 4400)$. The maximum range, $\theta_{max}$, is defined at 30,000kgs. This setting implies that operating $\theta$ at $\theta_{max}$ allows bypass for up to 90% of the overweight trucks that could have been pulled in if operating $\theta = W$ when the truck weights follow $N(20500, 4400)$.

Note that the minimum threshold limit will affect the amount of bypass trucks that could have been pulled-in and contributed to queue spillback. If the WIM measurements have no error, only the maximum threshold limit would be required.

C. Simulation Study Results

The proposed algorithm is evaluated in two test scenarios with the truck participation rates of 15% and 30%. The 15% participation level denotes the status quo scenario. The 30% scenario represents a future condition. Simulation results are averaged from 10 simulation runs for each test scenario. Table I provides a summary of the simulation study. The enforcement rate is defined as the number of overweight vehicles caught over the total number of trucks. The average travel time is the sum of truck travel times divided by the total number of trucks.

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<th>TABLE I SIMULATION RESULTS</th>
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<td>Overweight enforcement</td>
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<td>Misdirected bypass trucks ($e_p$)</td>
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<td>Unauthorized overweight bypass ($\delta_o$)</td>
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<td>Total weight of unenforced overweight trucks</td>
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<td>Misdirected pull-in trucks ($e_d$)</td>
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<td>Percentage closure time over total simulation period</td>
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* Percentage over the total overweight trucks (average 435 vehicles per 8 hours)
** Percentage over the total legal and registered (15%) trucks (average 370 vehicles per 8 hours)
*** Percentage over the total legal and registered (30%) trucks (average 740 vehicles per 8 hours)

The simulation results indicate that the proposed algorithm performs reasonably well in both test scenarios, but greater benefits are observed with 30% participation rate. With 30% participation rate, the overweight enforcement improved from 81.9% to 89.2% with the metering control. The queue spillover reduced by 36% from 21 times to 13 times. $\delta_o$ reduced from 51.4 vehicles to 28.8 vehicles by 44%. The proposed algorithm also effectively improved the overweight enforcement during non-peak periods. Observed $e_p$ reduced from 27.3 vehicles to 18.1 vehicles by 34%.

With 15% penetration rate, the overweight enforcement improved from 74.8% to 76.6%, mainly resulting from the reductions in the queue spillover (and $\delta_o$). With the metering control, queue spillover decreased by 8.8% from 34.1 times to...
31.0 times. The amount of $\delta^o$ decreased from 95.4 vehicles to 81.6 vehicles by 14.4%. An interesting result is that the number of $e_\beta$ increased with the metering control. Increased pull-in truck flows due to a lower participation rate resulted in that $\theta$ maintained greater than $W$ in most time periods. As a result, more frequent type II errors occurred compared to the without metering control scenario. Figure 6 displays the overweight bypass trucks by types ($\delta^o$ and $e_\beta$) resulting from the $\theta$ adjustments of a selected simulation run with 15% participation rate.

![Fig. 6. Weight Threshold Trajectory and Overweight Bypass with 15% Participation rate](image)

From the first graph in Figure 6, the $\theta$ trajectory is maintained lower than $W$ from the beginning of the simulation until approximately 10:20. Comparing the two bar graphs reveals that this operation prevented a few $e_\beta$ caused by the type II error during this period. Afterwards, however, $\theta$ gradually increases as the truck demand increases and eventually it reaches $\theta_{\max}$ at approximately 13:50 until the end of the simulation period. This result implies that the proposed algorithm bypassed all controllable trucks (registered trucks with their weights less than $\theta_{\max}$) attempting to prevent the queue spillover. The station closures and $\delta^o$ apparently reduced as a result compared to the “without” metering control scenario; however, this benefit is relatively insignificant compared to its negative impact that is increased $e_\beta$. Note that the proposed algorithm could have achieved greater benefits in preventing the station closure event and reducing $\delta^o$ provided more controllability (i.e., higher participation rates).

![Fig. 7. Weight Threshold Trajectory and Overweight Bypass with 30% Participation rate](image)

Figure 7 shows the simulation results with 30% participation rate. The bar graphs show that the overall enforcement rate notably improved with the metering control. From 8:00 am to 10:20 am, the algorithm adjusted $\theta$ lower and at the minimum level. As a result, $e_\beta$ significantly reduced compared to the results without the metering control. Afterwards, $\theta$ increases gradually in response to the increasing truck flow in the mainline. However, as a result of a higher participation rate (and more controllable trucks), the algorithm effectively prevented the queue spillover and reduced $\delta^o$. It is also noteworthy that the control range of $\theta$ is maintained lower than 28,000 kgs and consequently incurred less type II errors ($e_\beta$) during these time intervals as compared to the 15% participation rate scenario.

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 in terms of preventing the queue spillover was relatively ineffective due to lack of controllable vehicles.

VI. CONCLUDING REMARKS

An adaptive truck metering algorithm is presented in this paper. This algorithm uses a feedback mechanism to control the level of truck traffic in weigh stations. It is simple and relatively easy to implement as it requires only the truck count measurements from a mainline detector. The algorithm is also a model-free method, which is a much desirable for field implementation. The basic operation of the algorithm adjusts the weight threshold lower when the station is underutilized and increases the weight threshold when the station status is over-utilized, restricting the incoming
truck flow to prevent queue spillover. 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 could be insignificant when the penetration rate is insufficient. The importance of the penetration rate and its impact on the algorithm’s effectiveness was demonstrated by the significantly different results of the 15% and 30% penetration rate scenarios. It should be noted that the testing was conducted on a relatively small-sized 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.

A further innovative and potentially more effective application of the proposed algorithm may be achieved with the use of “pre-arrival” information. Currently, the proposed algorithm is a reactive system that responds to already observed conditions. The time-delay between the occurrence of unexpected (and often undesirable) event and when it is actually handled is in fact an inevitable limitation of many reactive systems. This problem was evident from the simulation results where it is observed that the proposed algorithm was not able to effectively prevent queue spillover for unexpectedly and significantly increased truck demands. Pre-arrival information of truck vehicles can be obtained either by a prediction model or by a pre-detection system. With this pre-arrival information available in real-time, the proposed algorithm can more efficiently utilize the weigh station’s capacity.

REFERENCES


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