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Truck Fleet Evaluation for Mechanistic - Empirical Pavement Design Method

Rosnawati Buhari[1*], Siti Khatijah Abu Bakar[2]

[1]Smart Driving Research Centre,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA

[2]Faculty of Civil and Environmental Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA

*Corresponding Author

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Abstract: The Mechanistic-Empirical (M-E) pavement design and maintenance method requires a prediction of actual distribution of dynamic load caused by the fleet of trucks that travels on particular section of the road. In this study, the importance of the dynamic nature of the load on the evolution of the real vertical profile was evaluated by performing both static and dynamic calculation using vehicle-truck dynamic-interaction approach. Several truck parameters were considered include type of axle, loading condition, axle configuration, vehicle speed etc. The results indicate that dynamic wheel loads generated by 1/3 loading trucks are the most variable or non-uniformed than others due to uncertainties in body bounce generated by the truck which are strongly influence by surface irregularities. Although the importance of developing truck fleet evaluation approach for (M-E) pavement design are not on the road irregularities individually, besides vehicle speed, loading condition and suspension types should be considered thoroughly.

Keywords: truck fleet, axle load, spatial repeatability, dynamic load, quarter truck model

1. Introduction

The prediction of dynamic loads for mechanistic empirical method of flexible pavement design needs a large number of numerical truck model runs. In theory, there are two components of the vehicle forces; (a) static load produce by a gross weight, geometry and the mass distribution of the vehicle while the static load shares the characteristics of the suspension system and (b) dynamic loads caused by vehicle bounce and pitch on the combined stiffness of the tyres and suspensions [1]. There are many tests carried out under real road conditions that are performed in order to identify and optimize the suspension parameters and to minimize tire wear. Although, yet it is no reliable method of predicting the mean pattern for typical traffic condition. Besides, the effect of a rough road surface on vehicle vibrations, and in particular, on the driver and passengers is still a subject of research among automotive manufacturers and research groups [2].

Therefore, the aim of this study is to reproduce the variance of dynamic loading of the truck fleet at a given real site consequence by several parameter of truck fleet includes truck axle, axle configuration, loading condition, truck speed and also level of road profile. Simple linear quarter car model was reproduced the variance of dynamic loading of the truck fleet at a given real site used with spatial repeatability method. The concept is demonstrated by using early determination of truck fleet to calculate a pattern of statistical spatial repeatability applicable for mechanistic-empirical method of pavement design and maintenance.

Corresponding author: rosna@uthm.edu.my

1.1 Spatial Repeatability of The Dynamic Tyre Forces

Spatial repeatability can be defined as the tendency for a set of vehicles to impose the same load patterns during different passes on a road surface with a given profile. This phenomenon was proven by a given testing speed and the wheel load time histories generated by a particular heavy vehicle [1], [3], [4]. The dynamic loads are concentrated at or near particular points on the road surface. If spatial repeatability is significant, then the response of the pavement to that concentration of loads will clearly influence the deterioration of the pavement in that area.

Several studies reported that, there were more damaging effects found when loads applied to the road surface by a heavy vehicle fleet were spatially repeatable [5]. A single and wide-based single tyres can result in damage factoring 1.5 to 10 times more to roads than the damage imparted from dual tyres. Viscous damping, soft spring and tyre stiffness are desirable for minimizing dynamic loads, dry (coulomb) friction, on the other hand, is undesirable. Also reported, the contribution of spatially repeated loading damage at some points along the pavement caused by dynamic loads was up to 14 times worse than the damage caused by static load when using the worst suspension type. Peak damage due to dynamic loads could fall between 1.5 and 12 times the level of damage caused by a static load [6]. If the damage is spread out evenly along the road, however, dynamic load will cause only 1.2 to 1.5 times the static damage level. The conclusion drawn was that road failure will be governed by localised peaks in the damage distribution rather than by the mean damage level.

Other than that, the rate of the degradation of road surfaces was claimed strongly sensitive to the levels of spatial repeatability of the applied dynamic loads particularly for thin asphalt pavements that are prone to fatigue failure. Assuming spatial repeatability, dynamic loads increased theoretical pavement damage by up to 25%. Nevertheless, current design guides assume that each point is subjected to a force that is statistically similar to all other points and the probability of deterioration is uniformly distributed along the pavement [6]. As a result, the damage prediction could error by 20 -150%. Having said that, spatial repeatability might be expected to vary around the world depending on road surface, the local size, weight regulation, homogeneity of the vehicle fleet and the standard of road roughness.

