

# Effects of Transverse Distribution of Heavy Vehicles on Thickness Design of Full-Depth Asphalt Pavements

R. BUITER, W. M. H. CORTENRAAD, A. C. VAN ECK AND H. VAN RIJ

One of the most important parameters involved in the design of road pavements is the expected traffic load. This factor has a direct bearing on the thickness requirements of the pavement. For practical purposes, only the loading from heavy-goods vehicles should be considered as, in comparison, the loading from private cars has a negligible effect. When deciding on the layer thicknesses of a road pavement, it is essential to know whether the traffic will be concentrated in one wheel path, or distributed across the width of the traffic lane. When commercial vehicles travelling along a roadway use wheel paths that are transversely distributed across the traffic lane (lateral shifts of the wheel path), the pavement is less severely loaded at representative points in the cross section than when the vehicles all follow the same wheel path (uniform wheel path). The Road and Hydraulic Engineering Division of the Dutch Department of Public Works has carried out further research into the phenomenon of transversely distributed heavy-goods vehicles and the effect of lateral shifts of the wheel path on the design of flexible pavements. The study was particularly concerned with investigating how this phenomenon relates to roads with a full-depth asphalt pavement with specific material properties.

The first part of the research project involved studying the influence of the width of the traffic lane on the wheel-path distribution. Relevant field data were obtained from tests conducted with a specially developed measuring system. It was shown that the lateral wheel-shift pattern of heavy-goods vehicles could be accurately represented by a normal distribution. The standard deviation (also called the lateral spread) associated with the normal distribution was taken to determine the extent to which wheel paths were spread out across the traffic lane. By dividing the traffic lanes into three width classes, characteristic lateral spreads were determined, which could be used as a basis for designing suitable asphalt layer thicknesses.

During the second phase of the research project, a design factor (the wheel-path shift factor) was defined to account for lateral shifts of the wheel path. This enabled the thickness of the asphalt layer to be linked to the lateral spread (or standard deviation) of the normal distribution. Furthermore by applying the wheel-path shift factor (or simply called the shift factor) to various traffic loads, a relationship was established between the thickness requirements of the asphalt and the lateral spread of the normal distribution. The maximum horizontal (tangential) strain occurring at the bottom of the asphalt

layer was assumed to be representative of the likely fatigue effects in the structure.

The third phase of the research work involved comparing the new approach for dealing with lateral shifts in the wheel paths with the method that had been used in the Netherlands until recently. It was concluded that the previous basis for estimating the effects of lateral wheel-path shift phenomena was incorrect. As a result, the new approach outlined in this paper has now been incorporated into the *Pavement Design Manual* used by the Road and Hydraulic Engineering Division, Department of Public Works, in the Netherlands.

## EFFECT OF LANE WIDTH ON LATERAL SPREAD

### Lane Width

Several factors influence whether a driver follows a fixed wheel path. Some such factors include the following:

- Weather conditions (such as wind and precipitation),
- Time (hour, day, month),
- Heavy-goods vehicle used (type, load, and width),
- Traffic conditions (speed, intensity, proportion of heavy-goods vehicles, oncoming traffic, traffic restrictions, and visibility),
  - Road characteristics (type of road, road surface, number of lanes, road roughness, traffic-lane width, width of the hard shoulder, superelevation, alignment, and road markings), and
  - Environment (open area, woodlands, built-up area, flyovers, tunnels, traffic barriers, and obstacles).

In the literature (1-7) dealing with the subject of transverse distributions of traffic loads caused by heavy-goods vehicles, it is generally concluded that the width of the traffic lane is the most significant parameter in determining the extent to which the wheel paths are distributed over the road surface.

The other factors mentioned above are primarily concerned with the most heavily loaded point in the pavement structure. The shape of the transverse distribution and, therefore, the extent to which damage is caused to the pavement structure below the most heavily loaded point are less affected by such factors. As a consequence, the current investigations have been restricted to examining the role played by the traffic-lane width in lateral wheel-path shift phenomena.

### Measurements of Lateral Wheel-Path Shifts

Measurements of lateral wheel-path shifts were made in the right-hand wheel track of the right-hand traffic lane (the most heavily loaded lane) of three motorways having three lanes in each direction ( $2 \times 3$ ), fifteen motorways with two lanes in each direction ( $2 \times 2$ ), and three roads with one lane in each direction ( $2 \times 1$ ) (see Table 1). Every effort was made to conduct the measurement trials under similar circumstances so that weather and road conditions would not adversely affect the results.

