Methodology for Estimating Safe Operating Speeds for Heavy Trucks and Combination Vehicles on Interchange Ramps

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A number of research studies have shown the significance of considering truck and combination vehicle performance in the geometric design of interchange ramps. The greater potential these vehicles have for offtracking and loss of control as well as rollover plays an important role in determining the safe speed of a ramp. The analysis procedure described provides highway engineers with a method, first, to determine the critical speed of a ramp for such heavy vehicles. The PHASE-4 computer model is used to simulate the dynamic behavior of the vehicle for a specified ramp geometry. The complete procedure is computerized with a user friendly interface for specifying ramp parameters and built-in data sets of vehicle parameters. Then, a method to convert the critical speed to a safe operating speed for the ramp is presented. Input parameters and results for an example ramp consisting of one simple horizontal curve are included as a demonstration. The ramp is analyzed with two types of combination vehicles. The method for estimating the safe operating speed is then demonstrated by converting the critical speeds to safe operating speeds.

A number of research studies have been performed over the last 30 years that investigated vehicle performance on interchange ramps. Most of these have proceeded from a statistical base of data, and the safety significance of a given level or type of geometric feature was then determined through statistical inference, given the confidence limits of the analysis. An investigation by Ervin et al. (*1*) combined a broad base of accident data with a computer simulation of the dynamic behavior of representative tractor-semitrailer combinations. Results of this study show the significance of the consideration of truck and combination vehicle performance in the geometric design of interchange ramps.

The analysis procedure developed by the Texas Transportation Institute in conjunction with the Texas State Department of Highways and Public Transportation (SDHPT) provides the highway engineer with a method to determine speed limitations of a given ramp on the basis of the rollover potential and directional response of heavy trucks and combination vehicles. The PHASE-4 computer program (*2*) is used to simulate the dynamic behavior of the truck for the specified ramp geometry. This program was also used by Ervin et al. (*1*).

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PHASE-4 is a detailed computerized model that can accurately simulate braking and directional response of heavy trucks and combination vehicles. The program is capable of simulating trucks, tractor-semitrailers, and double and triple combinations. The program has been validated against analytical models, predecessor simulation programs, and vehicle test data acquired separately by the Texas Transportation Institute and the University of Michigan Transportation Research Institute. However, the program is primarily a research tool, requiring a large volume of input and expertise in modeling vehicle dynamics. Therefore, the PHASE-4 program was modified to determine speed limitations of heavy trucks and combination vehicles on a specified ramp geometry.

The critical speed determined by computer simulation should be converted to a safe speed limit by the application of a factor of safety. Selecting a proper factor of safety is a matter of personal preference governed by truck operating practices on ramps and any special conditions unique to a certain site. The method proposed for use by the Texas SDHPT is presented as an example.

Geometric features specifying the ramp were selected to best suit the general design practice of the Texas SDHPT and were limited to features used in most common designs. This list of ramp parameters may or may not be sufficient for other states depending on their design philosophy. Hence, additional features may be needed before the program can be used nationwide. A few additional features that can be added to improve the specification of ramp geometry are listed in the section on recommendations.

ORGANIZATION OF THE ANALYSIS PROCEDURE

The ramp analysis computer model was organized to perform the following tasks:

1. Provide the user a choice of different, easily accessible, built-in tractor-trailer vehicle data sets;
2. Read the geometric parameters specifying the ramp;
3. Determine the geometric parameters needed by the PHASE-4 program to simulate dynamic response of the chosen vehicle; and
4. Determine the critical speed of the ramp for the chosen vehicle by incrementing the speed from a user-defined lower bound and simulating the vehicle response for each speed.

BUILT-IN DATA SETS OF TRACTOR-TRAILER VEHICLE PARAMETERS

Parameters for two types of tractor-trailer vehicles are currently built into the program, for easy access to the user. When the program prompts for the type of vehicle, the user simply has to select one of the types.

The first of these two is a baseline vehicle representing a conventional five-axle tractor-semitrailer, which is loaded to the legal maximum of 80,000 lb gross combination weight, with a payload center-of-gravity (cg) height representing a medium-density freight (*1*). The normal height of the payload center of gravity in this case is 83 in. above ground. The vehicle is also defined with a common set of suspension properties representing popular levels of spring stiffness.