The statistical spatial repeatability algorithm for multiple sensor weight in motion was studied by O'Brien et al., [1]. A new algorithm was proposed for processing the outputs from such arrays and finding an improved estimate of the static axle weights. The basis of this new algorithm is to remove the bias and average the corrected force measurement. The statistical spatial repeatability (SSR) as an extension of the well-known concept of spatial repeatability study. They presented a method for predicting patterns of SSR, through the use of a truck fleet model inferred from measurement of dynamic tyre forces. The Bayesian statistical inference algorithm was used to determine the distribution of multiple parameters of a fleet of quarter car heavy vehicle ride models based on a prior assumed distribution and the set of observed dynamic tyre force from a true fleet of 100 simulated models. They found that the fitted model provides excellent agreement in the mean pattern of dynamic force with the originally generated truck fleet.

2. Methodology

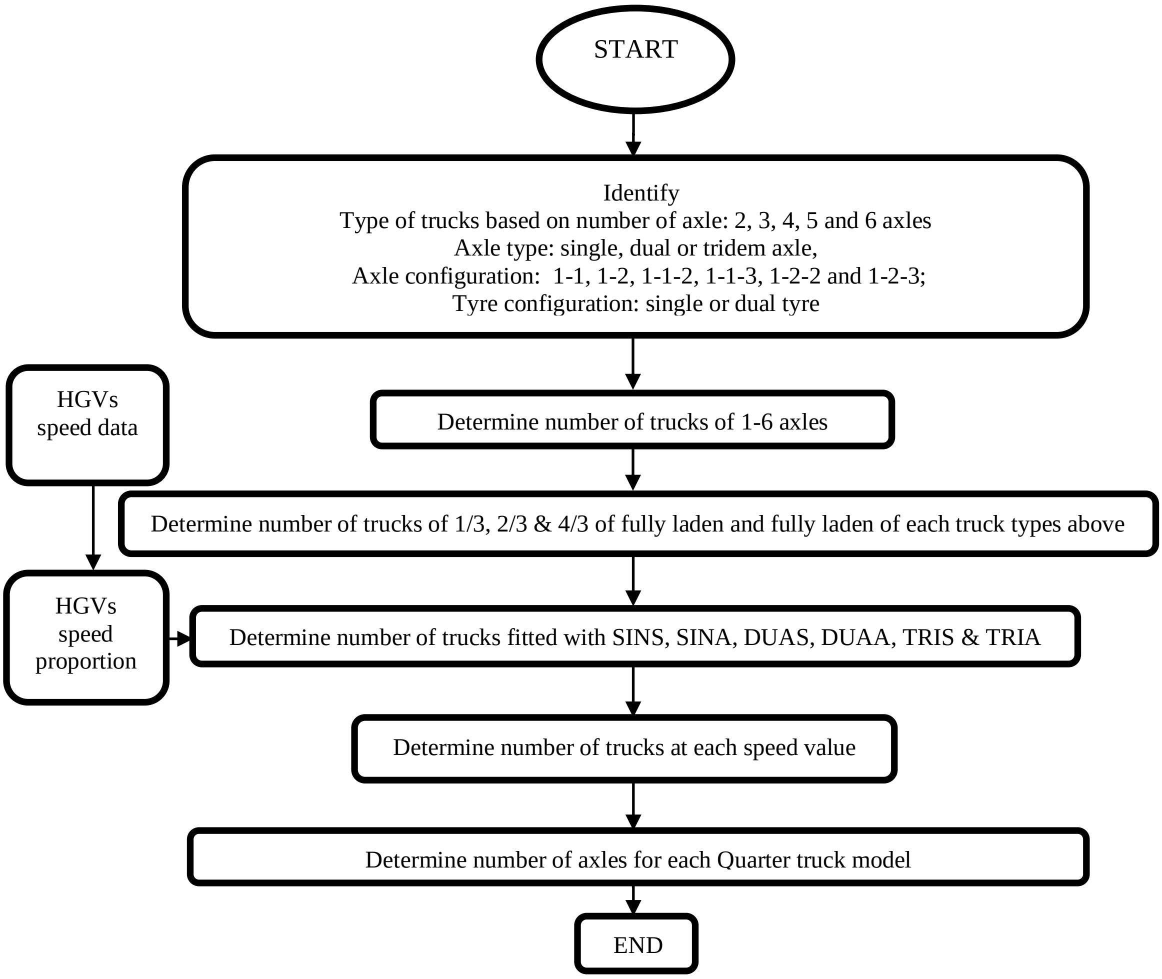
2.1 Development of Truck Model

Fig.1 shows a detail procedure to develop the truck fleet model. The vehicles speed data for 6 different locations along the North–South Highway in Malaysia was obtained from the Road Traffic Volume Malaysia 2006 Report, Highway Planning Unit, Ministry of Works Malaysia [7]. Within that, there were 1200 speed variations from 1200 different Heavy Good Vehicles (HGVs). The HGVs in this task are defined as vehicles with an allowable total weight of 3 tonnes or more. To develop the truck fleet model, the information on the total allowable weight of the vehicles follows the weight limits in Malaysia. Detailed information of the truck types according to their numbers of axles and their proportion, axle load distribution includes fully laden and 1/3, 2/3 and 4/3 of fully laden, for single, tandem and tri-axle are based on data published by the Highway Planning Unit, Ministry of Works Malaysia [8], [9]. The repeatability of tyre forces from the trucks was then investigated to include the spatial repeatability effects on pavement performance.

2.2 Quarter Truck Model

The vehicle was simplified into a quarter-truck model that is adopted by many previous researchers [10-13]. Excluding the detailed suspension non-linearity and complexities of body mass motions that are typical for heavy vehicles, the frequency content of the dynamic loads is sufficiently realistic for the purpose of the study to uncover pavement response. This point of view was verified in the work of Hardy and Cebon who examined the importance of structural dynamics in the primary response of a flexible pavement to fluctuating, moving wheel loads by means of a quarter-vehicle model [14].

