satisfy all of 'the hypotheses must be obtained first as a standard of reference.

ACKNOWLEDGMENT

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Effect of Increased Truck Size and Weight on Rural Highway Geometric Design (and Redesign) Principles and Practices

OGILVIE F. GERICKE AND C. MICHAEL WALTON

A summary is presented of a study of the effects that an increase in legal truck limits would have on highway geometric design elements and of the cost implications should various segments of the Texas highway system require redesign and modification to facilitate their safe and efficient operation. The paper includes (a) a review of past and current research concerning the effects of a possible change in legal vehicle dimensions and weights on the geometric design elements of rural roads, (b) an identification of those geometric elements most affected by a change in truck dimension and weight, (c) an assessment of the effects a change in legal truck size and weight will have on these geometric design elements for a variety of operating conditions, and (d) an estimate of the cost required to redesign and modify the highway section.

A set of issues surrounding the legal limits on sizes and weights of motor vehicles has become a primary policy concern of government and the trucking industry. Such concern is reflected by current federal initiatives (stemming from the Surface Transportation Act of 1978), related study activities, and actions of several state transportation agencies.

Fuel shortages and rapidly increasing fuel prices have provided an impetus for resolving many of the problems associated with vehicle sizes and weights. The underlying notion is frequently reflected in the following simple relation: Large vehicles can carry more freight per unit of fuel. However, although fuel conservation is important, it is only one of many measures that may be used in an analysis of size and weight issues.

Today's highway network is the result of an evolutionary process that represents, among other things, a mix of geometric design principles and practices. Any significant change in vehicle operating characteristics should require an assessment of geometric design practices and the impact on the existing highway system in terms of operational as-

pects and safety. Also needed would be an estimate of the cost required to redesign and modify the current network or segments of the network to accommodate the larger vehicles.

In Texas, a study is under way to evaluate some of the effects of operating larger and heavier vehicles on the highway system. Initial results, determined by using a study technique modified from the National Cooperative Highway Research Program (NCHRP) (1), showed estimated pavement costs, bridge costs, truck operating cost savings, and fuel savings that would result from increases in limits on axle weight and gross vehicle weight (GVW) coupled with corresponding changes in vehicle unit length and width. No change in the height of vehicles or trailers is considered in this study. The work reported in this paper focuses on the costs of the geometric design and redesign requirements associated with increases in vehicle size (length and width) as well as weight.

SCOPE OF THE RESEARCH

As an initial assumption, four different vehicle combinations (2) and two highway classification schemes (cases 1 and 2) are considered. The four vehicle scenarios are shown in Figures 1 and 2.

In case 1, the three functional rural highway systems are considered in the analysis: (a) the Interstate highway system, (b) the U.S. and state highway system, and (c) the farm-to-market (FM) road system. Case 1 represents a traditional approach that fits the Texas highway network of about 60 000 miles.

Case 2 differentiates on the basis of road use. In case 2, the following rural functional classes, or combination of classes, are also considered in

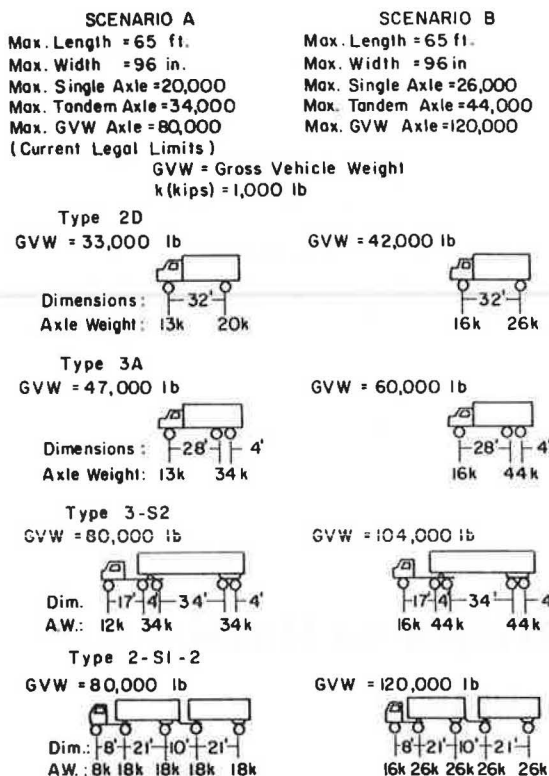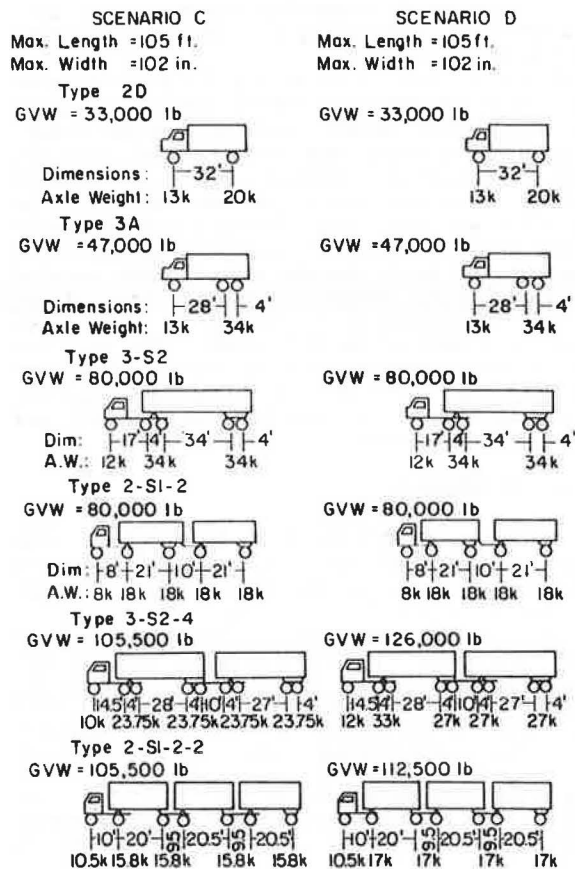Figure 1. Vehicle configurations for scenarios A and B.