The second option represents a high-cg vehicle (*1*) in which the same tractor-semitrailer vehicle was chosen with

1. Payload cg height raised to 105 in. above the ground to represent a worst-case loading, which is known to occur in everyday trucking practice, and
2. Spring stiffnesses at the tandem suspensions both of the tractor and the semitrailer reduced with respect to the baseline case to represent the more compliant suspension types, which are known to be in common service.

Both of these additional features tend to increase rollover potential.

SPECIFICATION OF RAMP GEOMETRY

Design of ramps along with other roadway features of highways in the state of Texas are presently accomplished by the use of the roadway design system (RDS) (*3*). Hence, the program input structure for ramp geometry was developed to relate to RDS output as much as possible in order to ensure speedy and effortless transformation of ramp parameters.

First, the program prompts for the following parameters to fix the general layout of the ramp:

- Beginning station,
- Ending station,
- Elevation of ending station,
- Width of road,
- Number of horizontal curves,
- Number of vertical curves, and
- Number of superelevation transition sections.

Then, the horizontal alignment is to be specified for each horizontal curve by entering

- *P.C.* station,
- *P.T.* station,
- Radius (ft),
- *P.I.* angle (degrees), and
- Curve direction (to left or right).

These parameters are listed in RDS horizontal alignment output (*3*). Next, the following parameters are read in for each vertical curve to define the vertical alignment.

- Vertical *P.I.* station,
- Vertical *P.I.* elevation,
- First, vertical curve length (if asymmetrical), and
- Second vertical curve length (if asymmetrical).

Finally, superelevation information is specified with the following parameters for each superelevation transition section

- Transition station,
- Transition length,
- Super rate,
- Beginning or ending transition,
- Curving to left or right,
- Transition type (1, 2, or 3), and
- First and second vertical curve lengths, if type is 2.

Both the vertical alignment and the superelevation parameters are identical to the respective RDS input form parameters and arranged in the same order.

Figures 1–4 show the horizontal alignment, vertical alignment, and beginning and ending superelevation transition curves, respectively, for a ramp consisting of one simple horizontal curve and two vertical curves. Parameters for this ramp that are required for the analysis are listed in Tables 1–4 as an example of the program input.

RAMP ELEVATIONS AND GRADIENTS

For the simulation of dynamic response of the tractor-trailer, the PHASE-4 computer program requires ramp elevations Z and gradients dZ/dX and dZ/dY (denoted by $Z_{,X}$ and $Z_{,Y}$), at given values of X and Y inertial coordinates (see Figures 5 and 6). The term "elevation" is used for Z herein for convenience, although the positive direction of Z in PHASE-4 is downwards into the ground. Elevation Z is needed at each wheel and gradients are needed at wheels as well as axle centers (*2*). The ramp surface can be of any shape subjected to the following restrictions:

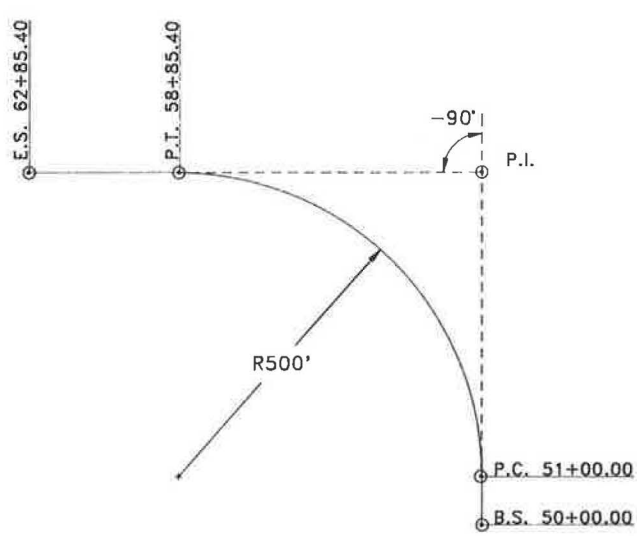

FIGURE 1 Horizontal alignment of example ramp.