There are six parameters of the vehicle components needed for calculating the vehicle acceleration. The vehicle body that is supported by the suspension system is designated as the sprung mass and considered rigid with mass properties concentrated at its center of gravity and a moment of inertia about the center of gravity in a pitch plane. The additional mass significant to dynamic wheel load performance proportionate to that of the suspension linkage is denoted as unsprung mass. The unsprung mass should include an appropriate contribution from all the links, the moving part of the damper, spring, etc. and be dominated by the wheel units. Sprung masses and unsprung masses are both constrained to move vertically. A tyre spring and damper is the result of the rubber around the wheel. The model has two degrees of freedom, the vertical displacements. The pavement surface profiles were generated by applying a set of random phase angles, uniformly distributed between 0 and 2π to a series of coefficients derived from the desired direct spectral density.



SINA	Single axle with steel suspension	DUAS	Tandem axle with steel suspension
SINA	Single axle with air suspension	TRIA	Triaxle with air suspension
DUAA	Tandem axle with air suspension	TRIS	Triaxle with steel suspension

Fig. 1 - Procedure of truck fleet models development.

The vehicle parameters for quarter truck models from a previous study are given in Table 1 and steel suspension elements are based on validated models. The parameters used in the models are based on the results from validated articulated vehicle simulations developed by Cole & Cebon [6]. It can be seen that, for a drive axle suspension, the suspension stiffness is lower for the air suspension, the air suspension has a higher level of hydraulic suspension damping and there is no friction. The steer axle suspension has lower suspension stiffness and a higher level of hydraulic suspension damping. The forces from a quarter-truck model for tandem and tri-axle are computed for single tyres and their effects on pavements are computed by multiplying the damage with the number of tyre in-lines, i.e. in the case of a tandem axle, forces from a single tyre (using parameter values for a tandem axle) doubled whereas for a tri-axle, forces from a single tyre (using parameters value for a tri-axle) trebled. Implementing the quarter truck model for tandem and tri-axle, forces from these axle types are computed for single tyres and their effects on the pavement are computed by multiplying damage with the number of tyres in-line, i.e. for tandem axle, forces from a single tyre (using parameter values for tandem axles) were multiplied by 2 as for tri-axle, forces from a single tyre (using parameter values for tri-axle) were multiplied by 3.

