Evaluation of weigh-in-motion in Manitoba

Xun Zhi, Ahmed Shalaby, Dan Middleton, and Alan Clayton

Abstract: The primary objective of a weigh-in-motion (WIM) system is to provide highway designers and agencies with information on the loads and traffic volumes using a particular highway, thereby facilitating improved pavement design, management, and weight enforcement. In this paper, the historic performance of WIM systems in Manitoba is evaluated. The results indicate that large numbers of unreasonable data are produced from the WIM systems, calibration procedures are not standardized, and there is drift in calibration. The performance of the Brokenhead WIM system was evaluated through a detailed survey conducted at the Brokenhead WIM site and the Westhawk Permanent Truck Weigh Station in August 1997. The Brokenhead site is on the Trans-Canada highway east of Winnipeg. It is the only WIM system in the country that measures truck characteristics and movements between eastern and western Canada. The survey produced a large database permitting the comparison of truck dimension measurements, truck weights, and vehicle classification between those produced by the WIM system and those observed manually. The results indicate that WIM axle-spacing data sets were outside the tolerance for 95% conformity specified by the American Society for Testing and Materials (ASTM). The system classified 5 to 9 axle combination trucks more accurately than some 2- and 3-axle vehicles. The WIM system underestimated about 90% of truck weights in the survey period. The degree of underestimation exceeded 50% of the corresponding static weights. This finding highlights the importance of quality control and corrections on WIM data prior to their use in research or engineering practice.

Key words: weigh-in-motion, vehicle classification, calibration, axle spacing, axle load.

Résumé : L'objectif primaire du système WIM est de fournir au concepteurs et agences d'autoroutes des informations sur les charges et les volumes de trafic sur une autoroute particulière. Le système facilite ainsi la conception et la gestion de chaussées et la mise en vigueur de poids. Les résultats indiquent que de larges nombres de données non-raisonables sont générés par les systèmes WIM, que les procédures d'étalonnage ne sont pas standardisées et qu'il y a dérive dans l'étalonnage. La performance du système WIM de Brokenhead a été évaluée par le biais d'une étude conduite au site WIM de Brokenhead et de la station de pesage de camions permanentes de Westhawk en 1997. Le site de Brokenhead est sur l'autoroute transcanadienne à l'est de Winnipeg. C'est le seul système WIM dans le pays qui mesure les caractéristiques de camions et le mouvements entre le Canada de l'est et de l'ouest. L'étude a généré une large base de données qui permet la comparaison de mesures générés par le système WIM et celles observés manuellement pour les dimensions de camions, le poids de camions, et la classification de véhicules. Les résultats indiquent que les données d'espacement des essieux générés par WIM étaient en-dehors de la limite de tolérance pour une conformité de 95 % spécifié par la American Society for Testing and Materials (ASTM). Le système classifie plus précisément les camions à combinaison de 5 à 9 essieux que les véhicules à 2 ou 3 essieux. Le système WIM a sous-estimé à peu près 90 % des poids de camions durant la période d'étude. Le degré de sous-estimation dépasse 50 % des poids statiques correspondants. Cette découverte met en évidence l'importance du contrôle de qualité et de corrections de données WIM avant leur utilisation dans la recherche ou le génie.

Mots clés : pesage en mouvement, classification de véhicules, calibrage, espacement d'essieux, charge d'essieu.

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Introduction

Weigh-in-motion (WIM) technology provides information on the characteristics of traffic loads, speeds and dimensions for the purposes of highway and pavement design as well as regulation enforcement and safety evaluation. WIM is an advanced technology that forms part of the intelligent transportation systems (ITS) specifically in the area of Commercial Vehicle Operations (CVO). WIM systems have been installed on many test pavements to record the loads that affect the site during its life span and to refine pavement design methods.

There are thousands of systems in use today across North America and around the world. WIM systems collect data

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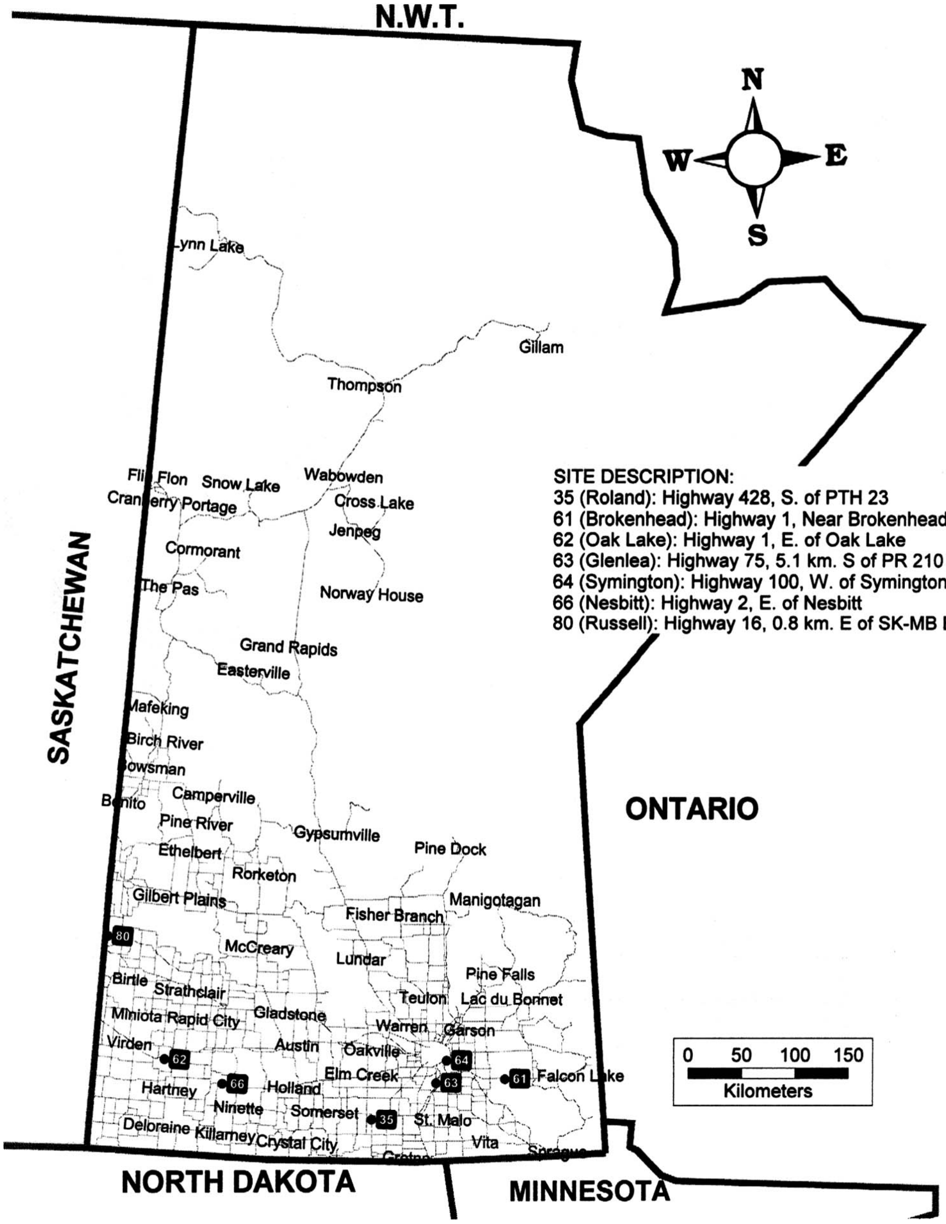
Fig. 1. Locations of WIM and AVC sites in Manitoba.



