AXLE-LOAD ESTIMATION WITHOUT WEIGH-IN-MOTION SURVEY

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ABSTRACT

Modern road pavement design requires the knowledge of axle loads. These are usually obtained by means of Weigh-In-Motion (WIM) measurements. The WIM technology is complicated and measurements are expensive. However, reasonably good estimates of the axle-load distribution can be obtained by a method combining the current knowledge of road and traffic with the WIM information obtained in the past. The method estimates the distribution of axle loads that is likely to occur on a route with a certain type of axle-load distribution, with a certain split of short, medium and long heavy vehicles, and under certain intensity of law enforcement against overloading. The estimation method, called *ALDIS*, was derived from a comparison of WIM records obtained under condition of no law enforcement and strong law enforcement, and from an analysis of good-quality WIM measurements done on 22 permanent sites in 2012. The axle-load distribution produced by the *ALDIS* method can be used in mechanistic pavement design tools such as *cncPAVE*, or *Cyrano*, to arrive at practical and economic pavement configuration.

1 INTRODUCTION

In contrast to the conventional pavement design that is based on the amount of equivalent standard axle loads (*ESAL*, also called *E80*), the modern mechanistic methods use *actual* axle loads to calculate stresses and strains that cause the pavement to fail after a period of time. Information on the magnitude and composition of heavy-vehicle traffic, its growth, and the distribution of axle loads in particular, are therefore crucial input items in these calculations. Information on the distribution of axle loads is usually supplied by means of *frequency histogram*, or *frequency polygon*. An example of a frequency histogram is shown in Figure 1, whereas a frequency polygon was used in Figure 2.