2.3 Axle Group Model

Types of trucks were determined from a typical commercial vehicle fleet in Malaysia. It includes legal trucks with 2, 3, 4, 5 and 6 axles. In accordance, the number of trucks with 2, 3, 4, 5, and 6 are 462, 73, 132, 303 and 230, respectively. For a 4-axle group model, from 132 vehicles, 82 of them are rigid. That is, approximately 62% while others are articulated. For a 5-axle group model approximately 78% from 303 vehicles are rigid, others articulated.

Table 1 - Parameter of Quarter Truck Model [5].

Quarter truck model		MODEL1	MODEL 2	MODEL 3	MODEL 4	MODEL 5	MODEL 6	MODEL 7
Parameter	**Symbol /Units**	**Steer Axle**	**Single Axle-Steel suspension (SINS)**	**Single Axle-Air suspension (SINA)**	**Tandem Axle-Steel suspension (DUAS)**	**Tandem Axle-Air suspension (DUAA)**	**Tridem Axle – Steel suspension (TRIS)**	**Tridem Axle-Air suspension (TRIA)**
Sprung mass	**ms/(kg)**	**ms***	**ms***	**ms***	**ms***	**ms***	**ms***	**ms***
1)Unsprung	mu/(kg)	0.4	0.6	0.6	0.5	0.5	0.4	0.4
2)Suspension stiffness	k1/(MN/m)	0.23	0.86	0.5	0.9	0.2	0.9	0.2
3)Suspension damper	c1/kNs/m)	1.5	6.5	13.0	1.0	8.0	1.0	8.0
4)Tyre spring	k2/(MN/m)	1.0	2.0	2.0	2.0	2.0	1.3	1.3
5)Tyre damping	c2/(kNs/m)	1.0	2.0	2.0	2.0	2.0	1.3	1.3

*ms value based on the maximum axle load [7]

2.4 Axle Load Proportion

As the problem of overloading is of serious concern, the proportion of trucks with overloading is essential to be taken into account. Formerly, it has been estimated that in some countries, up to 45% of HGVs are overloaded. It has been noted that semi-trailers present the highest percentage of overloading especially at a level of more than 10 percent above the legal limit. In this study, the proportion of overloading trucks is determined. The proportion of trucks axles groups as given in Table 2. The proportion of each loading condition is based on the axle load distribution for a typical highway and is estimates 0.52, 0.37 and 0.11 for trucks that are 1/3, 2/3 and fully laden, respectively [9]. The proportion of 1/3 fully laden trucks was then reduced from 52% to 49% to provide 3% of trucks being overloaded. As a result of this, 36 trucks from the total 1200 trucks are overloaded, 588 are 1/3 fully laden, 444 are loaded to 2/3 of their full load and the remainder are fully laden.

Table 2 - Proportional of trucks axle group [9].

Axle group	Rigid/Articulate	Proportion of vehicles
2 axles	Rigid (a)	38.52
3 axles	Rigid (b)	6.05
4 axles	Rigid (c)	6.82
	Articulate (d)	4.18
5 axles	Articulate (e)	19.7
	Articulate (f)	5.56
6 axles	Articulate (g)	19.17

2.5 Axle Type Distribution

When using a quarter-truck model, unsprung and sprung mass are calculated for a single wheel. The maximum axle weights of each axle type single axle, tandem axle and tri-axle for each truck follow the Guideline for Vehicle Axle Load and Weight Restriction [Federal Road] Amendment Orders 2003 for Malaysia [7]. The procedure to determine the number of each truck model is simplified in Fig. 2. The number of single, tandem and tri-axle was determined according to the axle group model. ‘Single axle’ refers to a single axle with more than 1.8m spacing from other axles, ‘tandem axle’ refers to a configuration of two axles with less than 1.8 spacing between the axles and ‘tri-axle’ refers to a configuration of three axles with relatively short longitudinal distance between the axles. Single axle group models were used to represent a tractor steer axle with steel suspension (STERS) and a tractor drive axle with steel or air suspension (SINS, SINA). For all the axle group suspensions (except the steer axle) the first three letters denote the number of axles: SIN for single axle, DUA for tandem axles and TRI for tri-axle. The last letter indicates whether the suspension is steel sprung (S) or air sprung (A).