under a variety of dynamic and climatic conditions. The systems are designed to measure a wide range of axle loads and to operate for extended periods in harsh environments. This combination of factors resulted in WIM outputs being frequently rejected and considered unreasonable. The quality and amount of WIM data have been sources of frustration and disappointment to many engineers.

It has been argued that the acceptable tolerance of a WIM system output should not exceed ±30% or ±50%. Although these margins are seen as ends of the spectrum in some engineering fields, many researchers believe that this is a practical and sufficient precision level for WIM measurements. It is widely recognized now that WIM technology will not see significant advancements in the near future and that highway professionals should work with existing data to devise quality control procedures that can extract the usable data from the plethora of WIM outputs. In this paper, a survey was conducted to simultaneously collect data from a major WIM site that participates in the long-term pavement performance program (LTPP) and from a static permanent truck weigh station. Pairs of matching records were examined to assess the quality of WIM data and to develop relationships among the axle loads, axle-spacings, gross vehicle weights (GVW), and vehicle lengths, as well as to evaluate WIM abilities to classify vehicles.

Historic performance of WIM systems in Manitoba

WIM systems are in place at seven locations in Manitoba. Six of them were installed in the early 1990s, and one was installed in late 1997. The locations of these sites are shown in Fig. 1. Each system consists of a capacitive strip sensor and two inductive loops linked to a roadside processing unit. A capacitive sensor is made of a hollow aluminum extrusion with an insulated inner copper electrode. The sensor extends

Table 1. WIM data summary.

		Site					
	Data type	35	61	62	63	64	66
(*a*) 1996 data	Days of operation	307	299	306	290	258	291
	Total records	136 819	490 593	679 354	548 520	432 595	211 356
	Records with overall length ≤ 0	0	23	20	325	4	8
	Records with GVW ≤ 0	5	3 508	29 594	292	107	286
	Records with axle count ≤ 1	1	0	4	169	1	2
	Records with overall length ≤ 0 and GVW ≤ 0	0	3	19	50	0	1
	Records with overall length ≤ 0 and axle count ≤ 1	0	0	0	55	0	0
	Records with GVW ≤ 0 and axle count ≤ 1	34 370	25 712	288 919	166 044	274 147	48 944
	Records with overall length ≤ 0, GVW ≤ 0 and axle count ≤ 1	0	2	9	127	92	10
	Total unreasonable records	34 376	29 248	318 565	167 062	274 351	49 251
	Unreasonable records (%)	25	6	47	30	63	23
(*b*) 1997 data	Days of operation	359	358	343	219	—	350
	Total records	76 034	654 869	592 933	437 898	—	119 331
	Records with overall length ≤ 0	51	35	4	27	—	24
	Records with GVW ≤ 0	290	1 104	203	526	—	161
	Records with axle count ≤ 1	0	21	0	0	—	0
	Records with overall length ≤ 0 and GVW ≤ 0	13	8	2	2	—	15
	Records with overall length ≤ 0 and axle count ≤ 1	0	8	0	0	—	0
	Records with GVW ≤ 0 and axle count ≤ 1	43 249	50 978	304 754	283 565	—	28 731
	Records with overall length ≤ 0, GVW ≤ 0, and axle count ≤ 1	0	8	1	375	—	1
	Total unreasonable records	43 603	52 162	304 964	284 495	—	28 932
	Unreasonable records (%)	57	8	51	65	—	24

across the lane and, when compressed, during the passage of a vehicle, the capacitance between the extrusion and the electrode changes proportional to the load. An axle load is computed by integrating the signal from the sensor with the speed information. When a vehicle approaches, the upstream inductive loop is used to alert the system and the downstream loop is used to detect the length of the vehicle to determine gross vehicle weight and overall length. The following sections present the historic performance of those six earlier-installed WIM systems in terms of reasonability of WIM data, physical conditions of WIM sites, calibration techniques, and WIM system "out-of-calibration."

Reasonability of WIM data

For the purpose of this research, the "reasonability" of WIM data is defined as a rational measure that determines if each vehicle record reflects a real passing vehicle. The reasonability is assessed by screening the data produced from the six WIM sites in Manitoba in 1996 and 1997 according to the following criteria: overall length ≤ 0; gross vehicle weight (GVW) ≤ 0; and axle count ≤ 1. If one of the three conditions occurs, the data record is considered unreasonable and is removed from the database. As shown in Table 1*a* and *b*, of the six WIM sites, the percentage of unreasonable records was higher than 20% for most sites. None of the WIM systems functioned year-round. According to the Manitoba Department of Highways and Transportation (1996*a*, 1997), this was caused by problems with (1) equipment shutdown during system maintenance; (2) a low battery; and (3) natural disasters, such as flooding. Records with both axle counts ≤ 1 and GVW ≤ 0 accounted for 99% of "unreasonable" records.