Figure 2. Vehicle configurations for scenarios C and D.

the analysis: (a) the Interstate highway system, (b) principal arterial systems (including Interstate), and (c) a combination of "all classes" (Interstate, other principal arterials, minor arterials, and major and minor collectors, excluding county roads that may be part of the roadway types mentioned above).

It was desirable to examine highway upgrading costs for these rural systems according to differences in their use, design standards, and vehicle composition. Four alternative scenarios were developed to provide a framework for analyzing a significant change in truck dimensions and weight patterns. Scenario A represents the current statutes and assumes that these weight and dimension limits will remain the same over the 20-year analysis period. The other three scenarios represent an array of changes in GVW, single- and tandem-axle weights, and vehicle length and width.

ELEMENTS AFFECTED BY SIZE AND WEIGHT CHANGES

From an evaluation of present geometric design principles and practices, the following elements were identified as those that may be affected by a change in vehicle dimension and weight:

1. Design elements--(a) Stopping sight distance, (b) passing sight distance, (c) pavement widening on curves, and (d) critical lengths of grades;
2. Cross-section elements--(a) Lane width and (b) width of shoulder; and
3. Intersection design elements--(a) Minimum design for sharpest turns, (b) widths for turning roadways, (c) sight distance at at-grade intersections, and (d) median openings.

Stopping Sight Distance

Design stopping sight distance is, according to the American Association of State Highway and Transportation Officials (AASHTO) (3,4), "the minimum distance required for a vehicle traveling near the design speed to stop before reaching an object in its path."

The minimum stopping sight distance is calculated according to the following formula (3,4):

$$SSD = 1.47 \times V \times 2.5 + V \times V/30 \, (f \pm g) \qquad (1)$$

where

SSD = stopping sight distance,
V = vehicle speed (miles/h),
2.5 = value assumed to represent perception and reaction times (s),
f = coefficient of friction between the tires and the roadway surface, and
g = percentage grade divided by 100.

The first part of the formula (1.47 x V x 2.5) gives the distance traveled during perception-reaction time. The second part [V x V/30 (f ± g)] gives the distance required to stop after brake application.

In measuring stopping sight distance, the following assumptions are made by AASHTO (4): (a) that the height of the operator's eye is 3.50 ft above the road surface and (b) that the operator must be able to detect an object 6 in high in his or her path.

The above formula and measuring criteria for minimum stopping sight distance were derived for passenger car operations. But AASHTO (4) states that, although trucks require a longer stopping distance from a given speed, the additional braking distance

is balanced by the higher eye position of the truck operator. The Federal Highway Administration (FHWA) Motor Carrier Safety Regulations specify a deceleration rate of 14 ft/s/s for truck combinations and 21 ft/s/s for passenger cars. This indicates that cars should stop in two-thirds the distance required for trucks (5).

Full-scale tests have been conducted by the transportation departments of California, Utah, and the province of Alberta, Canada, to assess the braking performance of trucks (5-7). Figure 3 shows the results obtained by these agencies. All of the dry-pavement results are well under the FHWA curve. A theoretical evaluation was performed by the Illinois Institute of Technology (8), and their results, based on analytic studies, computer simulation, and examination of experimental data, confirmed the results obtained in California, Utah, and Alberta.

Maximum vehicle height remains the same for the four scenarios, and no change in operator eye height is expected. This will therefore effect no change in stopping sight distance.

Passing Sight Distance

AASHTO states that, although most rural highways are two-lane highways, vehicles must frequently use a lane that is regularly used by opposing vehicles in order to overtake slower-moving vehicles. Passing sight distance is the length needed to safely complete this passing maneuver on two-lane highways (4) with an operator eye height of 3.50 ft and an object height of 4.25 ft:

$$PSD = d(1) + d(2) + d(3) + d(4) \qquad (2)$$

where

PSD = passing sight distance;
$d(1)$ = initial maneuver distance (ft)
= $1.47 \times t(V - m + a \times t/2)$ (3,4), where
t = initial maneuver time (s),
V = average speed of passing vehicle (miles/h),
m = speed difference between the two vehicles (miles/h), and
a = average acceleration (miles/h/s);
$d(2)$ = distance traveled in the left lane by the passing vehicle (ft)
= $(Lf + Ls + 150)V/Vi$, where
Lf = length of faster vehicle (ft),
Ls = length of slower vehicle (ft),
V = speed of faster vehicle (miles/h),
Vi = speed difference between the vehicles (miles/h), and
150 = additional distance between the two vehicles before and after the passing maneuver (ft);
$d(3)$ = distance at the end of the passing maneuver between the passing vehicle and an opposing vehicle (ft); and
$d(4)$ = distance traversed by an opposing vehicle (ft).

