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CHALLENGES OF APPLYING AND IMPROVING WIM SYSTEMS FOR WEIGHT ENFORCEMENT IN REPUBLIC OF KOREA


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Abstract
We elucidated the reasons behind the challenges in implementing direct enforcement using the WIM system in Korea and discussed avenues for improvement. Compared to other WIM system standards, the performance evaluation standard for Korean ITS lack specific guidelines and quantitative recommendations. Improvement in this aspect is necessary. Furthermore, data concerning enforcement from WIM systems and mobile enforcement teams were collected, and statistical analysis was conducted to identify the causes of decreased accuracy. When tires exceed the sensing area of the WIM system in cases of abnormal driving, weighing errors of up to 20% can occur. This issue can be addressed by implementing a bypass system that can induce normal driving or by improving the GVW compensation algorithm. Considering the changes in correlation coefficients, the retractable axle contributes more to the GVW error of the WIM system than the rear axle. While we cannot control the manipulation of retractable axles, we can utilize the correlation coefficient analysis approach to detect such manipulation.
Keywords: HS-WIM, Direct enforcement, Standard, Abnormal driving, Retractable axle

1. Introduction

Weight enforcement is important to ensure legal compliance for commercial vehicles on the road while also safeguarding road pavement and infrastructure from potential damages. As widely recognized, the initial issue stemming from a commercial vehicle is damage to the road pavement, which subsequently leads to incidents (resulting in property damage). In addition, it prevents vehicles from driving safely, and these problems lead to secondary accidents (not only property damage, but also injury). In order to prevent secondary accidents accompanying road damage, increased maintenance costs and human casualties, the MLIT(Ministry of Land, Infrastructure and Transport) is conducting R&D projects for effective overload management in Republic of Korea.(KAIA, 2022) These projects are primarily focused on increasing the performance of WIM(Weigh-in-motion) system that measures the weight of vehicles in motion.

The WIM system has globally enhanced the efficiency and efficacy of weight enforcement measures. According to our preliminary investigation results, the US and EU have established standards and frameworks for weight enforcement using the WIM system since 1990s, with the system continuing to operate effectively to this day. For example, Caltrans(California Department of Transportation) operates weigh station bypass systems that combines WIM system with ITS(Intelligent Transport System) device. If a vehicle passing through the WIM system is suspected of being overloaded, the driver will be directed to detour to the weigh station by a telematics device or application. In this bypass system, the WIM system is used for pre-selection of overloaded vehicles.(Caltrans, n.d.) However, in Czech Republic, the WIM system is used for direct enforcement. The legal metrology decree in Czech Republic quantifies the accuracy required for WIM systems to be used for the purpose of direct enforcement. Also the legal road network act specifies specific functions for WIM systems to report vehicles that have been regulated.(Republika, Č., 2015; 2018)

It is clear that direct enforcement has more advantages than pre-selection method in terms of weight enforcement. 1) It operates almost unmanned, 2) makes completely non-stop enforcement possible and 3) induces driver’s compliance preventing overload by increasing the number of enforcement cases. Despite its many advantages, there are various reasons that make its implementation challenging. In this paper, we explain why it is difficult to conduct direct enforcement using the WIM system and we discuss ways to improve the operation of the WIM system. The purpose of this study is to enable the application of more accurate pre-screening and direct enforcement through the WIM system in Korea.

2. Obstacles to the implementation of direct enforcement

2.1. Consistent weight restriction

There is a basic problem with the regulation of vehicle weight in Korea. The classification of vehicles and the type of axle grouping do not influence the establishment of weight restrictions. According to the Korean enforcement decree of the road act, restrictions on operation of vehicles are only based on an axle load of 10 tons and GVW(gross vehicle weight) of 40 tons. On the other hand, in the case of US and EU, the restriction of the GVW and axle load are determined by the class or the type of axles.