Physical conditions of WIM sites

The features of a site significantly affect the performance of a WIM system. The ideal conditions are achieved when force is applied to a smooth and level road surface by perfectly round and dynamically balanced rolling wheels at a constant speed in a vacuum (Izadmehr and Lee 1987, Sharma et al. 1990). However, this ideal situation does not exist in real life. The geometric features and pavement conditions of the six WIM sites considered in this research were determined by referring to the "1995 Inventory and Appraisal of Existing Conditions on Provincial Trunk Highways," Manitoba Highways Programming Branch (Manitoba Highways and Transportation 1996*b*). To obtain the most recent information about the physical condition of these sites, a personal interview was held with the staff of the MDHT Programming Branch, and field surveys were conducted at the sites. The WIM site on the east TransCanada highway

Table 2. WIM calibration results.

		Single axle	Tandem axle		GVW
(*a*) Glenlea site (1991)	No. of observations	77	145		72
	Mean of percentage difference (%)	–0.4	4.4		3.1
	95% confidence interval	–30.8 to 29.9	–28.0 to 36.7		–26.8 to 33.1
	ASTM tolerance (%) at 95% conformity	±20	±15		±10
		Single axle	Drive tandem	Trailer tandem	GVW
(*b*) Brokenhead site (1994)	No. of observations	95	93	93	91
	Mean of percentage difference (%)	–2.74	–1.74	–3.71	–2.96
	95% confidence interval	–38.9 to 33.4	–32.8 to 29.4	–27.3 to 19.9	–26.9 to 20.9
	ASTM tolerance (%) at 95% conformity	±20	±15	±15	±10

(Brokenhead WIM site) and the site on Highway 75 (Glenlea WIM site) are not located in zones of free traffic flow characterized by low traffic volumes and high travelling speeds. Additionally, due to the presence of distress on road surfaces, no WIM sites in Manitoba fully comply with the requirements for a smooth and level road surface.

Calibration techniques

Four group factors, as indicated by Lee (1988), may cause the difference between WIM and static measurements: (1) dynamic factors (e.g., vehicle speed, vehicle suspension system, and profile of pavement); (2) equipment (e.g., WIM sensor used); (3) signal interpretation; and (4) static reference (e.g., static axle-group load and static GVW). The discrepancy between static and WIM weights is considered to be a WIM system error. WIM errors are comprised of systematic errors and random errors. The purpose of WIM system calibration is to reduce systematic errors (Davies and Sommerville 1990). The calibration technique adopted by MDHT is different from that recommended by the system manufacturer (Golden River Traffic 1992), and that recommended by ASTM standards (1993) in terms of (1) the calibration vehicle used, (2) the method of determining the static weight of the calibration vehicle, (3) the method of testing calibration results, and (4) lack of consideration given to effects of seasonal and temperature variations in Manitoba (Zhi 1998).

To evaluate the calibration results, two truck weight surveys were conducted at the Emerson Permanent Truck Weigh Station and Glenlea WIM site (Ostroman 1993) and at the Westhawk Permanent Truck Weigh Station and Brokenhead WIM site (Kelly 1994). Both surveys were conducted immediately after system calibrations. Table 2 summarizes the analysis of the survey data. The WIM weights were compared with the corresponding static weights by axle units and GVWs in terms of the percentage difference (the ratio of the difference between WIM and static weights to the static weight). The mean of percentage difference (PD) and 95% confidence interval for the percentage differences are listed in the tables. The tolerances of 95% probability of conformity for WIM axle unit weights and GVWs proposed by ASTM are shown in Table 2 for comparison purposes. For both calibrations, all WIM weight data sets are outside the 95% conformity ranges specified by ASTM.

WIM system “out-of-calibration”

The “out-of-calibration” problem is experienced by many WIM systems. “Drifting,” or a shift of WIM weight distribution, is one of the phenomena that is observed, and is indicative of “out-of-calibration.” A method introduced by Clayton and Cordeiro (1994) and Escobar (1995) based on the shift of WIM weight cumulative frequency distribution CFD with time, is used to identify the drifting problem experienced by the WIM systems in this research. This method compares the monthly cumulative frequency distribution of the gross vehicle weight of a 3-S2 truck with that obtained immediately after system calibration (post-calibration cumulative distribution). It was found that “out-of-calibration” generally starts 3 months after the system calibration. The outcome of the drift is different from site to site. The differences are shown in two ways: (1) the degree of drift and (2) the direction of the drift relative to the post-calibration curve. The direction of drift indicates under-weighing or over weighing of axle loads.

Evaluation of the WIM system at Brokenhead

To evaluate the performance of WIM systems in Manitoba, an extensive 5-day survey was conducted at the Westhawk Permanent Truck Weigh Station and the Brokenhead WIM site located on the east Trans Canada highway in August 1997. The objectives of the survey were (1) to compare the static and WIM weights, (2) to compare the static and WIM dimension measurements, (3) to assess the accuracy of vehicle classification by the WIM system, (4) to assess the effect of bumper height on the WIM overall length, and (5) to assess the effect of suspension systems on WIM weights.

Survey methodology

The Brokenhead WIM Site was selected for the survey. This site is on the Trans-Canada highway, about 90 km west of the Westhawk permanent truck weigh station and the Manitoba–Ontario border. It is the only site in Canada that captures most Canadian-routed truck traffic between eastern and western Canada. There is no major intersection between the two locations, and the truck volume is constant on this road segment. This ensures that most trucks that are statically weighed and measured at Westhawk also cross over the

Table 3. Statistics of dimension difference.

	n	Dimension	Mean difference (m)	Std. dev. of difference (m)	95% confidence limits (m)
(*a*) 3-S2 trucks	127	Axle spacing 1	0.045	0.255	0.551 to –0.461
		Axle spacing 2	0.069	0.084	0.237 to –0.980
		Axle spacing 3	–0.011	0.434	0.850 to –0.872
		Axle spacing 4	0.080	0.083	0.245 to –0.085
		Overall length	–1.147	1.384	1.599 to –3.892
(*b*) 3-S3 trucks	39	Axle spacing 1	0.008	0.180	0.375 to –0.359
		Axle spacing 2	0.067	0.070	0.209 to –0.075
		Axle spacing 3	0.035	0.290	0.621 to –0.551
		Axle spacing 4	0.058	0.079	0.217 to –0.101
		Axle spacing 5	0.069	0.078	0.226 to –0.089
		Overall length	–0.954	0.980	1.025 to –2.933
(*c*) 3-S3-S2 trucks	39	Axle spacing 1	0.028	0.271	0.581 to –0.525
		Axle spacing 2	0.064	0.089	0.246 to –0.118
		Axle spacing 3	–0.003	0.350	0.711 to –0.716
		Axle spacing 4	0.078	0.069	0.218 to –0.063
		Axle spacing 5	0.088	0.082	0.254 to –0.079
		Axle spacing 6	0.059	0.163	0.391 to –0.273
		Axle spacing 7	0.086	0.070	0.229 to –0.057
		Overall length	–0.371	1.099	1.873 to –2.615

Note: *n* is sample size; axle spacing 1 to axle spacing 7 are the lengths of axle spacings which include inter-axle spacing and axle unit spacing (e.g., axle spacing 1 is the length between the first and the second axles); overall length is the bumper-to-bumper vehicle length.