Whereas an increase in vehicle weight and width will have no effect on the elements defined above, an increase in vehicle length will have a pronounced effect on $d(2)$ and $d(4)$. This was confirmed by tests in Utah and Alberta (5,6).

Design values of AASHTO and the Texas State Department of Highways and Public Transportation (TSDHPT) (3,9) are based on requirements for a passenger car passing a passenger car. Since it is common practice for cars to overtake trucks, additional length will be needed or more abortive passing maneuvers will result when the truck length is increased. This does not include consideration of

the relative change in engine power associated with today's vehicles. The increase in abortive movements may have a detrimental effect on safety.

The following assumptions were made in calculating the extra passing sight distances required because of increased truck length:

1. Car length = 19 ft (3).
2. Truck length = 65 ft for scenarios A and B and 105 ft for scenarios C and D.
3. The speed difference between the two vehicles is 10 miles/h (3,4).
4. Values for t and a are assumed according to observed AASHTO values (3,4).
5. Overtaken vehicles travel at a uniform speed.
6. The passing vehicle slows down and trails the overtaken vehicle on entering the passing zone.
7. Values for d(3) are in the suggested range of 100-300 ft (3,4).
8. d(4) = 0.666 x d(2).

The values obtained are given in Table 1. It can be seen that passing sight distance will increase considerably with an increase in vehicle length. Pavement markings that prohibit passing maneuvers are warranted according to the Manual on Uniform Traffic Control Devices (MUTCD) (10). These values are also given in Table 1.

Pavement Widening on Curves

AASHTO (3,4) states that "pavements on curves are sometimes widened to make operating conditions on curves comparable to those on tangents." The justifications are based on truck operating characteristics: (a) that the rear wheels track inside of the front wheels (off-tracking) and (b) the difficulty of steering the vehicle.

The following formula gives maximum off-tracking values that were experimentally found to be close to the real, measured off-tracking (4,11):

$$MOT = R(1) - SQRT[R(1) \times R(1) - SUM(L \times L)] \qquad (3)$$

where

MOT = maximum off-tracking (ft),
$R(1)$ = turning radius of outside front wheel (ft),
$SQRT$ = square root (here and as shown in other formulas), and
$SUM(L \times L)$ = $L(1) \times L(1) + L(2) \times L(2) + \ldots$, where
$L(1)$ = wheelbase of tractor (ft),
$L(2)$ = wheelbase of first trailer (ft),
$L(3)$ = distance between rear axle and articulation point (ft),
$L(4)$ = distance between articulation point and front axle of next trailer (ft), and
$L(5)$ = wheelbase of next trailer (ft).

Extra width to compensate for the difficulty of driving on curves can be computed from the following (3,4):

$$Z = V/SQRT(R) \qquad (4)$$

where

Z = extra width (ft),
V = design speed (miles/h), and
R = radius of centerline (ft).

The width of the overhang can be computed as follows (3,4):
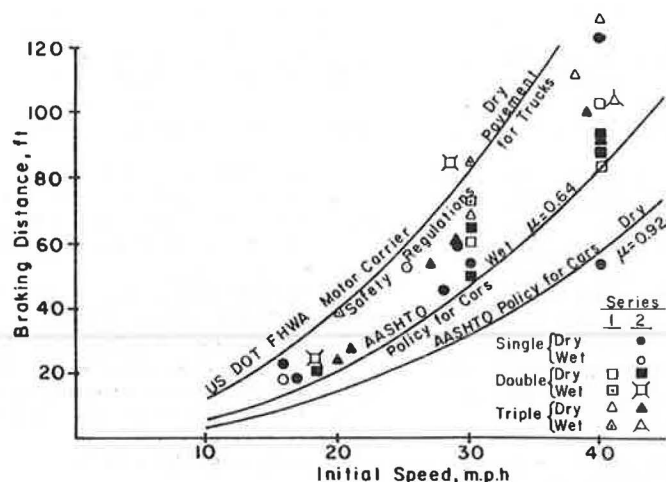
Figure 3. Braking distance.

Table 1. Minimum passing sight distance for two-lane highways for scenarios A-D.

Design Speed (miles/h)	Assumed Speed (miles/h)		Avg a (miles/h/s)	t (s)	Passing Sight Distance (ft)			
					Calculated		AASHTO (4)	MUTCD (10)
	Passed Vehicle	Passing Vehicle			L=65 ft	L=105 ft		
30	26	36	1.40	3.6	1700	1900	1100	500
40	34	44	1.41	3.8	2100	2400	1500	600
50	41	51	1.45	4.1	2500	2800	1800	800
60	47	57	1.48	4.4	2800	3200	2100	1000
65	50	60	1.50	4.5	3000	3400	2300	–
70	54	64	1.50	4.5	3200	3600	2500	1200
75	56	66	1.50	4.5	3300	3700	2600	–
80	59	69	1.50	4.5	3400	3900	2700	–

Note: L = maximum vehicle length.