In the majority of the cases, the width of the hard shoulder at the measuring location was greater than 1.20 m. All measurements were carried out on straight horizontal sections of

road. Although most of the roads selected for inclusion in this study were constructed from asphaltic concrete, two sets of measurements were conducted on cement concrete roads. Only heavy-goods vehicles were included in these measurement trials, which were always carried out during the day. No measurements were taken in traffic jams, and vehicles that changed traffic lanes were excluded from the study.

### Measuring Equipment

Work has also been carried out in other countries to study the transverse distribution of heavy-goods vehicles on road pavements. However, due to the lack of suitable, commercially avail-

TABLE 1 MEASUREMENT LOCATIONS AND RECORDED RESULTS

Road nr.	Measurement		Width		Lanes
	Location	Date	B [m]	S [m]	
13	Delft	15-07-82	3.16	0.234	2x3
12	Bodegraven	21-07-82	3.55	0.265	2x2
20	Vlaardingen	25-07-82	3.26	0.294	2x2
16	Willemsdorp	27-07-82	3.50	0.276	2x3
216	Rotterdam	29-07-82	3.20	0.228	2x2
15	Rotterdam	20-08-82	3.50	0.313	2x3
12	Zoetermeer	03-09-82	3.50	0.301	2x2
27	Maarssen	16-09-82	3.50	0.270	2x2
12	Harmelen	20-04-83	3.30	0.267	2x2
225	Amerongen	09-05-83	3.10	0.249	2x1
4	Hoogmade	09-03-84	3.24	0.224	2x2
44	Noordwijk	12-03-84	2.98	0.235	2x2
12	Harmelen	14-03-84	3.28	0.293	2x2
28	Hulshorst	04-04-84	3.47	0.305	2x2
--	Bergschenhoek	27-11-84	3.41	0.252	2x1
59	Vlijmen	04-10-85	3.40	0.304	2x2
27	Lexmond	30-05-86	3.32	0.309	2x2
59	Volkerak	14-08-86	3.20	0.268	2x1
44	Sassenheim	05-11-86	3.30	0.263	2x2
44	Sassenheim	12-11-86	2.99	0.237	2x2
44	Wassenaar	02-12-86	3.15	0.257	2x2

able equipment, most of the research institutes involved have been obliged to develop their own measuring devices for registering the transverse position of wheels (8-10).

The Road Research and Development Branch of the Road and Hydraulic Engineering Division has also developed equipment capable of performing such measurements. The sensing element in this unit consists of a thin mat of synthetic material, which can be readily attached to the road surface using double-sided adhesive tape. The mat contains 120 switch elements, each 0.02 m wide. As a wheel or wheel configuration crosses the sensor, several switches are activated, and the information is registered by means of a microcomputer. This allows conclusions to be drawn from the recorded bit-

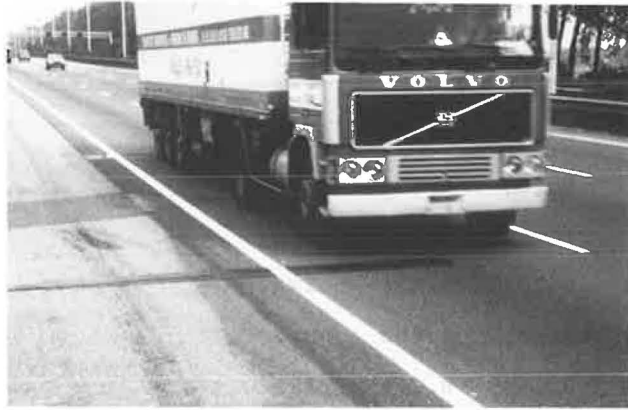


FIGURE 1 Sensing mat for measuring lateral shifts of the wheel path.

pattern about the transverse position and width of the tires that crossed the mat.

The computer software is able to distinguish between three types of tires: single-wheel, wide tire (super single), and twin-wheel. The distinction between single-wheel and wide tires depends on the width of the tire tread. Tires with a tread width of 0.25 m or more are classified as wide.

### Measurement Results

An example of the results obtained during a typical measurement (Figure 1) is given in Figure 2. This diagram shows the overall lateral wheel-shift pattern recorded at the Willemsoorp location on the A16 motorway. The number of switch movements at each contact point on the mat is plotted as a function of its transverse position. The position of the mat relative to the right-hand edge marker on the road is also shown.