Table 1 presents the regulations concerning GVW and various axle load restrictions for both the US federal and state jurisdictions. Federal regulations establish a broad framework for

Table 1 – The weight restriction for commercial vehicle in US

	Federal regulation	State regulation	
		California	Alabama
GVW	36.29	36.29 (34.84*)	36.29 (38.10**)
Single axle load	9.07	9.07 (5.67*, 8.16***)	9.07
Tendem alxe load	15.42	15.42 (15.24*)	15.42(16.33*)
Tridem axle load	N/A	N/A	19.05

* Derived based on a calculation method separately governed by the legislative code of the state of California

** Applicable to vehicles with six or more axles, on roads other than interstate highway

*** Applicable when using high-pressure or solid rubber tires.

weight restrictions, while individual states (California and Alabama) set weight restrictions based on this framework. In each state, these restrictions can be applied differently based on the type of tires and the type of axles.(FHWA, n.d.)

Table 2 shows how the EU restricts GVW based on vehicle classes, following the COUNCIL DIRECTIVE 96/53/EC. 2-axle and 3-axle trailers have relatively low GVW limits of 18 tons and 24 tons, respectively. However, road train with four or more axles and articulated vehicles have higher GVW restrictions, exceeding 36 tons. Under specific circumstances, these restrictions can be permitted to reach a maximum of 44 tons.(EC, 2013)

Compared to weight restrictions in the US and EU, Consistent weight restrictions tend to lead drivers to overload. In Korea, during weight enforcement, a 10% tolerance is typically allowed over 40 tons, leading many drivers to mistakenly believe that overload up to 44 tons is permissible. Furthermore, such issues could lead to a degradation in the recommended performance of the WIM system. For instance, if the recommended accuracy of the WIM system is ± 10% for consistent weight limits (40 tons), it allows for a wide margin of error of ± 4 tons. However, in cases where there are minimum weight limits such as in the EU (18 tons), the error range of the WIM system could be reduced to ± 1.8 tons.

Table 2– The weight restriction for commercial vehicle in EU

Number of axle	Trailer	Grouped vehicle	
		Road train	Articulated vehicle
2	18	N/A	N/A
3	24	N/A	N/A
4	N/A	36	36 (38*)
5	N/A	40	40 (42**, 44***)
6	N/A	40	40 (44***)

* An additional allowance of 2 tons is provided when the Maximum Authorized Weight (MAW) and the Tandem Axle's MAW are adhered to, and if the driving axle is equipped with twin tires and air suspension

** 2-axle vehicles with a 3-axle semi-trailer capable of carrying one or more containers

*** 3-axle vehicles equipped with a 2 or 3-axle semi-trailer capable of transporting one or more containers

2.2. Rough Guideline

Providing specific guidelines for the installation and performance evaluation of WIM systems enables effective enforcement against overload. However, in Korea, the standard for ITS performance evaluation officially offers only a rough overview of the accuracy class of WIM systems by errors and the installation environment. In contrast, the FHAW(Federal Highway Administration) provides information about the types, features, and installation guidelines of WIM systems used in the US. Based on this guideline, approximately 125 operational WIM systems are in place in California. Data obtained from these WIM systems have been analyzed and utilized not only for weight enforcement but also by numerous researchers for the preservation of road pavement.(Lu et al., 2009; Sowman, 2014)

2.3. Qualitative Recommendation

ASTM E1318, OIML R134-1, and COST 323 consider influence factors that reduce the accuracy of WIM systems and provide clear recommendations for installation sites and performance evaluations. Table 3, 4 illustrates a comparison between the standard of Korea and these WIM system standards from the perspective of commonly addressed major influence factors in previous research (temperature, vehicle speed). In case of Korea, there are no recommended guidelines for the other major influence factors, except for temperature. Furthermore, the recommended temperature is not quantitatively specified. On the other hand, the three standards offer quantitative recommendations for operational temperature and vehicle speed ranges of WIM systems. (ASTM, 2017; Jacob et al, 2002; OIML, 2006)

These two major factors significantly diminish the accuracy of WIM systems, thus making their careful consideration crucial when selecting installation sites. Notably, temperature affects the properties of road pavement and influences the vertical stress distribution caused by tire loading.