The ratio of the number of steel to air suspensions was taken from Collop study [9], that is, 62 percent steel to 38 percent air suspension. This proportion was determined from a conjunction of the same WIM measurement data with the results published by previous research [14]. The ratios of the steel and air suspension for tandem and tridem axles are given in Table 3. For vehicles with axle configurations of 1-1, 1-2 and 1-2-2, vehicle distribution was determined by multiplying the number of vehicles in each group (differentiated by load) by the steel and air ratio, i.e. for 2-axle trucks with 1/3 loading and configuration axle 1-1, the first-1 is the STERS and the second-1 is the second axle either SINS or SINA. The number of vehicles fitted with SINS and SINA is derived from multiplying 226 by the ratio of 0.62 for SINS and 0.38 for SINA, giving 140 and 86, respectively. However, to ensure that all trucks will have the same types of axle (either steel or air suspension) for the second and third axles and, at the same time, comply with the distribution rates as set out in Table 3, for vehicles with more than two configurations, including 1-1-2, 1-1-3 and 1-2-3, the distribution must consider all vehicles within the configuration.

Table 3 - Proportions of trucks axle group suspension types [9].

Axle group model	Suspension type	Proportion by each axle group
Steer axle	Steel	1
Single axle	Steel	0.62
	Air	0.38

It has been stated that each configuration has four groups categorized by their axle weight. For each group of vehicles in one configuration, the number of vehicles to have either steel or air suspension depends on the ratio of second and third axles. For example, vehicles with 1-2-3 configuration have four vehicle groups that are vehicles 1/3 loaded, 2/3 loaded, fully loaded and 1/3 overloaded. The number of vehicles in each group that have their tandem axle fitted with either steel or air suspension is based on the specified ratio for tri-axle steel or air suspension. It can be determined by trying all possible combinations (in groups) to confirm that the ratio between DUAS and DUAA, TRIS and TRIA approach a prescribed percentage. The result in term of the number of trucks fitted with steel and air suspensions is listed in Table 4.

Table 4 - Number of trucks according to the suspension type.

Vehicle type	Loads proportions	Number of trucks		Vehicle type	Loads proportions	Number of trucks	
		Steel suspension	Air suspension			Steel suspension	Air suspension
2 AXLE (1+1) - Rigid	1/3	140	86	5 AXLE (1+2+2) Articulate	1/3	87	29
	2/3	106	65		2/3	65	22
	1	32	19		1	20	6
	1 1/3	9	5		1 1/3	5	2
3 AXLE (1+2)-Rigid	1/3	26	10	5 AXLE (1+1+3) Articulate	1/3	17	16
	2/3	20	7		2/3	16	10
	1	6	2		1	4	2
	1 1/3	1	1		1 1/3	1	1
4 AXLE (1+1+2)-Rigid	1/3	25	16	6 AXLE (1+2+3) Articulate	1/3	86	28
	2/3	23	8		2/3	42	42
	1	5	3		1	13	13
	1 1/3	2	0		1 1/3	5	1
4 AXLE (1+1+2) Articulate	1/3	15	9				
	2/3	11	7				
	1	5	1				
	1 1/3	2	0				

2.6 Vehicle speed

The vehicle speed distribution for 1200 HGVs is presented in Fig. 3. It is taken from the 24-hour HGV speed data measured on the Seremban (R&R) (Southbound), North-South PLUS highway, Malaysia [8]. The method of observation utilized a video recorder. As shown in the Figure, the vehicle speeds range between 47.5 km/h to 106 km/h with a mean speed 78.8 km/h. The speed standard deviation is 11.2 km/h; however, the number of HGVs within the speeds of 77.8 km/h to 90km/h is 410 vehicles or 34.2% of the total HGVs, less than 77.8 km/h is 57.8% and above 90 km/h, i.e. above the HGVs speed limit set by the government, is 8%.