It can be clearly seen that the overall lateral wheel-shift pattern of all the recorded wheel paths is well described by a bell-shaped normal distribution with lateral spread ( $S$ ), as shown by the bold line in Figure 2. The lateral spread can be approached by the standard deviation from standard statistics. The calculated lateral spread, the corresponding measured traffic lane width ( $B$ ), and the number of lanes are given in Table 1 for each of the measurement locations. These results have been plotted in Figure 3.

The lateral spread associated with the different distributions can be seen to increase with the width of the traffic lane. As a result of the relatively low correlation coefficient ( $r = 0.63$ ) between the width of the traffic lane and the lateral spread,

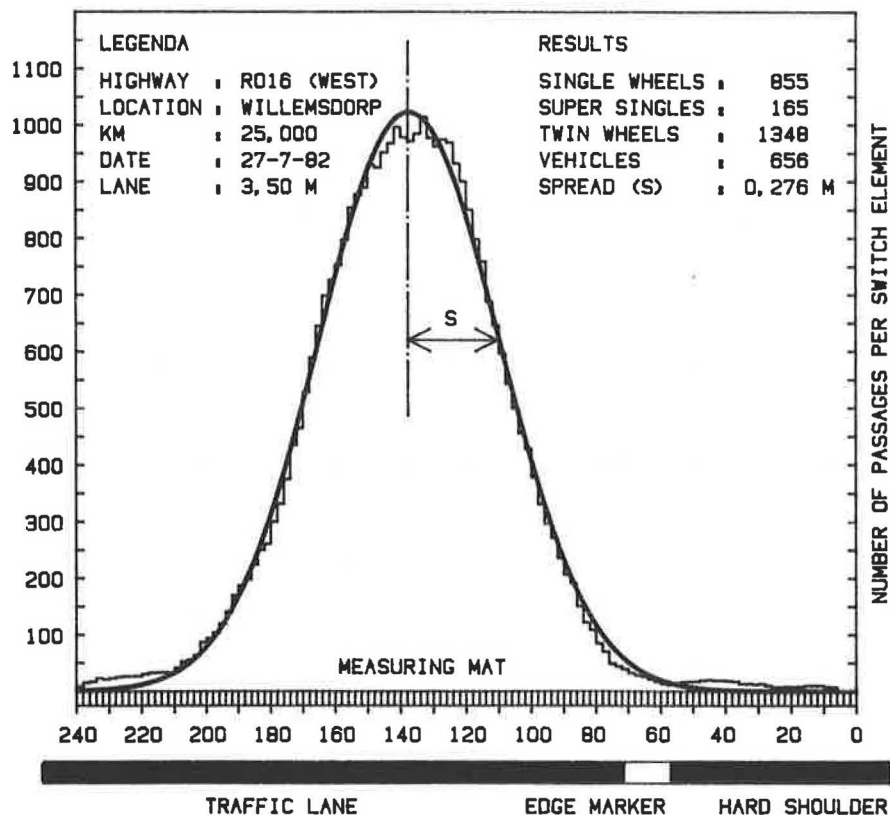


FIGURE 2 Measured lateral wheel-shift pattern.

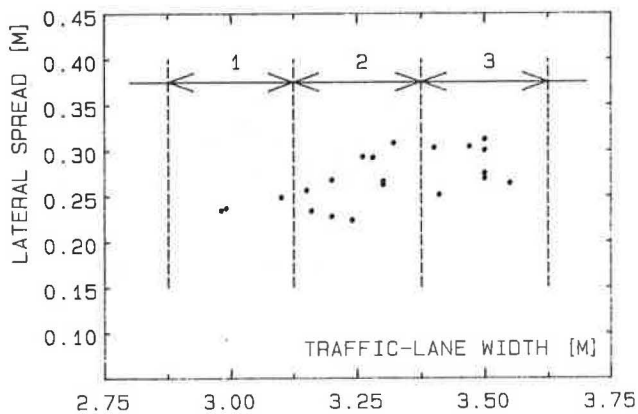
it was decided that a linear regression analysis would be inappropriate. As a practical solution, the fairly narrow range of traffic lane widths was subdivided into three classes, 0.25 m apart (Figure 3). The average lateral spread of the normal distributions for each width classification has been determined and is shown in Table 2.