WIM site at Brokenhead. With the objective of maximizing the number of vehicles to be captured in the survey, previous Brokenhead WIM data produced in August were analyzed to determine on which day of the week the average daily truck traffic is highest and at what time of the day the average hourly truck traffic is highest. Through the analysis, the survey was conducted during the summer of 1997, from 9:00 a.m. to 8:00 p.m. on the following 5 days; Thursday, July 31; Saturday, August 9; Sunday, August 10; Wednesday, August 13; and Thursday, August 14, 1997.

During the survey, one person was at the WIM site to record the identification number produced by the WIM system for each truck, time stamp, truck colour, company name, truck configuration, and body type. Others at the permanent weigh station recorded the passing time, truck colour, company name, truck configuration, body type, axle weight, suspension type, and truck dimensions (axle-spacings, overall lengths, and bumper heights). The data were then linked by observed passing time, truck colour, company name, truck configuration, and body type. In this way, the pairs of WIM and static data were identified As the two sites are 90 km apart, a time lapse of 55 min was used to compare time stamps.

Summary of survey

During the survey, 910 trucks entered the permanent weigh station, 770 trucks were weighed and had their suspension systems identified,and the dimensions of 335 trucks were measured. Seven hundred three static weights recorded at the station have matched WIM weights from the Brokenhead WIM site, and 275 truck dimensions measured at the station have matched WIM dimension measurements from the Brokenhead WIM site. Of the 703 pairs of WIM and static weight data, 345 vehicles were 5-axle (3-S2) tractor–semi-trailer combination trucks. Since 3-S2 accounted for 49% of the data set, the evaluation of weight measurements is based on the 3-S2 trucks only. Of the 275 pairs of WIM and static dimension measurements, 127 (46%) are 3-S2 truck dimensions, 39 (14%) are 6-axle (3-S3) truck dimensions, and 30 (11%) are 8-axle (3-S3-S2) truck dimensions. The evaluation of dimension measurements is based on the three truck types.

Dimension measurements

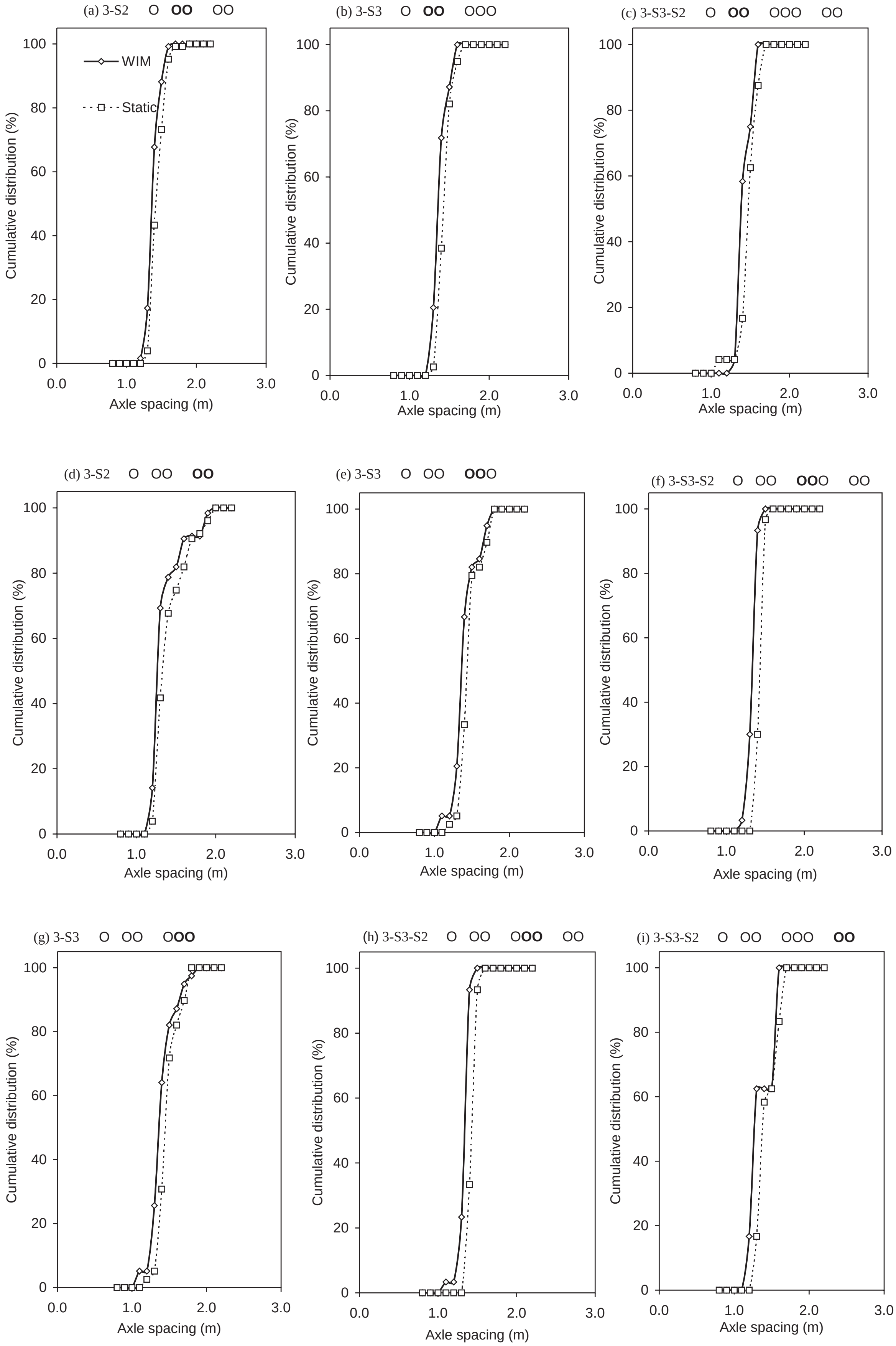
Axle spacing is used by WIM systems to classify vehicles and to determine maximum allowable axle and gross vehicle weights. The accuracy of the dimension measurements produced by the WIM system affects the accuracy of WIM vehicle classification. ASTM specifies that the tolerance for 95% probability of conformity for axle spacing is ±150 mm. The difference between static axle spacing and WIM axle spacing is calculated as:

$$[1] \quad \text{Difference} = \text{static axle spacing} - \text{WIM axle spacing}$$

The difference between a static overall length and a WIM overall length is calculated in the same manner. The mean and the standard deviation of the difference are shown in Table 3. For the purpose of comparison with the tolerance specified by ASTM, the 95% confidence limits for the differences are calculated and are shown in the table. It can be seen from the table that all WIM axle-spacing data sets are outside the 95% conformity range.