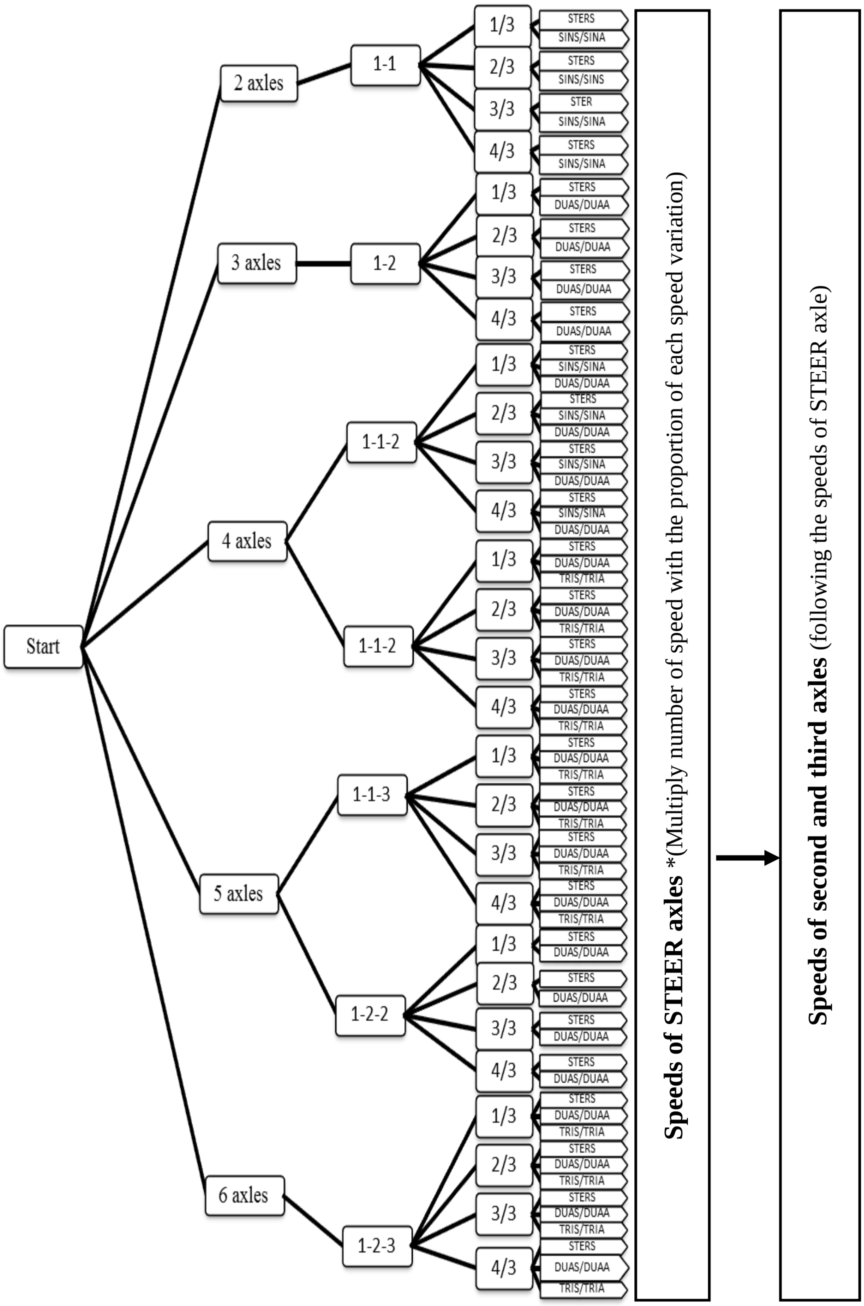


Fig. 2 - Work breakdown for determining number and speed of vehicles for each truck model.