Analysis of the results revealed no grounds for deriving different average lateral spreads for each type of road. Moreover, the measurements showed that the center of the normal distribution—which is considered to be the most heavily loaded point—is not at a constant distance from the right-hand edge marker on the road. An explanation of this phenomenon is outside the scope of the present paper. Finally, it should be noted that research has shown (11,12) that the observed lateral spread cannot be simply linearly extrapolated to traffic lane widths outside the measured range.

**RELATIONSHIP BETWEEN SPREAD AND ASPHALT THICKNESS**

**Design of Full-Depth Asphalt Pavements**

In discussing the relationship between the lateral spread and the thickness requirements of an asphalt course for given



**FIGURE 3** Calculated lateral spread plotted as a function of the measured lane width.

traffic loading conditions, attention is specifically focused in this paper on full-depth asphalt pavements. The required thickness of the asphalt layer is dependent on traffic load, climate, and the material properties of both the asphalt and the base course (subbase and subgrade).

It is generally recognized that material properties are extremely difficult to measure accurately in the field. As a result, such properties are usually determined in the laboratory using standard tests. For instance, in the case of asphalt-based materials, dynamic flexural tests are typically used to measure stiffness and fatigue characteristics. The conditions under which bending tests of this type are carried out are strictly limited, with restrictions being placed on the size of the specimens and the test temperatures. Although these tests are conducted at several stress or strain levels, only one frequency is used (13). It is clear that the test conditions in the laboratory are not directly comparable to the actual situation in the field. In general, no consideration is given to the random loading spectrum, the random rest periods, or the seasonal influences that occur in practice.

To be able to translate the traffic loading distribution in practice into a design load, certain correction factors must be applied. The Road and Hydraulic Engineering Division uses an asphalt healing factor, to deal with the effects of intermittent loading and self-healing of asphalt material. Road damage in practice increases gradually. Based on a desired percentage of damage after the design life, a certain discrepancy between the design load and the traffic load should be created by multiplying the traffic load by a safety factor. In the future, a probabilistic approach of road design should give a prediction of damage based on variation in design parameters. A detailed treatment of the healing factor and the safety factor and how they should be applied is outside the scope of this paper (14).

Lateral shifts of the wheel path cause the traffic load to be distributed across the transverse section. This means that, for a given traffic load, the asphalt course need not be as thick as when the traffic is concentrated in a uniform wheel path. The favorable effect of lateral shifts of the wheel path can be expressed by means of the shift factor.

In order to design a pavement for a specific application, the expected practical traffic load must first be expressed as a number of standard axle loads (for instance, 100 kN). To

**TABLE 2** AVERAGE LATERAL SPREAD PER TRAFFIC LANE WIDTH CLASSIFICATION

Traffic-lane width [m]			Average spread
Class	From - To	Average	[m]
1	2.88 - 3.12	3.00	0.24
2	3.13 - 3.37	3.25	0.26
3	3.38 - 3.62	3.50	0.29

convert this traffic load ( $N1$ ) to an equivalent number of standard axle loads ( $N0$ ) to be applied under design conditions, the following equation is used:

$$N0 = V \times H \times F \times N1 \quad (1)$$

where

- $V$  = shift factor for the traffic load,
- $H$  = asphalt healing factor,
- $F$  = safety factor,
- $N1$  = traffic load (standard axle loads of 100 kN), and
- $N0$  = design load (standard axle loads of 100 kN).

The stiffness and fatigue properties of various gravel asphaltic concrete mixes were determined in the laboratory (15) and found to comply with the current requirements of the Dutch Department of Public Works (16).

Calculations were carried out with the BISAR computer program (17) and the stiffness and fatigue properties found in the laboratory to determine the relation between the design loading conditions ( $N0$ ) to be imposed and the required asphalt thickness. This is illustrated in Figure 4. The calculations were performed assuming an air temperature of 14°C, a subgrade modulus of 100 MPa, the wheel configuration as described in the Shell method (18), and a standard axle load of 100 kN. To calculate the asphalt stiffness, the procedure described in the Shell method was used (18).

The following section describes how this information can be used to incorporate the shift factor into the design procedure for selecting the correct layer thickness of an asphalt pavement.

#### Assumptions Made in Deriving Shift Factor

In deriving a design factor to account for lateral shifts of the wheel path, it was assumed that the transverse position of the wheels was independent of the wheel-load configuration. This assumption was necessary because data from axle-load measurements were not available. The passage of each wheel or wheel configuration was assumed to be equivalent to one standard load (in this case a point load) of a particular magnitude.