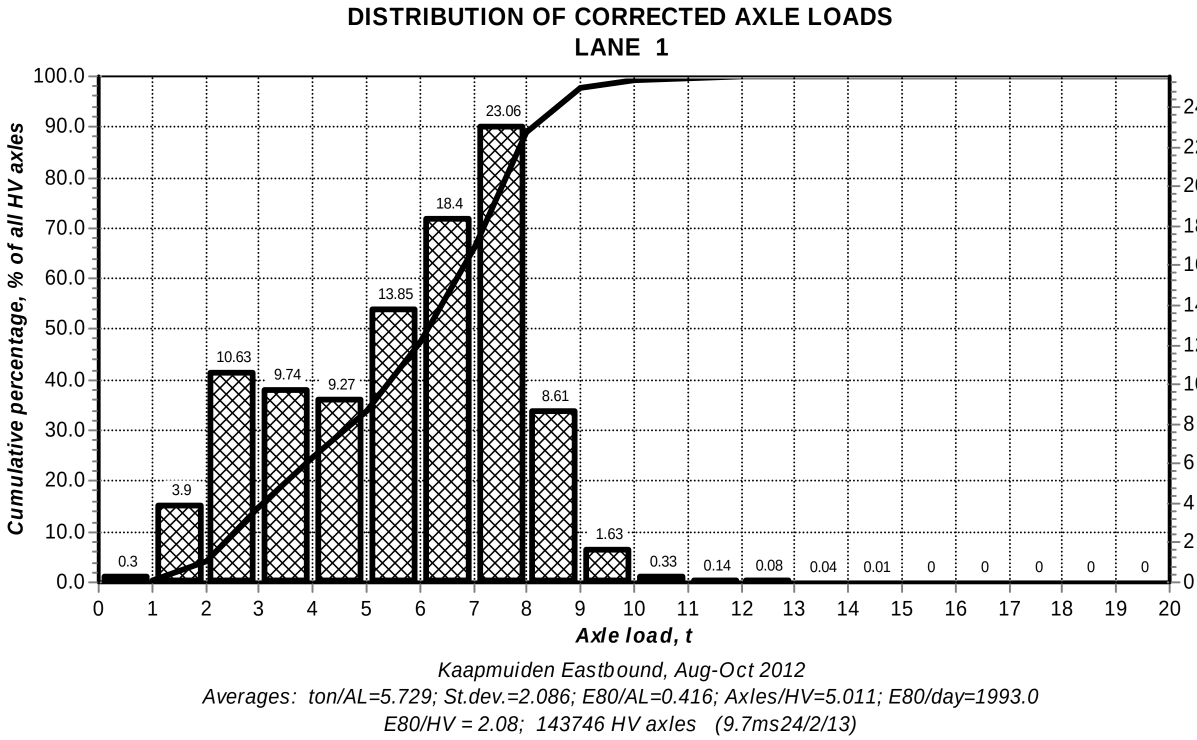


Figure 1. Example of a distribution of heavy-vehicle (*HV*) axle-load masses expressed as a frequency histogram

The main factors influencing the distribution of axle loads are

- intensity of law enforcement against overloading,
- route category by the axle loads, and
- percentage split of heavy vehicles (*HV*) into light, medium and long.

The following paragraphs briefly explain the manner in which the method, called *ALDIS* (suggesting *axle loads* and their *distribution*), takes the above factors into consideration.

2 HISTORY

The idea of combining site-specific input information with the knowledge on axle-load distribution obtained previously was used in this country already in 2006 (Slavik and Bosman, 2006), and was subsequently applied in two mechanistic pavement design computer programs, viz. *cncPAVE* and *Cyrano*. The main input items were the strength of law enforcement and percentage of long heavy vehicles. Based on these, the axle-load distribution observed at a similar WIM station in the past was selected and supplied.

The authors of a recently published paper (Zhao *et al., 2012)* propose a method requiring as input the percentage of overloaded heavy vehicles at a specific site. The logic of this method, however, is problematic: vehicle-weighing equipment has to be installed at the given site to supply the percentage of overloaded HVs. Once such equipment is installed it may just as well supply the needed site-specific axle-load distribution.

In the previous version of the *cncPAVE* software (5.02) the selection of axle-load distribution was based on law enforcement (*strong* or *weak*) and the percentage of *long* HVs (longer than 18 m). The improvements and additions of the 2013 version of *cncPAVE* (v. 5.04) include practical implementation of the *ALDIS* method as described below.

3 INFLUENCE OF THE INTENSITY OF LAW ENFORCEMENT

The law enforcement does not influence the axle-load frequencies in the low region, between 0 t and 5 t, but impacts appreciably on the distribution of axles heavier than 5 t. In case of strong law enforcement against overloading there are relatively few axles heavier than 8 tons and relatively many axles between 5 t to 8 t. When there is no law enforcement the opposite is true – there are relatively many axles above 8 t and relatively few axles between 5 t and 8 t. The presence of law enforcement causes *migration* of axle loads from upper load region to middle region. The magnitude of the axle-load migration became evident from a study of a year-long records obtained by WIM measurements done in 2002 in the vicinity of the Heidelberg Northbound and Southbound weighbridges (before these started influencing the behaviour of truckers), and in 2011 when both weighbridges were operating with full force on a permanent basis. The study (Slavik, 2012) revealed the following facts.

The migration of axle loads is appreciable as is apparent from the two distributions of axle loads shown in Figure 2.