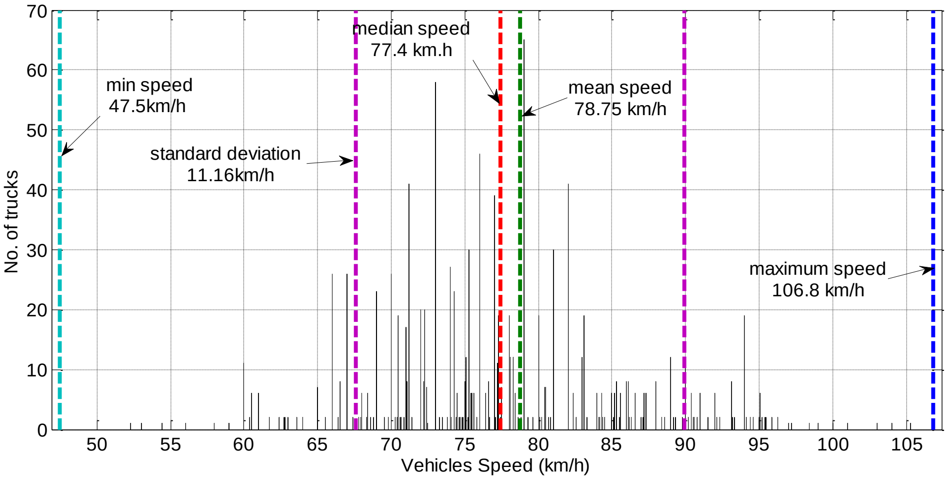


Fig. 3 - Number of vehicles for each speed variations.

2.7 Quarter Truck Sprung Masses

When using a quarter-truck model, unsprung and sprung mass are calculated for a single wheel. The maximum axle weights of each axle type single axle, tandem axle and tri-axle for each truck follow the Guideline for Vehicle Axle Load and Weight Restriction [Federal Road] Amendment Orders 2003 for Malaysia [7]. Maximum sprung mass was calculated by dividing the maximum load for each axle by the total number of tyres. For example, if the type of axle is tandem, then the number of wheels per axle is 2 and the maximum axle load is 9.6kg, the weight for each tyre calculated by dividing 9.6 kg by 4, makes it equal to 2.4 kg. The maximum sprung masses are chosen, as 3.0 kg, 2.4 kg and 2.13 kg for single, tandem and tri-axle, respectively. In order to determine the total loading of sprung and unsprung masses for quarter-truck models, for trucks with 1/3 and 2/3 loads and 1/3 overload, the proportion was multiplied by the maximum load of a single tyre. The sprung mass was then calculated by substituting the total loads with the unsprung mass. The unsprung mass is constant for a given loading condition (but varies according to single, tandem or tri-axle). In the end, the number of axles for each quarter-truck model is supplied in Table 5.

Table 5 - Total sprung and unsprung mass for difference loading proportions.

Loading proportion from fully laden	Single Axle (kg)	Tandem Axle, (kg)	Triaxle, (kg)
1/3	1.0	0.8	0.71
2/3	2.0	1.6	1.42
1	3.0	2.4	2.13
4/3	4.0	3.2	2.84

2.8 Spatial Repeatability

The aim of this section is to examine the spatial repeatability of dynamic tyre forces generated by the fleet of heavy commercial vehicles developed in foregoing sections. The Spatial Repeatability study is done for vehicles travelling on the road with International Roughness Index (IRI=2) that is, the supposed value for new pavements. The reference vehicle was determined using the method proposed by Collop [4]. Approximately 1200 trucks were included in the analysis. The SRIs were analysed in accordance to their loading condition (fully laden, 1/3 and 2/3 loaded and 1/3 overloaded), suspension type (air and steel) and axle type (single, tandem and tri-axle).In a beginning a symmetrical matrix of SRIs was developed with the SRIs for each vehicle in turn as reference. Therefore, there are 1200 columns and rows in the matrix with all the SRIs on the leading diagonal being 1. The number of vehicles in each row or column with *SRIs* greater than the threshold repeatability level of 0.7 was then computed. The reference vehicle was then chosen from the vehicle that is seen to correspond to the row or column bearing the greatest number of repeatable vehicles. Consequently, it was found that the reference vehicle is an articulated truck with 3 axles (1-2-2) with steel suspensions travelling at 77 km/h.

3. Results

3.1 Dynamic Load Coefficient (DLC)

To ensure the dynamic force level generated by the axle load group models are realistic, a level of dynamic variation of tyre force history plus dynamic load coefficient was computed as determined in the literature [14]. As a result, DLCs are sensitive to loading conditions. Loading DUAS with 1/3 load will always generate a force that has a DLC value significantly higher than that of the forces from a DUAS loading with other loading conditions with value 0.743. For the same loading condition, the DLC values for DUAA, TRIS, TRIA, STEER, SINS and SINA are 0.591, 0.717, 0.441, 0.169, 0.494, and 0.348 respectively. This phenomenon is a consequence of the bounce mode through immediate up/down levels of road surface. This has greater influence when the vehicle speed is higher. It is evidenced by the highest DLC for forces generated from a DUAS loading with 1/3 load travelling at a higher speed that is higher than 0.3 reported by previous studies [12-14]. As expected, the highest DLC comes from a vehicle speed of 30m/s speed and is, greater than 0.7. The higher DLC value are found for forces generated from vehicles fitted with steel suspension compared to vehicles fitted with air suspension. Extend the evaluation for several lengths of road profiles and vehicles speed, the higher the road length and vehicle speed were increasing the DLC value.