Table 2. Calculated values for pavement widening on two-lane pavements.

Degree of Curve	Design of Vehicle	Widening by Width of Pavement (ft)					
		30 ft	40 ft	50 ft	60 ft	70 ft	80 ft
1	3-S2-4	0.0	0.0	0.5	0.5	0.5	1.0
	2-S1-2-2	0.0	0.0	0.0	0.5	0.5	1.0
2	3-S2-4	0.5	1.0	1.5	1.5	2.0	2.0
	2-S1-2-2	0.5	0.5	1.0	1.0	1.5	1.5
3	3-S2-4	1.5	1.5	2.0	2.5	2.5	3.0
	2-S1-2-2	1.0	1.0	1.5	2.0	2.0	2.5
4	3-S2-4	2.0	2.5	2.5	3.0	3.5	
	2-S1-2-2	1.0	1.5	2.0	2.5	3.0	
5	3-S2-4	2.5	3.0	3.5	4.0		
	2-S1-2-2	1.5	2.0	2.5	3.0		
6	3-S2-4	3.0	3.5	4.0	4.5		
	2-S1-2-2	2.0	2.5	3.0	3.5		
7	3-S2-4	3.5	4.0	4.5			
	2-S1-2-2	2.5	3.0	3.5			
8	3-S2-4	4.0	5.0	5.5			
	2-S1-2-2	2.5	3.5	4.0			
9	3-S2-4	5.0	5.5	6.0			
	2-S1-2-2	3.0	3.5	4.5			
10-11	3-S2-4	6.0	6.5				
	2-S1-2-2	4.0	4.5				
12-14.5	3-S2-4	7.5	8.5				
	2-S1-2-2	5.0	6.0				

$$Fa = SQRT[R \times R + A(2 \times L + A)] - R \qquad (5)$$

where

    Fa = width of overhang (ft),
    A = overhang (ft), and
    L = wheelbase of unit (ft).

The width of a two-lane pavement on a curve can then be computed from

$$W1 = 2(U + C) + Fa + Z \qquad (6)$$

where U is the vehicle track width (in feet) and C is the lateral clearance per vehicle (2, 2.5, or 3 ft for 20-, 22-, or 24-ft pavement widths, respectively).

From the above formulas, it can be seen that vehicle configuration and length will have an effect on pavement widening. The maximum vehicle width proposed for scenarios B, C, and D is 8.5 ft, which is the same as the maximum for the AASHTO design vehicles but 6 in wider than the TSDHPT maximum. New widths for pavement widening on curves were calculated for vehicle types 3-S2-4 and 2-S1-2-2. Some of the results obtained are given in Table 2.

Critical Lengths of Grades

According to AASHTO (4), climbing lanes should be provided on the upgrade side of a two-lane rural highway when

1. The length of upgrade causes a speed reduction of 10 miles/h or more or
2. The added cost is justified by the volume of traffic and the percentage of trucks.

The size, power, gradeability, and entrance speed of trucks contribute to the performance of trucks on a grade. Their combined effect then will lead to the maximum allowable speed reduction of 10 miles/h (4,9).

AASHTO (4) uses the nationally representative truck with a ratio of GVW (pounds) to net horsepower of 300:1 to evaluate the performance (acceleration and deceleration) of trucks on grade. It seems reasonable to assume that vehicles with a GVW of as much as 126 000 lb will have a ratio of 300:1 (4,12). The current availability of engines big enough to provide the 300:1 ratio underlines this assumption (12).

Lane Width

AASHTO states (3,4) that, on rural two-way highways, hazardous conditions exist on pavements that are less than 22 ft wide when even a moderate volume of mixed traffic is present because of inadequate body clearance.

Body and edge clearances for meeting or passing vehicles were identified as critical factors in judging the adequacy of pavement width (1). In experiments conducted in the earlier days of highway construction, two important observations were made (13):

1. Only on 24-ft pavements were drivers apparently satisfied with both edge and body clearance.
2. Drivers of passenger cars prefer a body clearance of about 5 ft when meeting other passenger cars. This cannot be attained on pavements that are less than 22 ft wide.

These observations make it clear that only vehicle width will have an impact on lane width. The following AASHTO design vehicles all have a current width of 8.5 ft: the SU, the WB40, the WB50, the WB60, and the BUS. No change in vehicle width from the existing AASHTO standards is proposed in scenarios B, C, and D, but the proposed width will differ from the allowable TSDHPT standard of 8.0 ft (4,9). Should Texas or other states adopt a wider vehicle width, the following should be borne in mind.

Although a 10-ft lane width may be an acceptable minimum on arterials that carry a few commercial vehicles (4,13), it is difficult to control the number and movement of commercial vehicles. Although substantial lane flow is accommodated, driving on such lanes causes undesirable tension and strain for drivers, especially at other than low speeds (3).

The average body clearances of 2.6 and 3.5 ft for passenger cars meeting commercial vehicles on 18- and 20-ft pavements, respectively, appear to be inadequate for safety (13).