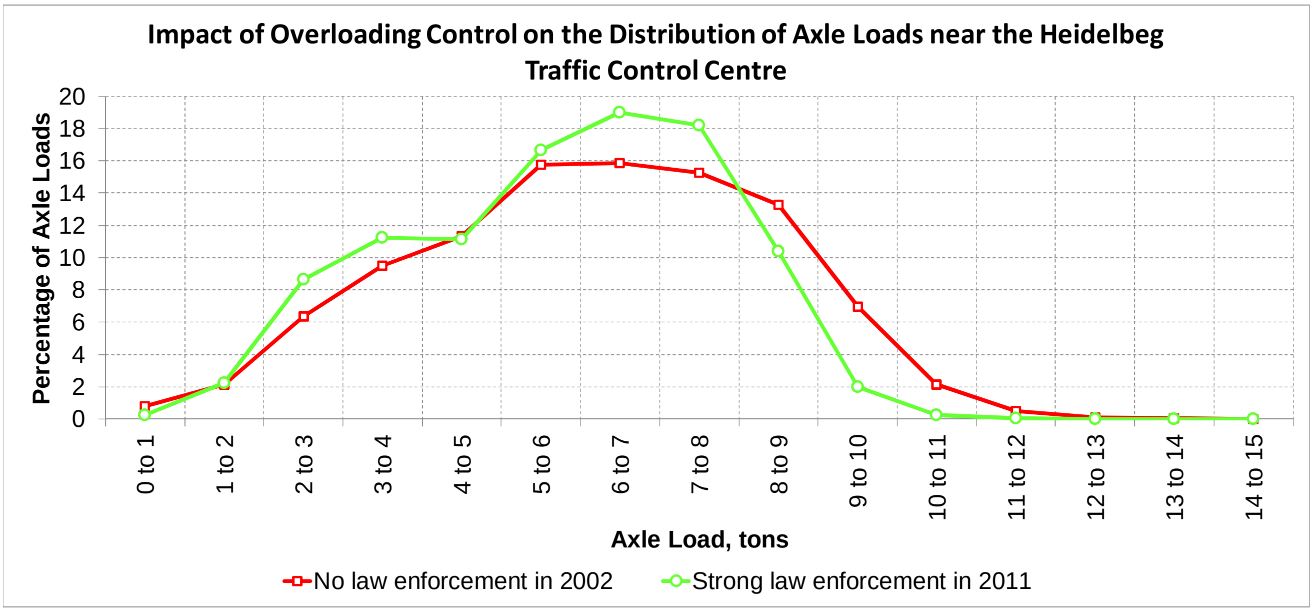


Figure 2. Distribution of axle loads with *no* law enforcement and *strong* law enforcement

Due to strong law enforcement a substantial percentage of axle loads exceeding 8 t – see the area between the red and green curves - moved to the 5 t to 8 t region. The area below the red curve in the 8 t to 16 t region is 23.01 % whereas the corresponding area under the green curve is only 12.62 %. The *above-8t* area under the red curve is 1.823 times greater than the corresponding area below the green curve. With the 23.01 % and 12.62 % tails taken each as 100 %, their spread across the upper region of axle loads is shown in Table 1.

Table 1. Spread of the '*above-8t'* frequencies across the upper region of axle loads

Law enforcement	Axle-load range, t							Sum
	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	
None	57.740%	30.190%	9.278%	2.108%	0.521%	0.130%	0.033%	100%
Strong	82.179%	15.604%	1.861%	0.277%	0.079%	0.000%	0.000%	100%

To cater for cases of *some* law enforcement a spread of frequencies was assumed halfway between *None* and *Strong*, as shown in Table 2.

Table 2. Spread of the '*above-8t'* frequencies across the upper region of axle loads in the case of *Some* law enforcement

Law enforcement	Axle load range, t							Sum
	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	
Some	69.961%	22.897%	5.569%	1.192%	0.300%	0.065%	0.016%	100%

Similarly, in the case of *Some* law enforcement, the area in the upper-region (8 t to 15 t) tail is assumed to be (1.000 + 1.822) / 2 = 1.411 larger than the corresponding area in the case of *Strong* law enforcement.

The magnitude of the tail area for envisaged intensity of law enforcement is derived from the current one by using factors shown in Table 3. The basic figures are 1.8228 for *None*, 1.4114 for *Some,* and 1.0000 for *Strong* law enforcement. The factors for transition from one intensity of law enforcement into another are calculated from fractions, with the figure for the expected future law enforcement intensity in the numerator and the current one in the denominator. The results are shown in Table 3. For example, the factor for the transition from *Some* law enforcement to *Strong* one is 1.0000 / 1.4114 = 0.7085.

Table 3. Factors for transition between various levels of law enforcement.