3.2 Spatial Repeatability Index (SRI)

Fig. 4 shows the spatial repeatability index of forces of all vehicles travelling on the road with IRI equal to 2 that is, the nominal IRI targeted for a new pavement. It includes the reference vehicle that discussed in the previous section. The 1200 trucks were travelled with 173 difference speeds in total. Details of the speed determinations are discussed in the previous section. As shown in the figure, the vehicles that give the highest corrected SRIs when correlated with the reference vehicle are similar vehicles with steel sprung trailer suspension. Conversely, the vehicles that give the lowest SRIs when correlated with the reference vehicle have a suspension less similar to that of the reference vehicle. Approximately 36.2% of the vehicles have SRIs above the threshold repeatability level. This percentage is lower than the desired percentage of about 40% to half of the heavy vehicles that contributed to a repeated pattern of road loading [9], [14] due to differences loading condition were taking into consideration whereas previous studies were merely analyzed using standard axle loading condition.

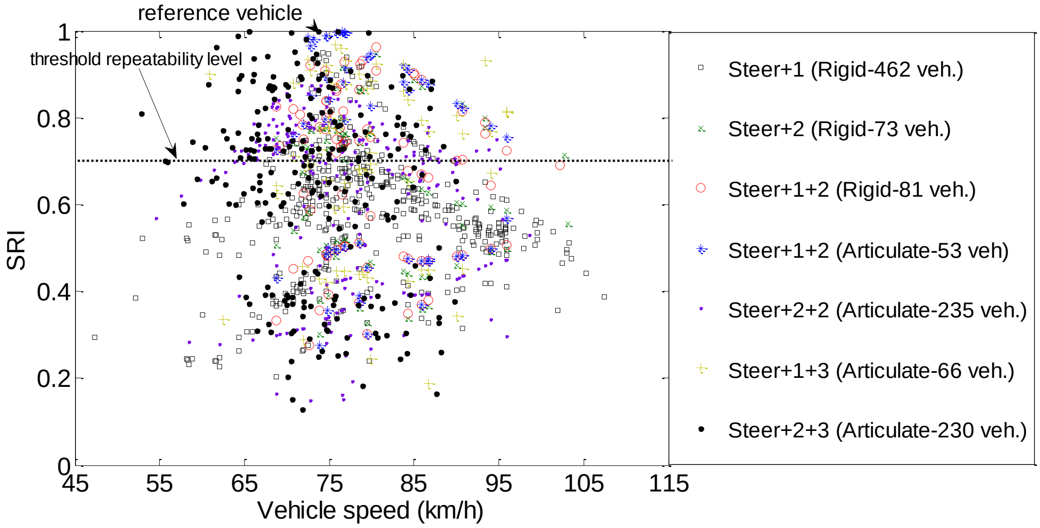


Fig. 4 - Spatial repeatability plotted against speeds for all trucks.

4. Conclusions

Through the empirical pavement design method, the following conclusions can be drawn about the truck fleet evaluation for mechanistic:

- The dynamic wheel loads generated by 1/3 laden trucks are the most variable or more non-uniformed than the dynamic wheel loads generated by other vehicles. This is due to uncertainties in body bounce generated by the truck which are strongly dependent on surface irregularities. The DLC values increase as the vehicle speeds increase and vice versa.
- DLCs are always smaller with air suspension in comparison to steel suspension for all conditions.
- The vehicles that give the highest corrected SRIs when correlated with the reference vehicle are similar vehicles with steel sprung trailer suspension. Conversely, the vehicles that give the lowest SRIs when correlated with the reference vehicle have suspensions less similar to that of the reference vehicle.
- Using the truck fleet model that has been developed, 36.2% of the vehicles have SRIs above the threshold repeatability level. The percentage is lower than the desired percentage of about 40% to half.

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