The question of minimum lane width for safe operation of 102-in-wide trucks is a difficult one, especially for multilane highways. According to R.J. Hansen Associates (14), there is no evidence to indicate that an increase in width of 6 in would result in an increased number of accidents. It seems practical to allow for a gradual modification of lane width to 12 ft for the operation of 102-in-wide trucks. AASHTO (4) did not specifically address this issue; however, the lane width that it recommends is 11-13 ft. During an initial period, the operation of 102-in-wide trucks could, for instance, be allowed on multilane divided highways that have 11-ft-wide lanes. These lanes should gradually be widened to allow for the safe and tension-free operation of 102-in-wide trucks.

Width of Shoulders

Shoulders are mainly provided to accommodate stopped vehicles, for emergency use, and for lateral support of the pavement base and surface courses (3,4).

In order to accommodate stopped vehicles, AASHTO recommends that vehicles should clear the pavement edge by at least 1 ft and that a 2-ft working space should be provided (3,4). Widths of the standard AASHTO vehicles vary from 7.0 to 8.5 ft (4). By using the standard widths and clearances required, AASHTO recommends that, for heavily traveled and high-speed highways, the usable shoulder width should be at least 10 ft but preferably 12 ft (4).

The following relations between shoulder width and accident frequency have been found (15):

1. On tangents, as the right-shoulder width increases beyond the width necessary to accommodate a parked vehicle, the safety benefits become insignificant.
2. As the right-shoulder width increases on curves, the accident rate decreases.
3. Paved right shoulders produce fewer accidents than unpaved right shoulders.

The capacity of a highway is reduced if there are restrictive lateral clearances (4). For obstructions farther than 6 ft away from the pavement edge, no reduction in capacity is experienced (4). By considering capacities, accident costs, construction costs, and other relevant costs for various shoulder types and widths, a cost-effective design can be obtained.

Minimum Design for the Sharpest Turns

According to AASHTO (4), it is sometimes necessary to provide for the turning of vehicles within minimum space, such as at unchannelized intersections. Then minimum turning paths of the design vehicle become highly significant. It is assumed that the vehicle is positioned 2 ft from the pavement edge at the beginning and the end of the turn. The inner wheel should at no point be closer than 9 in to the pavement edge during the turn.

The paths that the 2-S1-2-2, 3-S2, and 3-S2-4 vehicles are expected to follow are shown in Figure 4. These paths are obtained by using a model built according to the description of the "tractrix integrator" (11) and the vehicle configurations shown in Figures 1 and 2.

Width for Turning Roadways

The widths required for turning roadways are classified according to three types of operation (4). The three cases are

1. One-lane, one-way operation with no provision for passing;
2. One-lane, one-way operation with provision for passing; and
3. Two-lane operation, either one-way or two-way.

The formulas used to compute the width for cases 1-3, respectively, are as follows:

$$W = U + C + Z = U + 6 \tag{7}$$

$$W = 2(U + C) + Fa + Fb = 2U + Fa + Fb + 4 \tag{8}$$

$$W = 2(U + C) + Fa + Fb + Z = 2U + Fa + Fb + 10 \tag{9}$$

where

U = track width of vehicle (out-to-out tires) (ft),
Fb = width of rear overhang (ft),
C = total lateral clearance per vehicle (ft), and
X = extra width allowance due to difficulty of driving on curves (ft).

To compute U, Fa, and C, the same formulas used earlier in the discussion of pavement widening on curves were used (4).

It can be seen from these formulas that vehicle width, configuration, and length will have an effect on roadway width while weight and height do not. The maximum vehicle width proposed for scenarios B, C, and D is 8.5 ft, which is the same as the maximum width used for some of the AASHTO design vehicles but is 6 in wider than the TSDHPT standard. When the above formulas were used, new widths were calculated for the 3-S2-4 and 2-S1-2-2 vehicles. The results obtained from these calculations are given in Table 3.

Sight Distance at At-Grade Intersections

AASHTO (4) considers three general cases of required sight distance at intersections, and the designer must ensure that for the different assumptions there will be an unobstructed view along both roads. The three cases are

1. Enabling vehicles to adjust speed, in which case only reaction plus perception time and one additional second for acute braking is considered;
2. Enabling vehicles to stop, in which case safe stopping sight distance plays a role; and
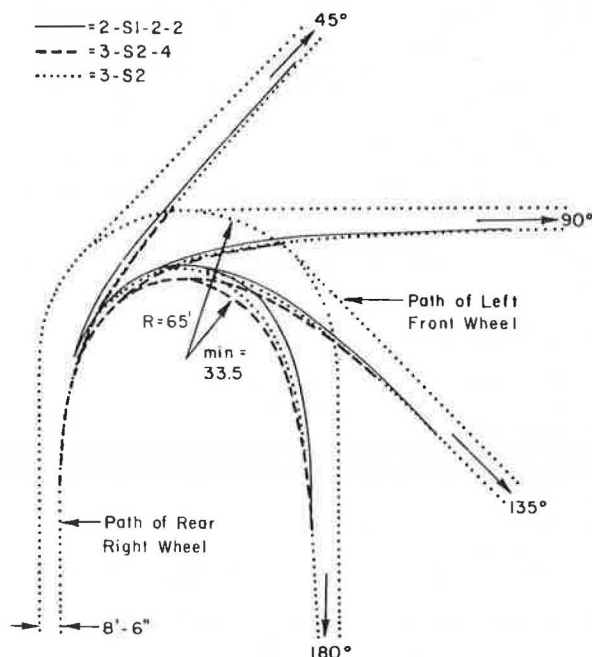
3. Enabling the stopped vehicle to cross a major highway, in which case the formula used to obtain the required sight distance is