The cumulative frequency distributions of axle spacings and overall lengths are plotted in Fig. 2 to Fig. 4. Compared with the distribution curves of overall lengths as shown in Fig. 4, the distribution curves of WIM and static axle spac-

Fig. 2. WIM versus static axle unit spacings. The axle spacing distribution shown in the graph is the spacing of the bolded axles.



(a) 3-S2 O **OO** OO

(b) 3-S3 O **OO** OOO

(c) 3-S3-S2 O **OO** OOO OO

(d) 3-S2 O OO **OO**

(e) 3-S3 O OO **OO**O

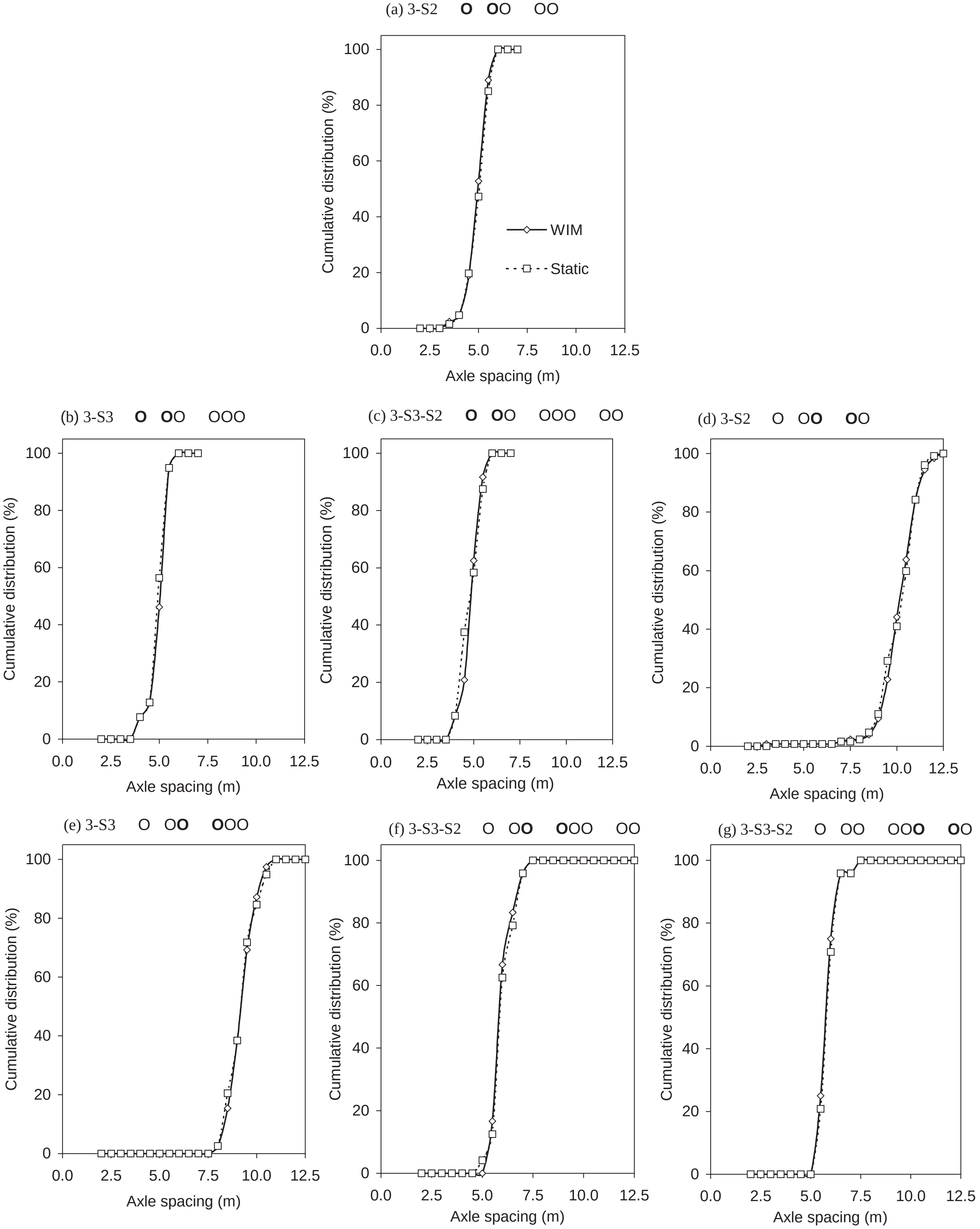
(f) 3-S3-S2 O OO **OO**O OO

(g) 3-S3 O OO O**OO**

(h) 3-S3-S2 O OO O**OO** OO

(i) 3-S3-S2 O OO OOO **OO**

Fig. 3. WIM versus static interaxle spacings. The axle configuration is shown above each graph. The axle spacing distribution is that of the bolded axles.