From \ To	None	Some	Strong
None	1.0000	0.7743	0.5486
Some	1.2915	1.0000	0.7085
Strong	1.8228	1.4114	1.0000

The study of the Heidelberg WIM records also revealed the destination of the migrating axle-load frequencies. The migrating total of axle load frequencies landed in the 5 t to 8 t region, in portions showed in Table 4.

Table 4. Portions of the *total of the migrating axle-load frequencies* landing in the 5 t to 8 t region of axle loads.

Tons	5 to 6	6 to 7	7 to 8	Sum
Portion	13.0%	44.9%	42.1%	100%

The above portions were used in the construction of the axle-load distribution for a given level of expected law enforcement.

4 DEFINITION OF ROUTE CATEGORIES IN TERMS OF AXLE-LOAD DISTRIBUTION

The route categorization is based on the analysis of WIM measurements done at 22 road localities in 2012. All WIM stations used in the analysis were situated on major roads, operated continuously under strict quality control, with calibration checks done on a monthly basis. The WIM sites were in all three law-enforcement scenarios mentioned above – *None*, *Some* and *Strong*, as indicated in Table 5, which also shows other important site characteristics.

Table 5. WIMs analyzed for the categorization of routes

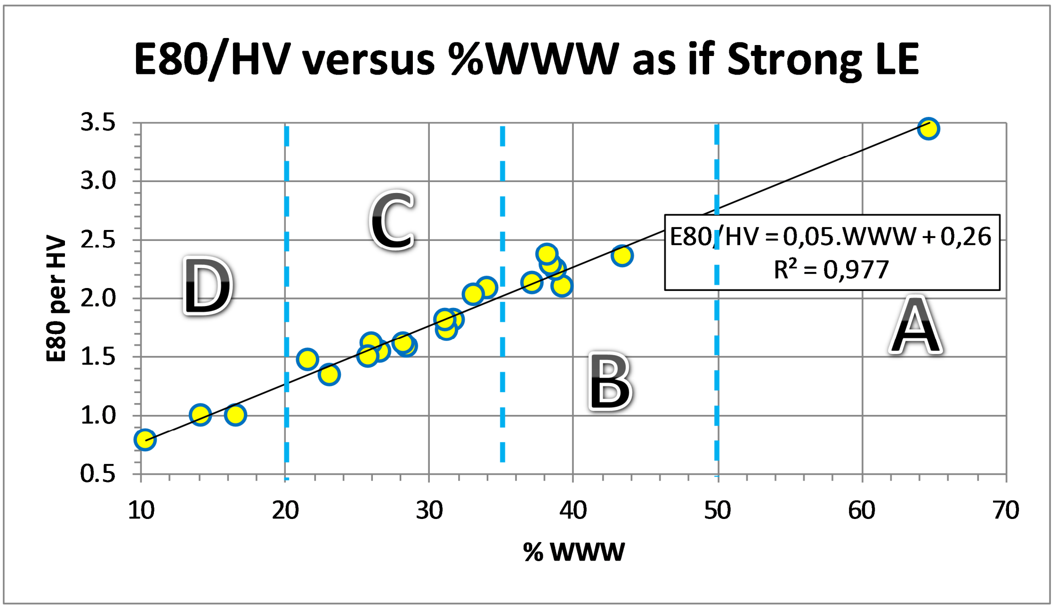
No.	Road and Weigh-In-Motion	Abbrev.	LE	ADTT	% SHV	% MHV	% LHV	AX/SHV	AX/MHV	AX/LHV	E80/HV	%AL>6t	%WWW
1	N4, Komati Eastbound	**KMTeb**	Strong	599	14.6%	8.6%	76.8%	2.22	4.35	6.75	3.432	74.2	64.69
2	N4, Komati Westbound	**KMTwb**	Strong	495	1.2%	8.9%	89.9%	2.33	4.70	6.51	0.789	12.7	10.38
3	N3, Heidelberg Northbound	**HDBnb**	Strong	1697	11.1%	18.6%	70.3%	2.28	5.06	6.35	2.289	52.0	38.38
4	N3 Heidelberg Southbound	**HDBsb**	Strong	1482	16.1%	29.7%	54.2%	2.45	5.43	6.44	1.807	42.5	31.07
5	N4, Farrefontein Eastbound	**FRFeb**	Strong	801	15.6%	13.8%	70.6%	2.22	4.11	6.46	2.355	55.6	43.43
6	N4, Machado Westbound	**MCHwb**	Strong	847	16.3%	15.6%	68.1%	2.15	4.22	6.35	1.609	37.2	26.00
7	N4, Bronkhorstspruit Eastbnd	**BRNeb**	Some	720	21.9%	21.1%	57.0%	2.20	4.24	6.45	1.493	36.5	25.76