$$d = 1.47V (J + Ta) \qquad (10)$$

where

  d = minimum sight distance along the major highway (ft),
  V = design speed of the major highway (miles/h),
  J = sum of perception time and time required to shift to first gear or actuate an automatic shift (s),
  Ta = time required to accelerate and traverse the distance S required to clear the major roadway (s), and
  S = D + W + L, where
  D = distance from the near edge of the pavement to the front of the stopped vehicle,
  W = width of pavement along the path of the crossing vehicle, and
  L = overall vehicle length.

From the above, it can be seen that only case 3 will be influenced by vehicle length and acceleration capability. If it is assumed that the acceleration capability of the 3-S2-4 and 2-S1-2-2 vehicles will be at least the same as that of the WB50 vehicle, then longer sight distances will be needed due to the increase in vehicle length. This assumption is affirmed by truck acceleration tests made by the Western Highway Institute (12). For scenarios C and D, additional sight distance along the major highway will be needed for the 3-S2-4 and 2-S1-2-2 vehicles (see Figure 5).

Median Openings

The design of median openings depends on the type of turning vehicle and the traffic volumes (4). The opening must accommodate the off-tracking characteristics of the design vehicle at slow speeds. The previous discussion of minimum design for the sharpest turns deals with the expected wheel paths of the 3-S2-4 and 2-S1-2-2 vehicles. Figure 6 was obtained by using the off-tracking characteristics obtained in that section of this paper. Figure 6 shows the minimum median opening for various widths of the median. An 85-ft control radius was used, since this fits the path of the turning vehicle without undue encroachment of the vehicle on the adjacent lane. A left turn from the major divided highway can be made without any encroachment.

While entering the divided highway from a left turn, the 3-S2-4 vehicle will encroach on the adjacent lane about 4 ft, but this can be minimized by swinging wide at the beginning of the turn.

Figure 4. Off-tracking for a 65-ft radius.

Table 3. Derived pavement widths for turning roadways for various design vehicles.

Radius (ft)	Case 1			Case 2			Case 3		
	WB50	3-S2-4	2-S1-2-2	WB50	3-S2-4	2-S1-2-2	WB50	3-S2-4	2-S1-2-2
50	26	—[a]	32	44	—[a]	57	50	—[a]	63
75	22	34	25	36	61	43	42	67	49
100	21	29	21	34	50	37	40	56	43
150	19	24	19	29	40	32	35	46	38
200	17	21	17	27	35	29	33	41	35
300	17	19	17	25	31	27	31	37	33
400	16	18	16	24	28	25	30	34	31
500	16	17	16	24	27	25	30	33	31
Tangent	15	15	15	21	21	21	27	27	27

[a]The 3-S2-4 vehicle cannot negotiate a 50-ft radius.

Figure 5. Required sight distance along major highways.

—————— P Design Vehicle
················ SU Design Vehicle
— — — — WB-50 Design Vehicle
—·—·—·— 3-S2-4 and 2-S1-2-2
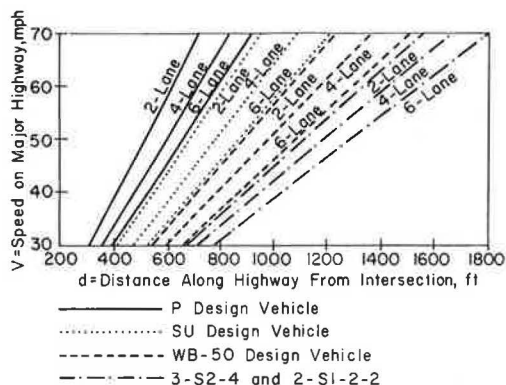
Figure 6. Minimum median openings.

Width of Median, M	Minimum Length of Median Opening, L
4'	140'
8'	136'
12'	120'
16'	112'
20'	104'
24'	96'
28'	90'
32'	84'
36'	78'
40'	72'
50'	64'
60'	56'

Figure 7. Additional cost to allow for implementation of scenario C.