(a) 3-S2 **O** **O**O OO

(b) 3-S3 **O** **O**O OOO

(c) 3-S3-S2 **O** **O**O OOO OO

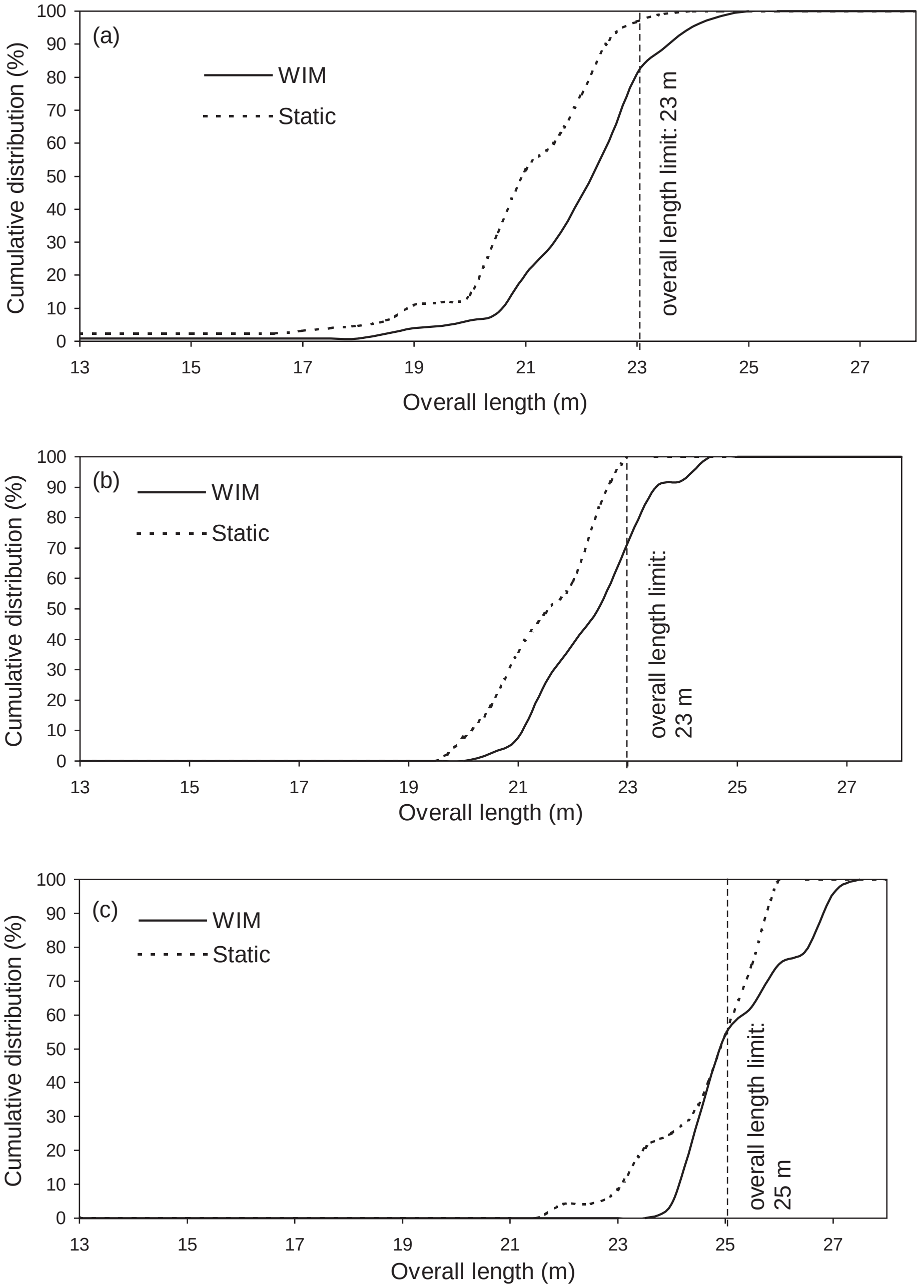
(d) 3-S2 O O**O** **O**O

(e) 3-S3 O O**O** **O**OO

(f) 3-S3-S2 O O**O** **O**OO OO

(g) 3-S3-S2 O OO OO**O** **O**O

Fig. 4. WIM versus static overall length measurements. (*a*) 3-S2, (*b*) 3-S3, (*c*) 3-S3-S2.



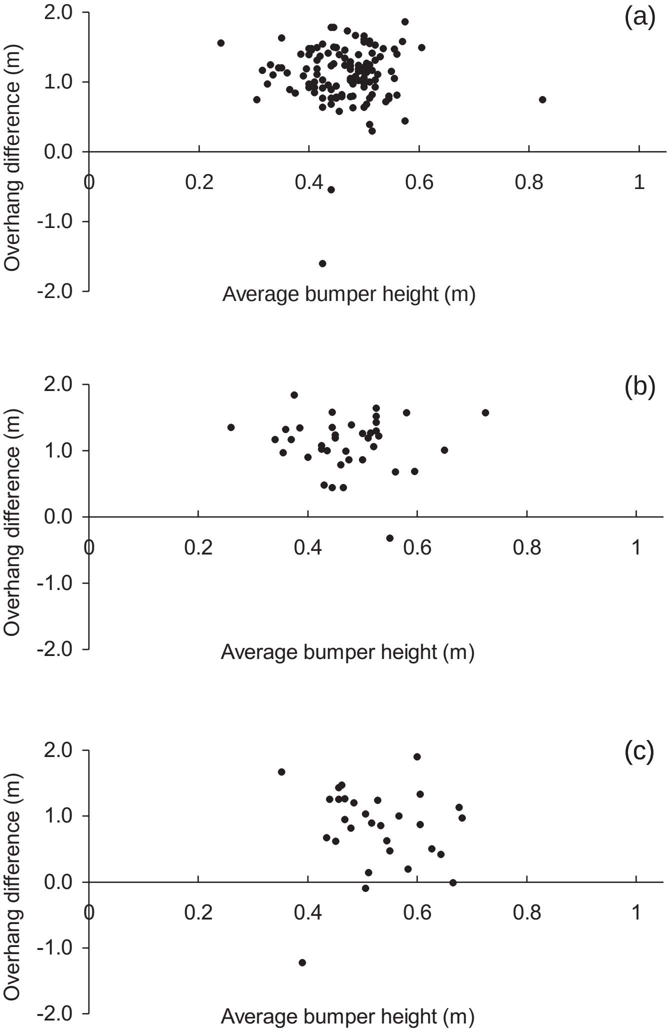
ings are close. This means that the WIM system estimated axle spacings more accurately than overall lengths. Additionally, the overall lengths were overestimated by the system. The length limit for both 3-S2 and 3-S3 trucks is 23 m (Manitoba Highways and Transportation 1995). From WIM measurements, about 20% of 3-S2 and 30% of 3-S3 truck lengths exceeded the length limit, while effectively all of the trucks were within the length limits according to manual measurements. The maximum length of 8-axle double trailer train combination (3-S3-S2) trucks is 25m. According to the manual measurements, more than 50% of 3-S3-S2 truck lengths exceeded the length limit, and the WIM system showed a similar response (Fig. 4). In summary, the errors in overall length as measured by the WIM system are considerably larger than errors in individual axle spacings. This finding is expected, as the overall length measurements are made using the outputs of the inductive loops while axle spacing measurements correspond to the tire contact with the axle sensors (Harvey and Champion 1996).