Table 3 - Temperature recommendations by each standard for WIM system

	Operating temperature (℃)	Recommendation for performance evaluation
Korea	N/A	The timing of performance evaluations should not be concentrated in specific time periods.
ASTM E1318	-20 ~ 60	Temperature should be recorded during performance evaluations, and the reasonable ambient air temperature at which the WIM system operates should be specified, along with providing supporting documentation.
OIML R134	-10 ~ 40	IEC 60068-2-1, 60068-2-2 and 60068-2-3 standards should be referenced to conduct the A.7.2.1 (Static Temperature) test specified in OIML R134-1.
COST 323	-28 ~ 50	Temperature (ambient or pavement surface) should be recorded, and sensitivity analysis of the WIM system with respect to temperature should be conducted.

Table 4 – Vehicle speed recommendations by each standard for WIM system

	Operating vehicle speed (km/h)	Recommendation for performance evaluation
Korea	N/A	N/A
ASTM E1318	30 ~ 130	Road tests should be conducted at a speed 8 km/h faster than the minimum speed specified by the user, a speed 8 km/h lower than the maximum speed, and at the legal speed limit. Particularly, the tests should examine whether HS-WIM can detect excessive acceleration at speeds between 50 to 60 km/h.
OIML R134	User defined	For WIM systems, the markers indicating maximum and minimum operating speeds should be displayed. Road tests should be conducted at the maximum operating speed, minimum operating speed, and at least five times near the midpoint between these speeds.
COST 323	60 ~ 90	Pre-calibration should be conducted four times at 75 km/h, and twice each at 90 km/h and 60 km/h. On-road testing should encompass a total of 110 trials within the speed range of 60 to 90 km/h.

For instance, it has been reported that temperature can lead to up to a 7% weighing errors for piezoelectric quartz and bending plate systems. Also, with piezoelectric polymer sensors, substantial weighing error of up to 50% have been observed at low temperatures. (Burnos et al., 2016; 2017) As road pavement becomes rougher and vehicle speed increases to about 100km/h, the impact load exerted on the ground by the tires also increases. When the IRI(International Roughness Index) exceeds 2 at 100km/h of vehicle speed, dynamic loads can become 10-20% greater than the actual load applied. (Choi et al., 2012)

3. Analysis of WIM Systems in Korea

3.1. Field test section

The aforementioned literature review explains the institutional obstacles that make the implementation of direct enforcement challenging. However, the most critical aspect is understanding how WIM systems are being utilized in Korea and exploring strategies to employ the data measured by these systems for the application of direct enforcement.

We chose areas where HS-WIM and mobile enforcement teams are linked to carry out weight enforcement as the field test sections, and collected the enforcement data. Figure 1a shows an enlarged view of the sensor platform. The sensor platform is a loadcell-type HS-WIM system produced in Korea, with a GVW margin of error of ± 5%, and axle load margin of error of ± 10%. Figure 1b shows the site of weight enforcement by the mobile enforcement team. A pre-screening method is applied at the field test section. When a vehicle passes the WIM system, information such as the vehicle number and weight is immediately stored on the server. If the

Figure 1 – (a) load cell-type HS-WIM and (b) mobile enforcement team in Korea

GVW exceeds 40 tons, or if an individual axle load exceeds 10 tons, the vehicle information is forwarded to the mobile enforcement team. The mobile enforcement unit then tracks the vehicle and inspects it using a portable axle scale. weight enforcement is carried out on the shoulder of flat roads with low traffic volume, verifying if the GVW or axle load actually exceeds the vehicle's operating restrictions. The axle scale used during the inspection is a portable axle scale from company P, which is inspected and calibrated annually. This axle scale's maximum permissible error is ± 0.5% during verification and ± 1% during use, indicating its precision.