8	N4, Bronkhorstspruit Westb.	**BRNwb**	Some	699	23.1%	21.8%	55.1%	2.20	4.38	6.46	1.611	39.8	28.16
9	N3, Cedara Northbound	**CDRnb**	Some	3072	15.0%	14.8%	70.2%	2.28	5.07	6.40	2.076	49.8	34.07
10	N3 Cedara Southbound	**CDRsb**	Some	2955	13.7%	15.8%	70.5%	2.24	5.00	6.34	2.020	45.0	33.13
11	N3, Harrismith Northbound	**HRSnb**	Some	1906	5.7%	26.1%	68.2%	2.26	5.53	6.45	2.362	52.5	38.16
12	N3, Harrismith Southbound	**HRSsb**	Some	1829	8.1%	30.3%	61.6%	2.26	5.53	6.46	2.241	48.0	38.81
13	N1, Kranskop Northbound	**KK nb**	Some	1394	21.2%	20.0%	58.8%	2.23	4.15	6.37	2.103	52.5	39.19
14	N1, Kranskop Southbound	**KK sb**	Some	1381	20.6%	21.2%	58.2%	2.20	4.19	6.33	1.590	40.0	28.49
15	N4, Marikana Eastbound	**MAReb**	Some	616	32.3%	12.1%	55.6%	2.21	4.32	6.59	1.534	36.5	26.57
16	N4, Marikana Westbound	**MARwb**	Some	635	33.9%	11.9%	54.2%	2.17	4.09	6.56	1.337	34.0	23.09
17	N4, Witbank Eastbound	**WTBeb**	None	1429	18.8%	17.1%	64.1%	2.22	4.76	6.58	1.463	32.5	21.54
18	N4, Witbank Westbound	**WTBwb**	None	1410	18.4%	16.1%	65.5%	2.21	4.71	6.60	1.807	44.0	31.75
19	N4, Kaapmuiden Eastbound	**KPMeb**	None	968	18.1%	12.0%	69.9%	2.18	4.41	6.41	2.118	55.0	37.17
20	N4, Kaapmuiden Westbound	**KPMwb**	None	998	20.0%	12.3%	67.7%	2.17	4.00	6.23	1.000	24.0	14.21
21	N4, Zeerust Eastbound	**ZEEeb**	None	473	28.2%	13.6%	58.2%	2.24	4.01	6.39	1.000	24.5	16.63
22	N4, Zeerust Westbound	**ZEEwb**	None	507	29.9%	13.5%	56.6%	2.26	4.04	6.45	1.724	46.0	31.21

The symbols used in Table 5 are as follows:

HV	Heavy Vehicles
ADTT	Average Daily Truck Traffic, HV per day
%SHV	Percentage of short heavy vehicles (< 12 m)
%MHV	Percentage of medium heavy vehicles (12 m to 17 m)
%LHV	Percentage of long heavy vehicles (> 17 m)
AX/SHV	Average number of axles per short heavy vehicle
AX/MHV	Average number of axles per medium heavy vehicle
AX/LHV	Average number of axles per long heavy vehicle
E80/HV	Average E80 (ESAL) per heavy vehicle
%AL>6t	Percentage of axle loads heavier than 6 t
%WWW	Percentage of HVs loaded over 80 % of their legal gross mass limit.