To study the effect of vehicle bumper heights on overall vehicle lengths, front and rear bumper heights of the trucks passing through the station were measured during the survey. The sample size for this analysis is 127 3-S2s, 39 3-S3s, and 30 3-S3-S2s. As shown in Fig. 5, the analysis indicates that the overall length estimates produced from the WIM system are independent of vehicle bumper heights.

Vehicle classification

The WIM systems used in Manitoba classify vehicles based on FHWA Scheme F (13 vehicle classifications),

Fig. 5. Effect of bumper height on overall length. (*a*) 3-S2, (*b*) 3-S3, (*c*) 3-S3-S2. Note: overall length difference is the difference between WIM and manual overall length measurements; average bumper height is the average of front and rear bumper heights.



Golden River Traffic (1992). This scheme defines vehicle types initially by the number of axles and then by axle spacing. During the survey, vehicles passing through the Brokenhead WIM site were manually classified. When the WIM and manual vehicle classifications are compared, larger differences are observed for Class 5 (single unit 2-axle trucks) and Class 8 vehicles (Table 4). As indicated by Fekpe (1993), WIM systems that classify vehicles based only on their axle configuration may misclassify vehicles into one of two classes. For example, a Class 5 vehicle is a 2-axle single unit truck and a Class 8 vehicle is a 2-axle tractor with 1 or 2-axle semi-trailer. The large differences between WIM and manual vehicle classification for Class 5 and 8 vehicles are caused by misclassifying large passenger cars and heavy pickups as Class 5 vehicles and misclassifying pickup trucks and vans pulling trailers or boats as Class 8 vehicles. The misclassifications led to an increase in the estimate of the truck percentage during the survey hours from 8% to 10%.

Table 4. AASHTO vehicle classifications.

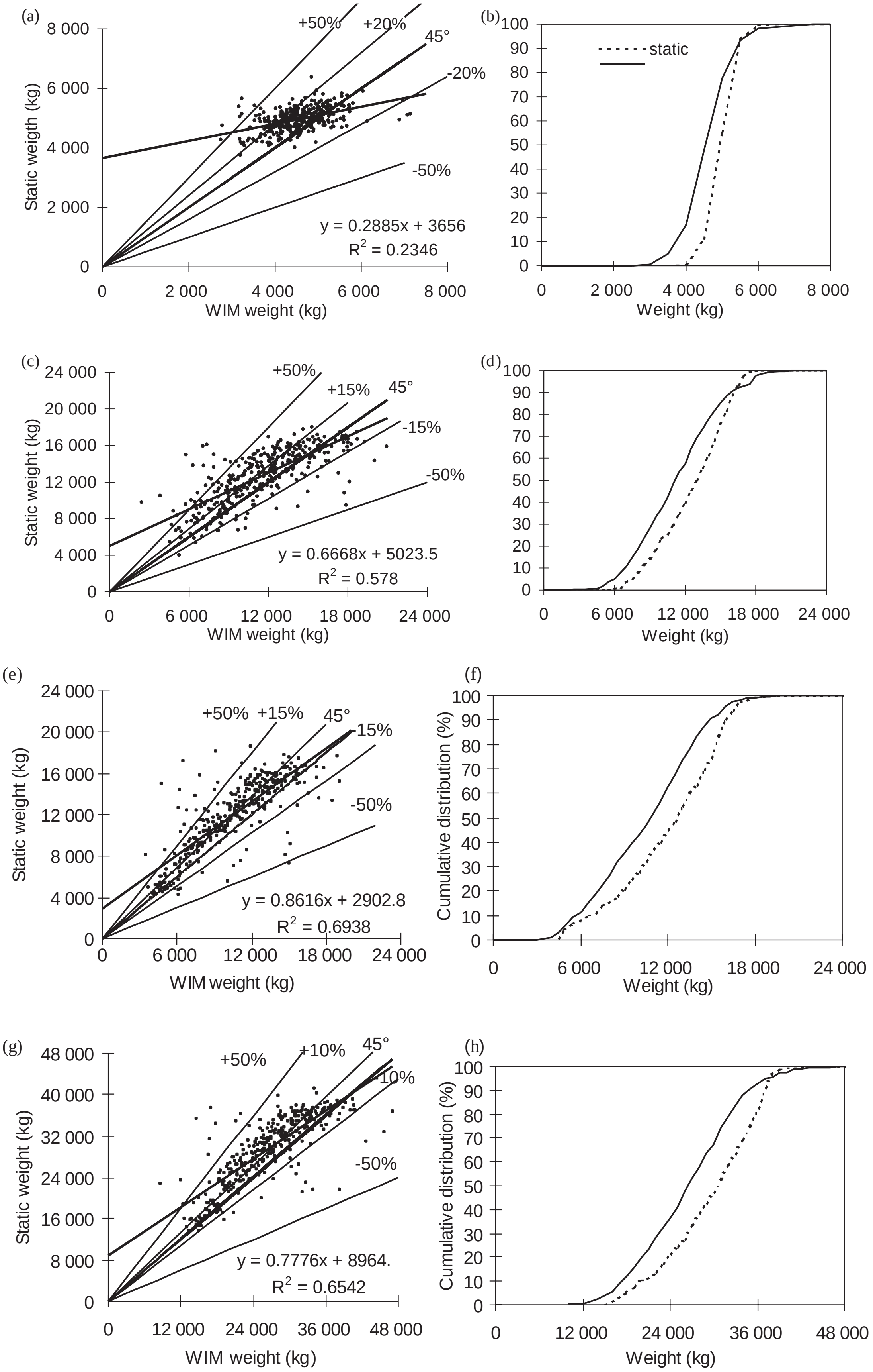
	Number of vehicles	
Vehicle class	Manual classification	WIM classification
2	6022	4027
3	4281	4598
5	68	150
8	19	172
9	519	501
13	173	165
Truck percent	8%	10%