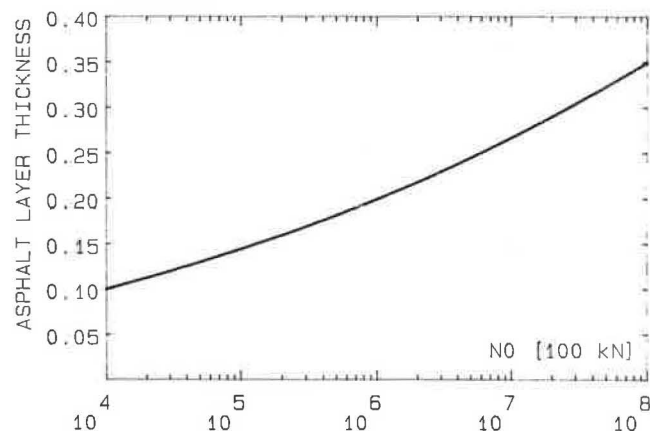


FIGURE 4 Thickness of the asphalt layer as a function of the design load.

Furthermore, the following conditions were also assumed:

1. The transverse distribution of standard loads could be represented by a normal distribution (Figure 5);
2. The number of standard loads imposed at a distance ( $x$ ) from the center of the transverse distribution could be calculated from the normal distribution;
3. The full-depth asphalt pavement could be reduced to a two-layer linear elastic system (Figure 6);
4. The horizontal tangential strain at the bottom of the asphalt layer could be regarded as the representative strain in pavement design; and
5. For asphalt, a relation exists between the induced horizontal tangential strain and the number of allowable load repetitions (Figure 7).

#### Derivation of Shift Factor

For the purpose of this paper, the shift factor ( $V$ ) for fatigue damage has been defined as the quotient of  $D_v$  and  $D_s$ .  $D_v$  equals the fatigue damage induced at a particular point on the underside of the flexible pavement by a number of trans-

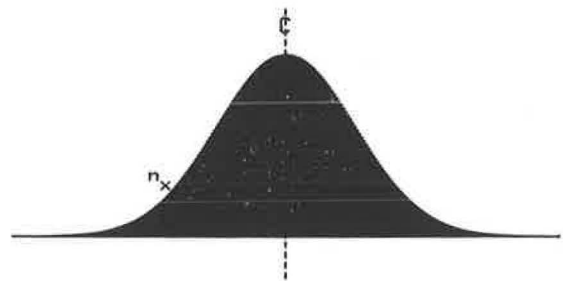


FIGURE 5 Transverse distribution of a given standard load.

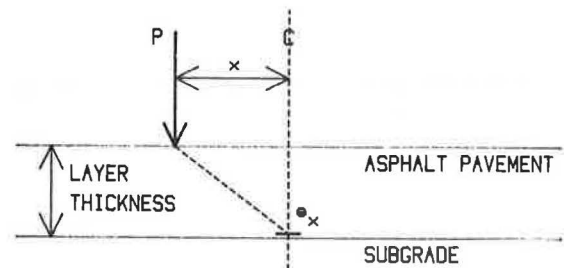


FIGURE 6 Two-layer linear-elastic asphalt pavement

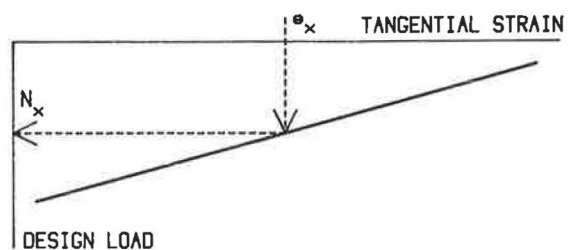


FIGURE 7 Asphaltic concrete fatigue line (15).



versely distributed heavy vehicles passing over the cross section, and  $D_s$  is the fatigue damage caused at the same point by the same number of heavy vehicles—now assumed to be traveling in a single path above this point.