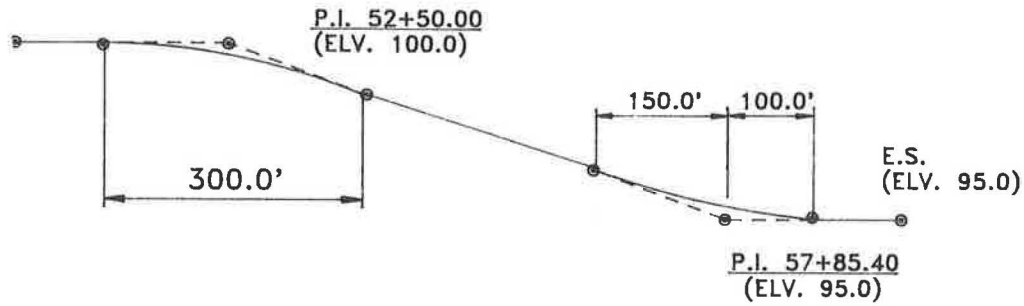

FIGURE 2 Vertical alignment of example ramp.

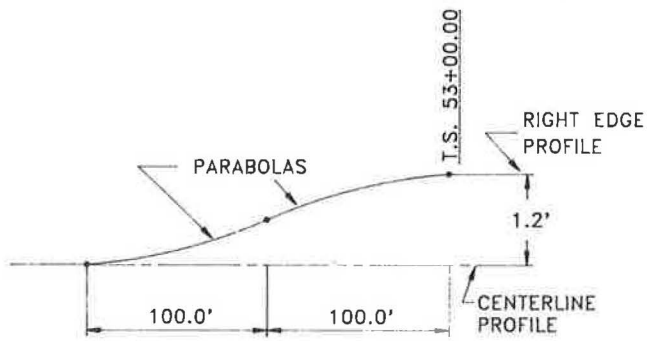

FIGURE 3 Beginning superelevation transition (Type 3) of example ramp.

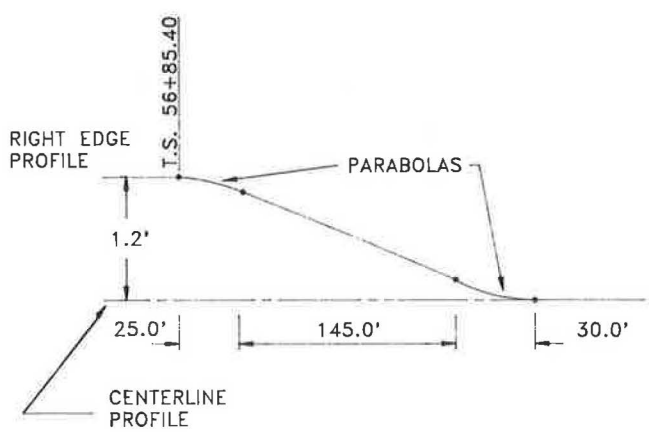

FIGURE 4 Ending superelevation transition (Type 2) of example ramp.

1. The complete vehicle train starts from a flat horizontal surface, and
2. All gradients (cross-slopes and grades) encountered by the vehicle train during the simulation remain less than about 0.1 (rise/run).

In order to facilitate the computation of ramp elevations and gradients, a curvilinear coordinate system $X'Y'$ was defined in which the X'-axis follows the ramp centerline and the Y' coordinates are measured perpendicular to the X' axis. This system is referred to herein as the "ramp coordinate system" (see Figure 5). Furthermore, the ramp is divided into (a) a set of horizontal alignment (HA) segments consisting of circular horizontal curves as well as straightline tangential portions connecting them, and (b) a set of vertical alignment (VA) segments consisting of parabolic vertical curves (both symmetric and asymmetric) as well as constant-grade sections connecting them.