3.2. Statistical analysis

Road pavement temperature and vehicle speed have been extensively studied as the main influence factors. (Burnos et al., 2016; 2017; Dontu, et al., 2020; Gajad et al., 2023;) Recent studies have also begun to explore minor influence factors, such as vehicle driving path and acceleration (Ryguła et al., 2021; Zhao et al., 2022). However, the amount of information on these minor factors is limited, as they have been studied less than primary factors. Also, some previous studies used calibrated vehicles in controlled environments. However, to understand whether the same size of measurement influence occurs in the field, analysis should be based on actual overloaded vehicle inspection data. To broaden our understanding of the influence factors, we conducted statistical analysis on minor influence factors, including driving path and vehicle class.

The accuracy of WIM system in the analysis process was calculated as a relative error, and both the relative error and error rate were indicated when presenting the results. Also the GVW and FAW(front axle weight) relative error were used to compare the changes in the WIM system's accuracy.

3.2.1. Driving path

To analyze the influences according to the driving path, the GVW and FAW relative error were calculated for each driving path for all vehicle classes, and the average and standard deviation were calculated. Driving paths were categorized into normal(N=604), two-lane(N=29), departure(N=70), and biased(N=109). Normal driving means that all axles of the vehicle are within a single sensor platform. Two-lane driving refers to when the vehicle axles are spanning two platforms. Departure and biased driving exhibit similar paths; if the vehicle's wheel completely leaves one platform, it is classified as a departure, and if it slightly overlaps, it is classified as biased.

Figure 2 shows the average relative error of the WIM system by driving path, regardless of vehicle class. A relative error greater than 1 signifies that the WIM system may overestimate the vehicle's weight, and vice versa if it is less than 1. During normal driving, the relative error was found to be 1.02 (2 ± 4%) for GVW and 1.02 (2 ± 8%) for FAW. The error ranges for GVW and FAW were about ± 6% and ± 10%, respectively, which closely matched the performance of the previously known loadcell-type HS-WIM system. For abnormal paths like departure driving, the relative error was found to significantly diverge from 1. During two-lane driving, GVW was evaluated 3 percentage points higher and FAW 4 percentage points higher than normal driving. However, it was relatively less affected compared to departure driving. The accuracy difference depending on the driving method is related to the GVW compensation algorithm of the WIM system. Unlike other driving methods, two-lane driving involves all axles of the vehicle being within two sensors, and the two sensors combine their individual measurements to calculate axle load. A slight error may occur depending on changes in the angle of entry or distance from the sensor center when the vehicle changes its driving path. (Ryguła et al., 2021)