Intersections — Bridges (Shoulder) — Bridges (Lane)
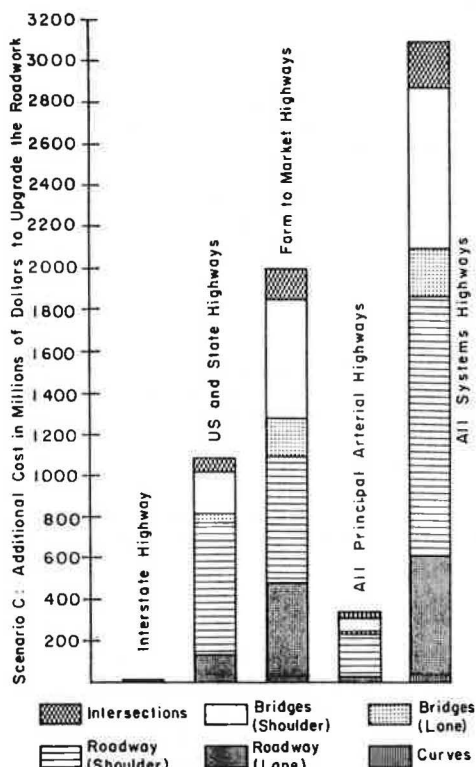Roadway (Shoulder) — Roadway (Lane) — Curves
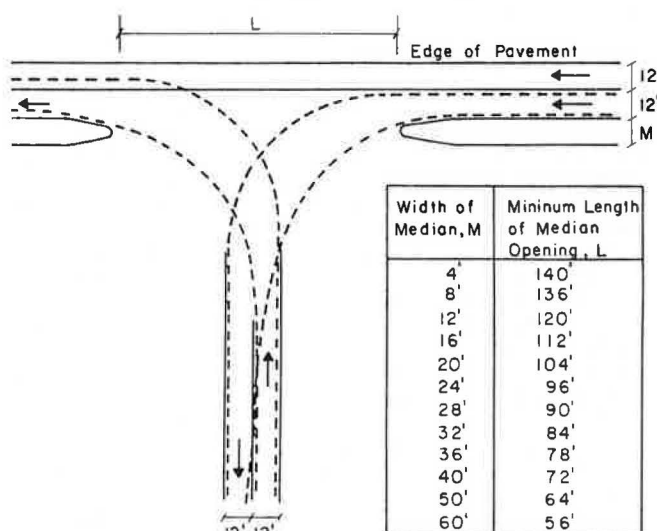
COST ESTIMATES

In order to derive cost estimates for the various elements with an acceptable interval of confidence, it was necessary to obtain information on a representative group of each road functional or system class. This information was obtained either by collecting data manually from "as-built" plans and doing a statistical test on the confidence interval obtained from the sample or by using information provided by TSDHPT.

FHWA, through the Highway Performance Monitoring System (HPMS), required a diversity of information from TSDHPT concerning the following rural functional road classes (16): Interstate highways; principal arterials; other, minor arterials; major collectors; and minor collectors. The sample sizes required for the HPMS were based on "a 90-5 precision level for the volume groups of the principal arterial system, 90-10 for the minor arterial system, and on an 80-10 precision level for the collector system" (16).

This information was made available for use in this study and proved to be invaluable. Whenever use was made of this information (hereafter referred to as the HPMS information) or of the extended form to derive a cost estimate, no statistical testing on

the adequacy of the sample size was done (this had been done by TSDHPT prior to the collecting of the required information). For all other estimates, statistical testing was done to ensure an adequate sample size.

A manual identification of the HPMS section identities was performed for the following road systems because it was necessary to distinguish between them: Interstates, U.S. and state routes, and FM roads.

Only the following items were taken into account when the cost estimates were made:

1. Widening of the existing pavement (excluding such items as grading, median barriers, curbs, guardrails, sign relocation, earthworks, additional right-of-way, culvert extension, or pavement markings) and
2. Widening of existing bridges.

Figure 7 shows a breakdown of the different element upgrading costs. Although the variation between the three scenarios is small, Figure 7 is approximately representative of all three scenarios.

SUMMARY

Assuming that one of scenarios B, C, and D is implemented, and assuming that the reasoning and assumptions made to establish the effect of these scenarios on design elements, cross-section elements, and intersection design elements are reasonable, then the following can be expected.

Stopping Sight Distance

No change from the current policy on stopping sight distance is foreseen due to the ability of the 2-S1-

2-2 and 3-S2-4 vehicle combinations to stop within the FHWA braking distances.

Passing Sight Distance

Although the implementation of any one of scenarios B, C, and D will require additional sight distance, the current pavement marking policy remains unaffected and no upgrading costs are required. This element is only applicable to two-lane, two-way operations and, if the current pavement marking practice is maintained, an adverse effect on safety can be expected.

Pavement Widening on Curves

Due to the increased off-tracking characteristics of the 3-S2-4 vehicle, additional pavement width will be needed if scenario C or D is implemented.

Critical Lengths of Grades

No adverse effect on the climbing ability of trucks is expected should scenario B, C, or D be implemented.

Lane Width

Although no change in the TSDHPT policy on lane width is expected, a 6-in increase in vehicle width will necessitate strict adherence to the current desirable standards. This will have a pronounced cost effect for either scenario B, C, or D. Although this is the existing policy and is being strictly adhered to, the cost estimates should not be considered as "over and above" that for scenario A because the same costs will be necessary if the TSDHPT road network is upgraded to the current policy.

Width of Shoulder

For shoulder width, as for lane width, no change in the current TSDHPT policy is expected, but a strict adherence to that policy is recommended. This will be very costly for some of the road classes. This cost should not be considered as over and above that for scenario A, for the same reason as that given for lane width.

Minimum Design for the Sharpest Turns

Due to increased off-tracking characteristics and decreasing turning ability, especially for the 3-S2-4 vehicle, additional pavement width will be needed in confined spaces to allow for the implementation of scenario C or D. Although it is assumed that the existing intersections on all road classes are designed to allow for the operation of scenario A, this is not so, especially for the FM roads. Estimates for all four of the intersection design elements are included because of their close relation.