To ensure compatibility of results, the measured axle-load distributions were adjusted to reflect the situation under conditions of *Strong* law enforcement. Tables 1, 2, 3 and 4 were used for this purpose.

The analysis revealed a strong relation between *E80/HV* and *%WWW*, as shown in Figure 3, and similarly a high correlation between *%AL>6*t and *%WWW*.



Note: LE means law enforcement.

Figure 3. Relation between E80/HV and %WWW

Based on Figure 3, four route Categories (Cat.), A, B, C, and D were defined as shown in Table 6.

Table 6. Characteristics of the routes categorized by axle-load distributions

Cat.	%WWW	E80/HV	%AL>6t	*Remark*	Typical
A	> 50	> 3	> 60	*Export routes with a majority of fully loaded HVs*	Komati Eastbound
B	35 - 50	2 - 3	50 - 60	*Routes with predominantly heavily loaded HVs*	Heidelberg Northbound
C	20 - 35	1 - 2	30 - 50	*Routes with a mix of lightly and heavily loaded HVs*	Kranskop Southbound
D	< 20	< 1	< 30	*Routes with predominantly lightly loaded HVs*	Zeerust Eastbound

The membership of the 22 road localities studied in the four route categories is shown in Table 7.

Table 7. Membership of the studied sites in the four route categories

Site	%AL>6t	E80/HV	WWW, %	*Category*	E80/HV
KMTeb	74	3.432	64.69	***A***	**> 3**
FRFeb	56	2.355	43.43	***B***	**2 to 3**
KK nb	53	2.103	39.19		
HRSsb	49	2.241	38.81		
HDBnb	52	2.289	38.38		
HRSnb	53	2.362	38.16		
KPMeb	56	2.118	37.17		
CDRnb	51	2.076	34.07	***C***	**1 to 2**
CDRsb	46	2.020	33.13		
WTBwb	44	1.807	31.75		
ZEEwb	47	1.724	31.21		
HDBsb	42	1.807	31.07		
KK sb	40	1.590	28.49		
BRNwb	41	1.611	28.16		
MAReb	38	1.534	26.57		
MCHwb	37	1.609	26.00		
BRNeb	37	1.493	25.76		
MARwb	34	1.337	23.09		
WTBeb	34	1.463	21.54		
ZEEeb	25	1.000	16.63	***D***	**< 1**
KPMwb	25	1.000	14.21		
KMTwb	13	0.789	10.38		

Note: The figures in the table reflect the Strong law enforcement scenario.

Because of the strong correlation between E80/HV, %AL>6t and WWW, one can determine the route category using any of the three, depending on the available information. Since the *worth-weighing* is synonymous with *heavily loaded*, the estimation based on WWW may be the most practical. Heavily loaded HVs can be identified by watching the truck speed, listening to the engine sound, and judging the tyre contact areas. Particularly helpful would be observations on uphill gradients. The WWW could thus be estimated simply from a manual count of all HVs and those labouring uphill.

5 IMPACT OF THE HEAVY-VEHICLE SPLIT ON THE DISTRIBUTION OF AXLE LOADS

The distribution of axle loads is strongly influenced by the split of heavy vehicles into *short* (shorter than 12 m)*, medium* (12 m to 17 m) and *long* (over 17 m). The construction of the distribution should therefore involve the knowledge of split. To do this, the distributions of axle loads under strong law enforcement at each of the 22 WIM sites were obtained *separately* for short, medium and long heavy vehicles. This exercise resulted in 22 axle-load distributions for short heavy vehicles, 22 axle-load distributions for medium heavy vehicles, and 22 axle-load distributions for long heavy vehicles. A weighted-average distribution of axle loads was then derived, separately, for short, medium and long heavy vehicles, in each of the four route categories defined in Table 6. The numbers of heavy-vehicle axles were used as weights in the calculation of the above-mentioned weighted averages, to reflect the relative value of data from various sites. The distributions thus obtained are shown in Table 8.