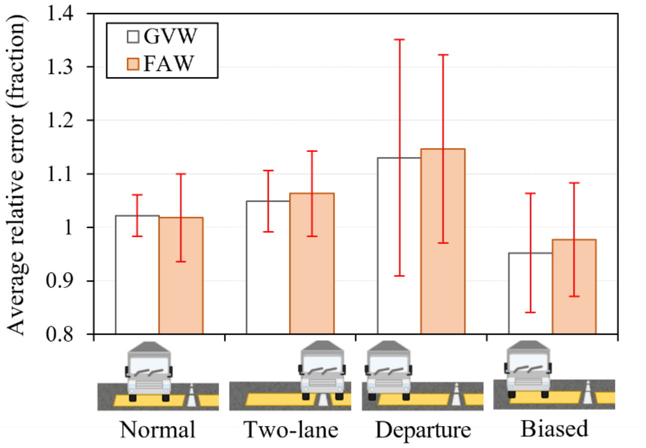

Figure 2 – Average relative error in GVW and FAW for each driving path

Nevertheless, the GVW compensation algorithm for two-lane driving operates based on the actual measurement results for all axles, so it is assessed that two-lane driving has higher accuracy than departure driving. In some cases of departure driving where several wheels completely left the platform, the GVW and FAW relative errors had the greatest deviation at 1.13 (13 ± 22%) and 1.14 (14 ± 20%) respectively. The large deviation during departure driving likely occurred because the WIM system compensates for a greater amount of weight than the actual weight of the vehicle in the process of compensating for the lost weight. For biased driving, the relative errors were 0.95 (-5 ± 11%) for GVW and 0.98 (-2 ± 11%) for FAW. The deviations were relatively small compared to departure driving, but the GVW was underestimated by an average of about 5 percentage points compared to normal driving. Biased driving refers to when a vehicle's wheels are only partially on the platform, making it impossible to properly compensate for the lost weight. The lower GVW and FAW estimates for biased driving compared to other driving methods.

3.2.2. Vehicle class and retractable axle

In Korea, vehicles are classified into 12 classes (MLTM, 2006). Vehicle classes 4, 6, 7, and 10 which are normal driving were selected as the vehicle classes for analysis. Classes 4(N=59), 6(N=245), and 7(N=76) correspond to 2-axle, 4-axle, and 5-axle semi-trailers, respectively. Class 10(N=129), one unit more than Class 7, corresponds to a 5-axle articulated vehicle. Based on the characteristics of each vehicle class, the accuracy difference of the WIM system was compared with the increase in axles and unit numbers.

Figure 3 shows the average relative errors of the WIM system for vehicles driving normally, distinguished by vehicle class. The GVW relative error was most accurate for class 6 vehicles at 1.00 (0 ± 4%). The FAW relative error was most accurate for class 4 vehicles at 1.01 (1 ± 6%) compared to other vehicle classes. Welch ANOVA analysis showed statistically significant differences in the mean GVW (F=47.856, DF=3, p<.001) and FAW(F=21.740, DF=3, p<.001) values by vehicle class.

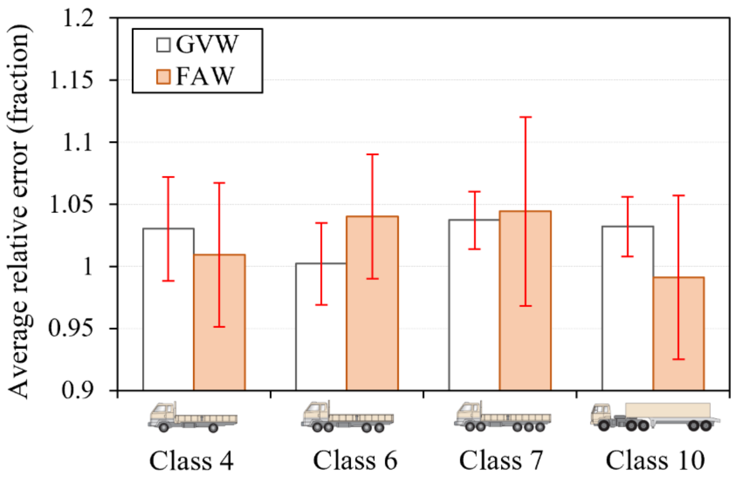

Figure 3 – Average relative error in GVW and FAW for each vehicle class

Table 5 shows the results of the Games-Howell post-hoc test used to compare differences in means between groups that do not satisfy the assumption of homoscedasticity. Compared to class 6 vehicles, the GVW of all vehicle classes was evaluated about 2.8 to 3.5 percentage points higher. Compared to class 4 vehicles, the FAW of class 6 and 7 vehicles was evaluated about 3 to 4 percentage points higher. Fig. 3 and Table 5 show that there is a significant difference in relative errors by vehicle class, but there is no specific trend with the increase in axle and unit numbers. Hence, it was not possible to effectively explain the measurement influence by vehicle class based solely on a comparison of averages.