Width for Turning Roadways

For width for turning roadways, as for minimum design for the sharpest turns, additional pavement width will be needed to accommodate the 3-S2-4 vehicle if either scenario C or D is implemented.

Sight Distance for At-Grade Intersections

Additional sight distance will be needed because of the increase in truck length and the additional time required to cross an intersection. No cost estimate was made to allow for scenario C or D due to the fact that insufficient information was available on the existing sight distances or the restriction on sight distance at intersections.

Median Openings

Due to the increased off-tracking characteristics of the vehicle combinations in scenarios C and D, additional pavement area will be needed to accommodate the 3-S2-4 and 2-S1-2-2 vehicles without undue encroachment on adjacent lanes.

CONCLUSIONS

Results of the Study

It can be concluded that, if any one of scenarios B, C, and D is implemented, some alterations to the Texas highway network may be necessary. There is little difference in the cost of modifying the geometrics of the highway system under these three scenarios, but other considerations, such as pavement and bridge effects, will have a bearing on the evaluation of changes in the legal size and weight of motor vehicles.

Need for Future Research

The existing procedure used by AASHTO to calculate required passing sight distance considers only the case of a passenger car overtaking a passenger car. Because of the serious safety implications, future research involving the relation between passing sight distance and passing maneuvers that involve trucks and truck lengths needs more attention.

The performance of trucks on grades (acceleration and deceleration) needs attention because the proposed AASHTO standards are based on a 300:1 weight-to-power ratio. If larger trucks are introduced, there may be a shift back toward the 400:1 ratio, and this will need future monitoring.

The questions of lane width, safety, and vehicle width also need additional attention so that a definitive standard for lane width can be established. A move toward a cost-effective design can be accomplished only if additional safety implications are known and a cost assessment is made in relation to the trade-offs of safety and lane width.

As for lane width, a more conclusive study of shoulder width, safety, and vehicle width is needed.

This study represents one element of a broad set of issues surrounding the legal size and weight of motor vehicles, principally trucks. One concern has been the cost of redesign or required modifications to the existing highway network to accommodate a range of possible vehicle types, sizes, and configurations. It is intended that this study, coupled with other ongoing studies in Texas and elsewhere, will assist in developing the necessary data on which future decisions can be based.

ACKNOWLEDGMENT

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Simulation of Highway Traffic on Two-Lane, Two-Way Rural Highways

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A summary is presented of research undertaken to develop a rural two-lane, two-way computer simulation model that could be used by the highway design practitioner to measure and evaluate traffic-flow consequences for various alternatives considered during the roadway design process. To this end, a microscopic computer simulation model written in FORTRAN was developed. For the simulation roadway, the model can incorporate vertical grades, intersecting side roads, climbing lanes, and no-passing zones. Traffic and speed data used by the model include driver desired speeds, overall posted speed for the highway, localized speed restrictions, individual main-road traffic lane volumes, side-road traffic volumes, vehicle composition in five categories, and vehicle acceleration and deceleration characteristics. Throughput statistics for use in design evaluation include distributions of space mean speed and speed change and a traffic-flow quality index. Effects on traffic flow of spot improvements in roadway geometry or traffic control can be obtained by placing windows in the program at specified locations. Output data are summarized and reported at user-specified time intervals. By using a FORTRAN level H compiler, the simulation model has been run on an IBM 370/165 computer. For an 8000-m (4.9-mile) long roadway and a real-time simulation of 3600 s, as two-way traffic volume varied from 400 to 800 vehicles/h, the actual computer time varied from 28.3 to 62.3 s. Model validation tests were performed and the results were found to be consistent with actual traffic-flow patterns. In addition, the model was applied to an actual field site, where the base condition and three redesign alternatives were simulated.

Highway engineers normally develop a number of preliminary design alternatives. These alternatives are then evaluated on the basis of environmental impact, cost, and traffic operation. The impact of an alternative on the environment is analyzed by comparing the "before highway location" situation with the "after highway location" situation. The cost study is a general economic analysis and involves an estimation of construction costs and vehicle operating costs. Traffic operation studies for preliminary design alternatives include estimation of traffic performance resulting from vehicle-roadway interactions. Due to its complexity and its often random nature, traffic flow on highways cannot be characterized in a straightforward manner. The highway engineer resorts to empirical relations based on real-world observations. Even though these relations provide a general idea of the nature of traffic operations, they are not sensitive enough to detect either roadway traffic-flow interactions for any individual design alternative or the differences in these interactions between two or more alternative designs.

Since the development of large-scale, high-speed computers, engineers have had available a technique for simulating those systems that require empirical study. In 1954, the first traffic simulation model in the United States was processed on a digital computer. Since then, many computer simulation models have been developed to describe traffic flow at either the macro or micro level. None of the models developed in the past, however, is able to simulate traffic flow on a rural two-lane roadway without major restrictions on the input roadway.

The object of the research reported in this paper was to develop a computer model for microsimulation of traffic flow on two-lane, two-way highways for the roadway and traffic volumes that are normally found on this class of highway. The following functional capabilities were deemed to be desirable in the computer model:

1. The model should be able to vary the directional distribution of traffic volumes and to accom-