In deriving the shift factor, it was assumed that the fatigue-damage mechanism in asphalt can be described by Miner's linear damage law (19). The fatigue damage that is induced by a number of standard loads imposed at a given distance from the center line on the underside of the asphalt layer at the midpoint of the transverse distribution can be determined as follows:

1. Determine the number of standard loads ( $n_x$ ) imposed at a distance ( $x$ ) from the center line (Figure 5);
2. Calculate the horizontal tangential strain ( $e_x$ ) that is induced on the underside of the asphalt layer at the midpoint, by a single standard load ( $P$ ) imposed at a distance ( $x$ ) from the center line (Figure 6);
3. Determine the service life ( $N_x$ ) that is associated with the calculated horizontal tangential strain level (Figure 7);
4. The amount of fatigue damage induced on the underside of the asphalt layer at the center line, by a single standard load ( $P$ ) imposed at a distance ( $x$ ) from the center line is  $1/N_x$ ; and
5. For a number of  $n_x$  standard loads imposed at the same given point, the amount of fatigue damage induced on the underside of the asphalt layer at the center line will be equivalent to  $n_x/N_x$ .

To assess accurately the total amount of fatigue damage induced ( $D_v$ ), the transverse distribution of standard loads was calculated in 240 positions, each separated by a distance of 0.01 m. Summation of the fatigue damage caused by the number of standard loads at each position resulted in the following expression:

$$D_v = (n_1/N_1) + (n_2/N_2) + \dots + \dots + (n_{240}/N_{240}) \quad (2)$$

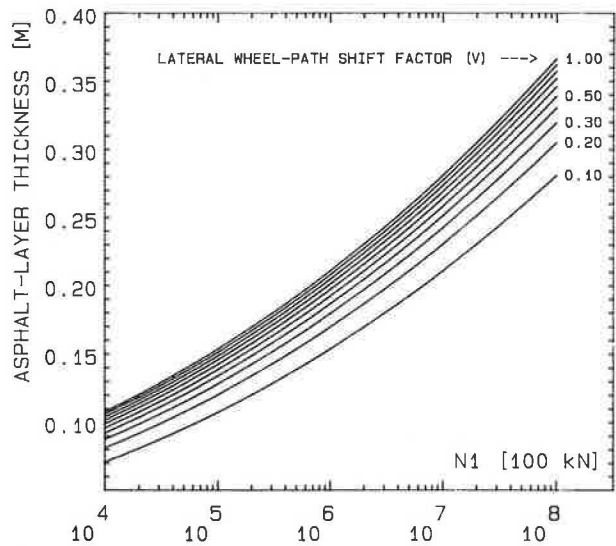
To determine the fatigue damage,  $D_s$ , the following approach was used. It was assumed that the distributed loading pattern, as referred to above, could be effectively replaced by the same collection of loads now concentrated at the midpoint. One standard load imposed at the center of the transverse distribution, was assumed to induce an amount of fatigue damage given by  $1/N_s$ . Summing the fatigue damage contribution caused by the loading per position placed in the center resulted in the following expression for the total amount of fatigue damage caused by the concentrated loading:

$$D_s = (n_1/N_s) + (n_2/N_s) + \dots + \dots + (n_{240}/N_s) \quad (3)$$

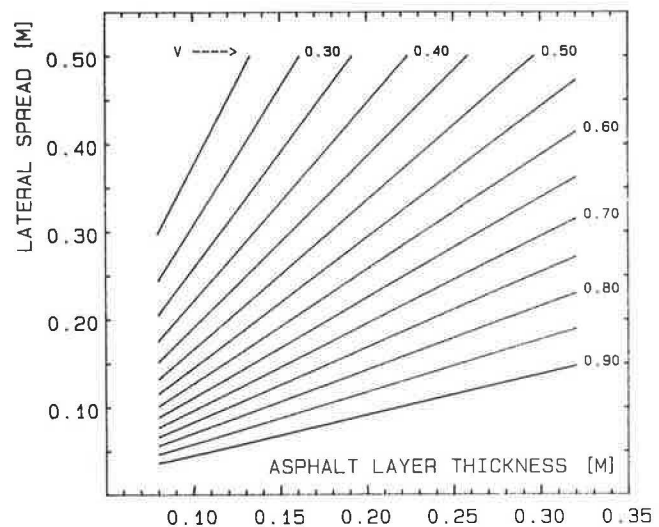
**Including Shift Factor in Design Method**

The relation between the traffic load ( $N1$ ) and the thickness requirements of an asphalt layer is shown in Figure 8 for a range of shift factors. The data presented in this figure have been calculated on the basis of the information contained in Figure 4 and by using Equation 1. The values of the correction factors applied in Equation 1 were  $H = 0.25$  and  $F = 6.00$ .