To analyze the measurement influence by vehicle class, it is necessary to reconsider how the GVW error is composed. The GVW is composed of the sum of axle loads. If in a class 4 vehicle, one axle was measured with a difference of +1 ton and a second axle with a difference of -1 ton compared to the actual axle loads, the errors cancel each other out, making the GVW appear almost accurate. The GVW and FAW relative errors of class 6 vehicles in Figure 3 effectively illustrate this offsetting phenomenon due to the sum of errors. The FAW relative error of class 6 vehicles was 1.05 (5 ± 10%), evaluated on average about 5% higher. However, the GVW was evaluated almost equal to the actual vehicle weight. Therefore, in the case of class 6 vehicles, the relative axle load errors offset each other, resulting in a relatively accurate measurement of GVW.

Table 5 – Games-Howell pairwise comparison by vehicle class

Vehicle class	GVW relative error		FAW relative error	
	Mean diff.	T-value	Mean diff.	T-value
4 – 6	0.028***	4.772	-0.031**	-3.780
4 – 7	-0.007	-1.192	-0.035*	-3.000
4 – 10	-0.002	-0.280	0.019	1.958
6 – 7	-0.035***	-10.344	-0.004	-0.389
6 – 10	-0.029***	-9.799	0.050***	7.496
7 – 10	0.006	1.627	0.053***	5.087

*p<.05, **p<.01, ***p<.001

Examining a few reasons for potential errors during axle load measurement reveals the following. 1) Each vehicle class has different axle spacing and wheel arrangement, which affects the load distribution of the vehicle. 2) The greater the suspension stiffness of the axle, the larger the axle load error can be on rough surfaces. (Park et al., 2014) 3) When passing through the WIM system, the operation of the retractable axle can result in the load of the retractable axle being measured lower than the actual value. (Park et al., 2022) Considering these three causes, each vehicle class may have a particular axle where the error is large. To examine this possibility, we analyzed how much each axle contributes to the GVW relative error and reviewed the characteristics of each vehicle class. GVW relative error was set as the dependent variable, and the relative error of axle load was set as the independent variable to analyze the correlation between the two variables. The larger the correlation coefficient, the greater the contribution of the axle to the GVW relative error.

Table 6 shows the correlation analysis results for class 6 vehicles among the vehicles analyzed. The Pearson correlation coefficient (r) here signifies the relative contribution of each axle to the GVW relative error. Each axle's relative error was found to have a positive correlation with the GVW relative error ($p<.001$), indicating that if the axle load is overestimated, then the GVW can also be overestimated. Notably, a strong correlation of 0.75 or above was observed at the rear axle compared to the front axle of the vehicle. In the case of class 6 vehicles, the 3rd and 4th axles, which correspond to the rear axle, are linked to the payload, thus bearing a large load. Consequently, the rear axles (3rd, 4th) experience greater load fluctuations than the front axles (1st, 2nd), which appears to be a key contributor to the increase in relative error in the GVW of class 6 vehicles.

Figure 4 displays the changes in correlation coefficient based on the axle position for each vehicle class. Examining the trends in the correlation coefficients, class 6 vehicles showed a

Table 6 – Impact of relative error of axle load on GVW relative error in vehicle class 6

		Relative error of the axle load			
		1st axle	2nd axle	3rd axle	4th axle
GVW relative error	r	0.363	0.443	0.789	0.752
	p	<.001	<.001	<.001	<.001

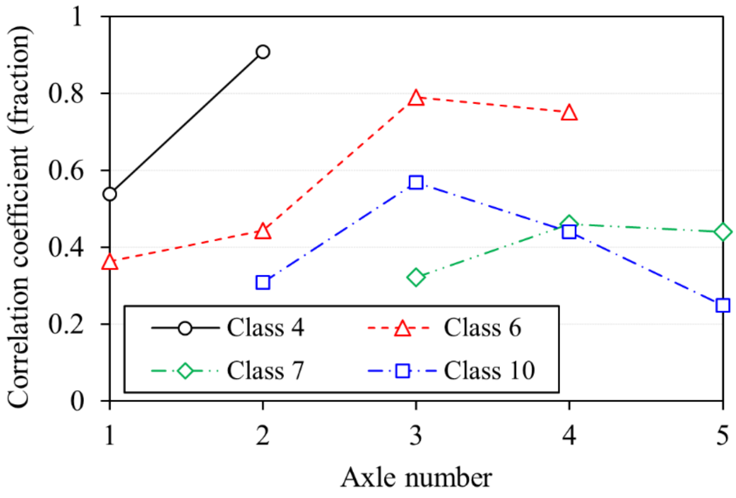

Figure 4 – Extent of individual axle contributions to GVW relative error by vehicle class