Table 8. Distribution of axle loads for short, medium and long heavy vehicles, under Strong law enforcement, in each route category

AL, t	Category A			Category B			Category C			Category D		
	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
0.5	0.242	0.000	0.000	0.541	0.243	0.052	0.295	0.436	0.104	0.870	1.416	0.050
1.5	7.200	4.381	0.379	8.134	1.847	1.120	7.633	4.611	3.198	8.623	7.111	2.846
2.5	26.177	11.778	2.109	17.895	7.131	5.637	25.648	12.452	11.604	33.857	19.418	39.710
3.5	20.385	11.120	5.591	19.714	11.638	8.025	23.084	14.936	12.582	27.551	18.033	26.125
4.5	16.446	14.384	4.441	18.073	15.679	10.048	18.144	14.839	10.180	15.957	17.334	9.055
5.5	9.780	18.592	7.405	13.626	23.360	17.832	10.740	18.800	15.163	7.031	13.862	10.255
6.5	6.729	14.470	23.512	10.026	18.434	21.653	6.867	15.064	17.614	3.153	10.603	4.470
7.5	6.891	12.656	36.186	7.355	15.123	25.379	4.756	12.288	21.081	2.009	8.335	5.258
8.5	5.054	10.370	16.745	3.809	5.379	8.426	2.330	5.403	6.963	0.780	3.195	1.833
9.5	0.960	1.969	3.180	0.723	1.021	1.600	0.442	1.026	1.322	0.148	0.607	0.348
10.5	0.115	0.235	0.379	0.086	0.122	0.191	0.053	0.122	0.158	0.018	0.072	0.042
11.5	0.017	0.035	0.056	0.013	0.018	0.028	0.008	0.018	0.023	0.003	0.011	0.006
12.5	0.005	0.010	0.016	0.004	0.005	0.008	0.002	0.005	0.007	0.001	0.003	0.002
13.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The values shown in Table 8 were used to construct axle-load distributions for site-specific composition of heavy-vehicle traffic. The computerized application of the *ALDIS* method is software called *ALDIS213*. The use of this tool is described in the next section.

6 APPLICATION OF THE *ALDIS* METHOD

The distribution of axle loads that is likely to occur

- under certain law enforcement (*LE*) intensity,
- for a given route category, and
- with a site-specific heavy vehicle split,

can be constructed using the *ALDIS* method either manually, or with the assistance of a spreadsheet, or by using the *ALDIS213* computer software. All three are based on the information contained in the above tables.

De Wet (De Wet, 2013) developed a spreadsheet for checking the correct operation of the *ALDIS213* software. Subsequently he expanded the spreadsheet and included additional functionality, such as interpolation between, and mixing of, several route categories.

The use of the computer tool (available from the author, gratis, on the evaluation basis) is perhaps the simplest and fastest. The input requirement and the output axle distribution are apparent from the screenshot in Figure 4.