Weight measurements

Weight evaluation is based on 345 pairs of WIM and static 3-S2 truck weights. Figure 6 (*a*, *c*, *e*, and *g*) shows the comparison of the WIM to static weights for each axle type, and Fig. 6 (*b*, *d*, *f*, and *h*) shows the cumulative frequency distributions of axle unit weights. The line of equality, which indicates perfect agreement between WIM and static data, is plotted on the 45° slope. Lines that represent ±20% of the values along the 45° line are shown for steering axle weight Fig. 6*a*. ASTM (1993) specified that for steering axle, the tolerance for 95% probability of conformity is ±20%. This means that 95% of WIM steering axle weights should be within ±20% of the corresponding static axle weights. Similarly, lines that represent ±15% and ±10% of the values along the 45° line are shown in Fig. 6 *c*, *e*, and *g* for drive tandem axle, trailer tandem axle and GVW, respectively. To determine the degree of “under-weighing” or “over-weighing,” ±50% of the values along the 45° line are also shown in Fig. 6. To evaluate the correlation between the WIM and static weights, a straight best-fit line is shown in each figure. The linear equation and the coefficient of determination of the regression are also shown in the figures. The linear regression resulted in relatively large constant terms (3000 to 9000 kg), because WIM systems are calibrated under loaded trucks and the data range does not include samples that are below the self-weight of unloaded axles, approximately 4000 kg. The following discussion relates to individual axle groups:

- Steering axle: About 90% of the steering axle weights were underestimated by the WIM, and the degree of underestimation was below 50%. Approximately 70% of the WIM weights were within the tolerance of ±20%, which is lower than the 95% probability of conformity specified by ASTM. The small coefficient of determination value (23%) indicates the lack of correlation between the WIM and static weights.
- Drive tandem axle: More than 70% of the drive tandem axle weights were underestimated by over 50%. Only 50% of the WIM weights were within the tolerance of ±15%, which is much lower than the ASTM limit of 95%. The correlation between the WIM and static weights is stronger than that of steering axles, which is indicated by the higher value of R^2 (58%).
- Trailer tandem axle: More than 90% of trailer tandem axle weights were by over 50%. The chance of underestimation is greater than steering axles and drive tandem axles. More than half of WIM weights were outside the toler-

Fig. 6. WIM versus static weights of 3-S2. (*a*) steering axle, (*b*) cumulative frequency distribution of steering axle, (*c*) drive tandem axle, (*d*) cumulative frequency distribution of drive tandem axle, (*e*) trailer tandem axle, (*f*) cumulative frequency distribution of trailer tandem axle, (*g*) GVW, (*h*) cumulative frequency distribution of GVW.



ance of ±15%. Compared with the standard specified by ASTM, the percent of conformity is very low. With the highest coefficient of determination value (69%), the correlation between the WIM and static weights is the strongest among the three axle units — steering axle, drive tandem axle, and trailer tandem axle.

- GVW: More than 90% of GVWs were underestimated by over 50%. More than half of WIM weights were outside the tolerance of ±10%. The correlation between the WIM and static GVWs is weaker than that of trailer tandem axles. Based on static measurements, there were no overloaded trucks (the limit for GVW is 39 500 kg), Manitoba Highways and Transportation (1995); however, WIM data showed about 2% overloaded trucks.

It can be concluded from the above discussion that about 90% of GVWs were underestimated by the WIM system during the hours of the survey. The degree of underestimation for steering axles is smaller than for other axle groups (less than 50% versus up to or more than 50%. Under the acceptable tolerance for WIM weights specified by ASTM, the WIM system was not capable of meeting the specified accuracy limits. The correlation between WIM and static weights of axle groups is stronger than that for the steering axles.

To assess the effect of suspension systems on WIM weight measurements, the type of suspension of passing trucks was identified at the Westhawk Permanent Truck Weigh Station during the survey. For 3-S2 trucks, three major types of tandem axle suspension system were observed. They were leaf-spring suspension, air-spring suspension, and air-bag suspension. For the purposes of this research, the difference between static weights and WIM weights is called "error." The errors in the WIM weights are represented in terms of percentage difference (PD), defined as

$$[2] \qquad \text{PD} = [(\text{static weight} - \text{WIM weight}) / \text{static weight}] \times 100$$

The mean "error" in WIM tandem axle weights of 3-S2 is calculated for different suspension system types. Results indicate that the mean error in WIM weights of air-bag suspension axles is about 8%; it is about 11% for air-spring suspension axles, and it is about 13% for leaf-spring suspension axles. Therefore, the WIM system can better estimate the weights of axles equipped with air-bag suspensions, and the "errors" in WIM weights are highest for axles equipped with leaf-spring suspensions.

It must be reiterated that this survey was conducted at a specific site, Brokenhead WIM Site, and the time of the survey was 9 months after system calibration. Major factors affecting the performance of a WIM system are the type of WIM sensor used and system maintenance, such as the calibration method and frequency. The WIM sensors installed at the Brokenhead WIM site are capacitive strip sensors. The weight-estimate accuracy of this sensor is typically lower than bending plate and single load cell sensors (Zhi 1998). On the other hand, different calibration techniques result in different levels of precision (Sharma et al. 1990). The Brokenhead WIM system performance presented in this paper represents one example among hundreds of WIM sites around the world.

Concluding remarks

Utilizing the WIM data of Manitoba for current and future SHRP and C-SHRP research on pavement performance will require a careful assessment of the reasonability of the data, and a corrective procedure to account for lack of calibration and for various site features including roughness and lane changes. WIM data are collected with the primary objective of associating pavement performance to traffic loading and environmental conditions. Given that the LTPP sites have been collecting data for over 8 years in Manitoba, it seems appropriate to develop a corrective measure that will extract useful information from WIM data to benefit pavement performance research and other studies.

An extensive survey of WIM and static weights, at Brokenhead and Westhawk respectively, showed that axle-spacing records were outside the 95% conformity range, with a mean difference of 0.6% for interaxle-spacing and 4.7% for axle unit spacing. On tridem axles the mean difference in axle spread (distance between outer axles) was higher than 4% because of error accumulation from two spacings. The WIM system classified over 95% of the vehicles accurately. However, significant errors were found in classes 5 and 8. The errors led to an overestimation of truck percentages by 25% (truck ratio of 8% from manual count and 10% from WIM). WIM weights were outside the 95% conformity range for the different axle groups.

Future research needs in this area include establishing a standardized calibration technique, determining the relationship between the monitoring period and the precision of WIM results, considering axle unit weight as a classification quality control measure, and building the related rule in the WIM software.

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