In Figure 2, it is shown that each measured distribution has its own lateral spread ( $S$ ). Once the standard load and trans-



**FIGURE 8** Thickness of the asphalt layer as a function of traffic load and shift factor for gravel asphaltic concrete (16) and a subgrade modulus of 100 MPa.



**FIGURE 9** Thickness of the asphalt layer as a function of lateral spread and shift factor for gravel asphaltic concrete (16) and a subgrade modulus of 100 MPa.

verse position have been selected and the necessary assumptions have been made regarding the material properties of the asphalt and the subgrade, the induced tangential strain becomes a relatively simple function of the thickness of the asphalt layer (Figure 6). Shift factors ( $V$ ) can, therefore, be determined for given combinations of lateral spread ( $S$ ) and asphalt thickness, on the basis of Equations 2 and 3. Buiter and Pronk give more precise details of the background to the calculation procedure (20).

Figure 9 shows typical shift factors (as a function of lateral spread and asphalt thickness) for the gravel asphaltic concrete mixes and subgrade referred to previously. It can be seen that the derived shift factors are variable quantities, even when the lateral spread (and hence traffic-lane width) is constant.

The shift factors increase with the thickness of the asphalt layer, which means that the effect of shifts in the wheel path are correspondingly smaller in thicker asphalt layers.

The method embodied in this approach was applied to the preparation of design charts as outlined below. For a constant traffic load ( $N_1$ ), the required asphalt thickness was determined for various shift factors ( $V$ ) using Figure 8. Following this, for each combination of shift factor and asphalt thickness, the associated lateral spread was read off from Figure 9. Finally Figure 10 was constructed, describing the relation between the required asphalt thickness and the associated lateral spread for a given traffic load ( $N_1$ ). It should be noted that Figures 4, 8, 9, and 10 are strictly valid for the set of material properties associated with the asphalt and subgrade concerned.

#### COMPARISON OF OLD AND NEW APPROACHES

In the approach described in this paper, the shift factor is dependent on (a) the lateral spread in the transverse distribution of heavy-goods vehicles, (b) the asphalt thickness, and (c) the material properties of the asphalt and the subgrade.

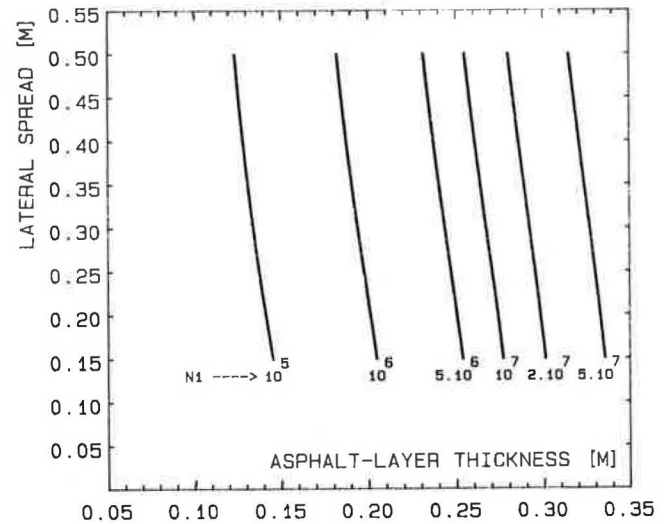


FIGURE 10 Thickness of the asphalt layer as a function of lateral spread and traffic load for gravel asphaltic concrete ( $I_6$ ) and a subgrade modulus of 100 MPa.

TABLE 3 SHIFT FACTORS BASED ON NEW APPROACH FOR THREE CLASSES OF LANE WIDTH AND DIFFERENT TRAFFIC LOADS

Lane width [m]			Traffic load ( $N_1$ )					
Class	B	S	$1.10^5$	$1.10^6$	$5.10^6$	$1.10^7$	$2.10^7$	$5.10^7$
1	3.00	0.24	0.484	0.621	0.703	0.734	0.763	0.797
2	3.25	0.26	0.451	0.588	0.673	0.705	0.736	0.772
3	3.50	0.29	0.408	0.543	0.630	0.664	0.696	0.736