decreasing trend between the 3rd axle (r=0.789, p<.001) and 4th axle (r=0.752, p<.001), while class 7 vehicles showed a decreasing trend between the 4th axle (r=0.456, p<.001) and 5th axle (r=0.440, p<.001). Class 10 vehicles experienced a large drop in correlation coefficient from the 3rd axle (r=0.568, p<.001) to the 5th axle (r=0.248, p<.01). Class 4 vehicles, where the load is concentrated on the rear axle, showed a large increase in correlation coefficient from the 1st axle (r=0.538, p<.001) to the 2nd axle (r=0.907, p<.001). For all vehicle classes, the degree to which axle load contributes to relative error in GVW increased as the load shifted from the front axles to the rear axles. However, excluding class 4 vehicles, this trend did not increase linearly but showed a decrease at specific axles.

The changes in the correlation coefficients could be attributed to the placement of the loaded cargo, external environmental factors, or potentially the influence of retractable axles. There have been consistent reports of cargo truck drivers manipulating the retractable axle to avoid weight enforcement (Kim et al., 2016). When a retractable axle is manipulated while passing through a WIM system, errors occur in the measurements for that axle. Examining the changes in correlation coefficients for class 6, 7, and 10 vehicles in Figure 6 reveals that the axle showing the highest correlation coefficient is where the retractable axle is installed in all cases. Class 10 vehicles are semi-trailers; except for the 2nd and 3rd axles, retractable axles cannot be installed. Nevertheless, the phenomenon of a larger correlation coefficient for the 3rd axle (where the retractable axle is present) than for the rear axles (4th, 5th) was observed. The analysis indicates that the accuracy of the GVW per vehicle class is influenced more by the retractable axle than by the rear axle.

4. Conclusion

This study compared four WIM system standards through literature review and explained the background of challenges in direct enforcement in Korea. The conclusion we have found to address institutional issues is as follows:

> Differentiating weight restrictions by vehicle type enables drivers to adhere to load limits without confusion. The minimum weight restrictions can potentially enhance the accuracy of WIM systems.

> Specified guidelines and quantitative recommendations are necessary. This is crucial for maintaining the recommended accuracy of WIM systems. Reference to internationally recognized WIM system standards should guide the enhancement of the Korean ITS performance evaluation for WIM system.

Also we conducted a statistical analysis on minor influence factors (driving path, retractable axle) based on the measurement results of a WIM system for overloaded vehicles and the inspection results of a mobile enforcement team. From the statistical analysis, we quantified the effects of minor influence factors on the WIM system's accuracy and explored their causes. If these results are utilized to improve GVW compensation algorithms and serve as foundational data for the advancement of retractable axle load estimation techniques, it is expected that they will provide significant assistance in the introduction of direct enforcement. The key conclusions drawn from the statistical analysis are as follows:

> Abnormal driving (two-lane, departure, biased) should be controlled. The Caltrans bypass system serves as a good example of guiding drivers to drive normally. Also the GVW compensation algorithm, inducing a deviation of 20%, for departure driving needs to be improved.

> Measuring GVW lower than the actual value would pose a greater problem than overestimation, as it could prevent authorities from controlling overloaded vehicles. Therefore, a method is necessary to identify cases where the retractable axle load is excessively low compared to other axles and conduct additional inspections when manipulation of the retractable axle is suspected. In the current state, based on the changes in axle-wise correlation coefficients, the contribution of GVW errors for retractable axles can be identified.

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