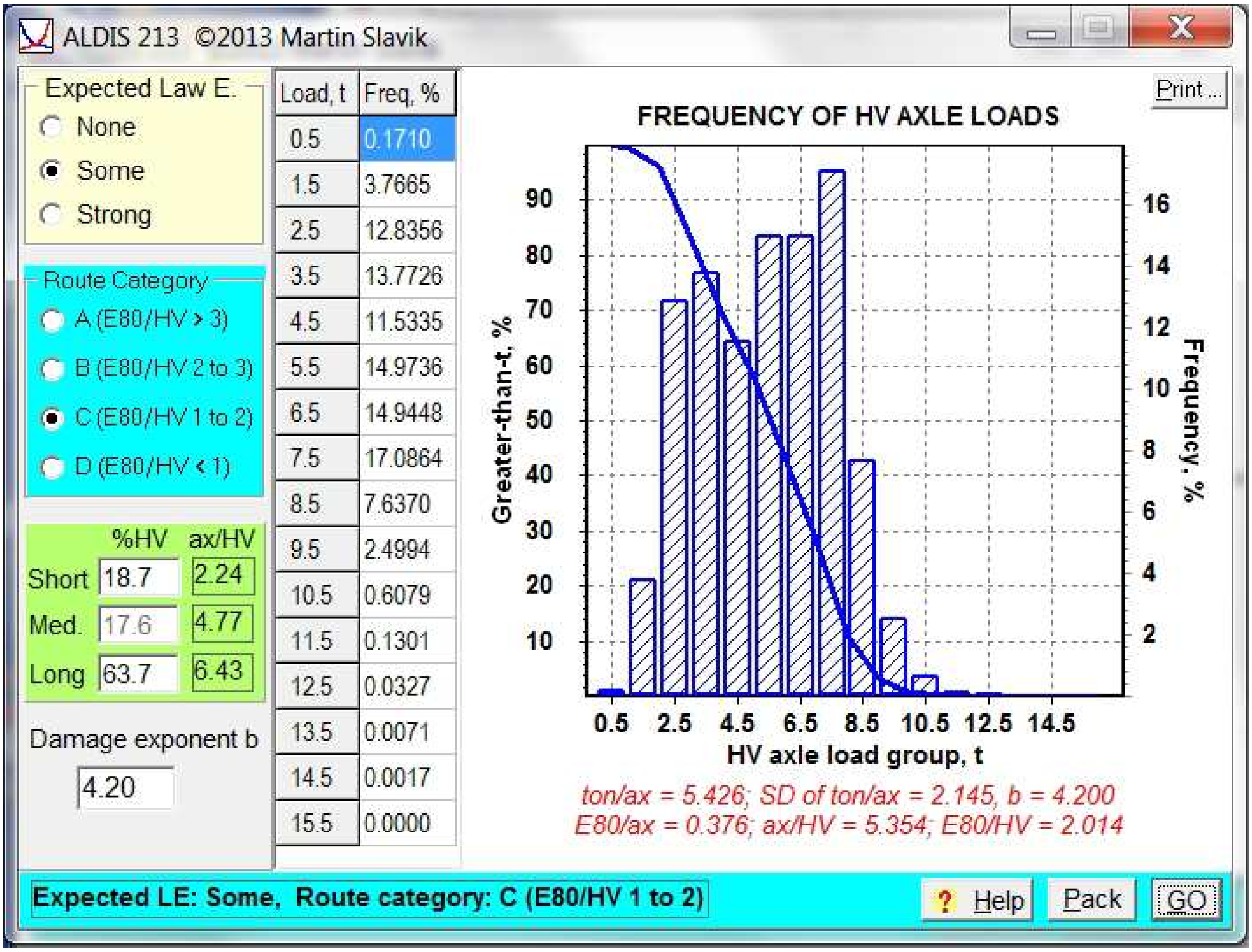


Figure 4. Screen shot of the *ALDIS213* software tool

The user has to click one of the radio buttons in the *Expected law enforcement* block, one radio button in the *Route Category* block, enter the anticipated percentages of *short and long heavy vehicles* (the program will calculate the percentage of *medium* heavy vehicles automatically), and click the *GO* button. A distribution of axle loads will appear in a graph, with the axle load frequencies shown in the table on the left of the graph. When the *Pack* button is clicked, these frequencies are written into a column in the computer clipboard from where they can be copied into appropriate input modules of pavement design programs, such as *cncPAVE*, *Cyrano*, or elsewhere as needed.

7 CONCLUSION

In a situation when distribution of axle loads is needed for purposes such as mechanistic pavement design and weigh-in-motion measurements are not available the proposed ALDIS method can produce a realistic estimate of the axle load distribution. The method is based on a combination of readily available current information with WIM information available from measurements done in the past. The method is simple enough to be handled manually, with the help of a spreadsheet, or by a computer tool called *ALDIS213*.

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