TABLE 4 THICKNESS REQUIREMENTS BASED ON NEW APPROACH FOR THREE CLASSES OF LANE WIDTH AND DIFFERENT TRAFFIC LOADS

Lane width [m]			Traffic load ( $N_1$ )					
Class	B	S	$1.10^5$	$1.10^6$	$5.10^6$	$1.10^7$	$2.10^7$	$5.10^7$
1	3.00	0.24	0.138	0.198	0.247	0.271	0.295	0.330
2	3.25	0.26	0.136	0.196	0.246	0.269	0.294	0.329
3	3.50	0.29	0.134	0.194	0.244	0.267	0.292	0.327

In Table 3, the shift factors based on this approach are given for the three classes of traffic-lane width (Table 2) and for different traffic loads ( $N1$ ). The thickness requirements for asphalt layers of roads with lane widths within the three classes have also been calculated on the basis of the new approach. These thicknesses are presented in Table 4 for different traffic loads ( $N1$ ). It can be seen that, for a given traffic load, only small differences exist in the thickness requirements among the three width categories.

In the Road and Hydraulic Engineering Division design method applied until recently, a constant (and therefore fundamentally incorrect) shift factor was used per traffic-lane width. This approach was based on the Shell method (18) and resulted in a constant shift factor of 0.40 being assumed for a traffic-lane width of 3.50 m. Table 5 gives the shift factors based on the old and new approaches for different traffic loads ( $N1$ ) and for lane-width Class 3 (Table 2). The thickness requirements for asphalt courses determined on the basis of the old approach are shown in Table 6, where they are compared with lane-width Class 3 values taken from Table 4.

As the traffic load ( $N1$ ) and, therefore, the thickness of the asphalt pavement increase, the difference in thickness requirements between the two methods becomes more apparent. It has been shown that, particularly in the case of heavily loaded motorways, the incorrect application of shift factors has led to significant deviations, as compared with the new approach. In the context of a general review, which aimed to bring theory and empirical method closer together, the approach described in this paper is one of the improvements that have been incorporated into the design method used by the Road and Hydraulic Engineering Division (21).

Even though the maximum difference of 22 mm (Table 6) is small when compared to the precision associated with other design parameters (for example, the standard deviation of the asphalt layer thickness is frequently greater than 10 to 15 mm), the research reported in this paper has produced valuable information that also can be used in a more probabilistic approach to road design.

**CONCLUSIONS AND RECOMMENDATIONS**

The variable shift factor presented in this paper is dependent on the wheel-path shift pattern, the asphalt concrete thickness and the material properties of the asphalt concrete and the subgrade. Assessing the effects of lateral shifts in the wheel path by using a constant shift factor for a given width of traffic lane is, therefore, fundamentally incorrect.

Use of a constant shift factor of 0.40 for lane widths of 3.50 m can lead to considerable differences in the asphalt thickness requirements, when compared with the described method based on variable shift factors. In the case of motorways that are subject to heavy traffic loads, a first-order thickness difference is predicted, which is equivalent to incorrectly estimating the traffic load by a factor of 2.

It is recommended that design methods, based on a constant shift factor per traffic-lane width, should be changed and that consideration should be given to the new techniques that have been developed. These are felt to provide a better insight into the significance of such effects on the different types of construction.

TABLE 5 COMPARISON OF SHIFT FACTOR BASED ON NEW AND OLD APPROACHES FOR DIFFERENT TRAFFIC LOADS AND LANE WIDTH CLASS 3

Traffic load	$1.10^5$	$1.10^6$	$5.10^6$	$1.10^7$	$2.10^7$	$5.10^7$
New approach	0.408	0.543	0.630	0.664	0.696	0.736
Old approach	0.400	0.400	0.400	0.400	0.400	0.400

TABLE 6 COMPARISON OF THICKNESS REQUIREMENTS BASED ON NEW AND OLD APPROACHES FOR DIFFERENT TRAFFIC LOADS AND LANE WIDTH CLASS 3

Traffic load	$1.10^5$	$1.10^6$	$5.10^6$	$1.10^7$	$2.10^7$	$5.10^7$
New approach	0.134	0.194	0.244	0.267	0.292	0.327
Old approach	0.134	0.187	0.230	0.251	0.273	0.305
Difference	0.000	0.007	0.014	0.016	0.019	0.022



## ACKNOWLEDGMENTS

This research project was conducted at the Road Engineering Branch, Road and Hydraulic Engineering Division. Appreciation is extended to all those who have in any way contributed to this project. More particularly, the authors want to thank J. H. Geerts, E. Vos, P. Hopman, and A. C. Pronk.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.