For each HA segment (see Figure 5), the following are computed using the input parameters read for horizontal alignment:

1. X' coordinate at the end of the segment, X'_{hi};
2. Inertial coordinates of the end of the segment (point on the ramp centerline), X_i and Y_i;

TABLE 1 PARAMETERS SPECIFYING THE GENERAL LAYOUT OF EXAMPLE RAMP

	Description	Numerical Value
1	Beginning Station	50+00.00
2	Ending Station	62+85.40
3	Elevation of Ending Station	95.00
4	Width of the Road (ft.)	30.00
5	Number of horizontal curves in the roadway	1
6	Number of vertical curves in the roadway	2
7	Number of transition sections for superelevation	2

TABLE 2 PARAMETERS SPECIFYING HORIZONTAL ALIGNMENT OF EXAMPLE RAMP

Curve no.	P.C. Station	P.T. Station	Radius (ft.)	P.I. Angle (deg.)	Curve Direction
1	51+00.00	58+85.40	500.00	90.00	L

TABLE 3 PARAMETERS SPECIFYING VERTICAL ALIGNMENT OF EXAMPLE RAMP

Vertical Curve No.	Vertical P.I. Station	Vertical P.I. Elevation (ft.)	First Vertical Curve Length (ft.)	Second Vertical Curve Length (ft.)
1	52+50.00	100.00	300.00	0.00
2	57+85.40	95.00	150.00	100.00

TABLE 4 PARAMETERS SPECIFYING SUPERELEVATION FOR EXAMPLE RAMP

Transtn. Section No.	Transition Station	Transtn. Length (ft.)	Super Rate	B or E Curve	Curve to L or R	Type	First VCL (ft.)	Second VCL (ft.)
1	53+ .00	200.00	0.080	B	L	3		
2	56+85.40	200.00	0.080	E	L	2	25.00	30.00

Note: B or E = Beginning or Ending
L or R = Left or Right
VCL = Vertical Curve Length

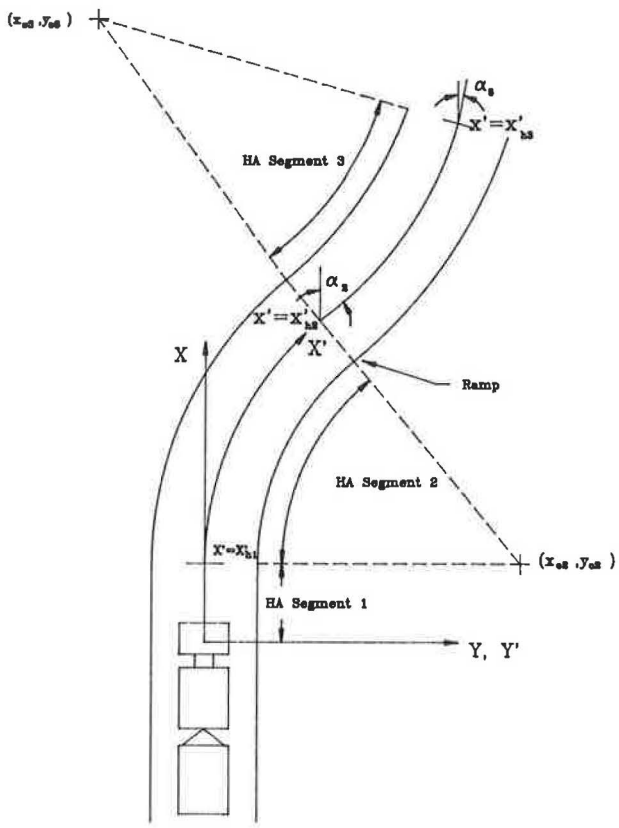

FIGURE 5 Parameters of horizontal alignment (HA) segments.

3. Inertial coordinates of the center (X_{oi}, Y_{oi}), (only for circular segments); and
4. Angle α_i between the inertial X axis and the tangent to the ramp centerline at the end of the segment (measured clockwise from X axis).

For each VA segment (see Figure 6), the following are determined using the input parameters read for vertical alignment:

1. X' coordinate at the end of the segment, X'_{vj};
2. Inertial Z coordinate at the end of the segment (on the ramp centerline), Z_j; and
3. Longitudinal gradient g_j at the end of the segment $(= -dZ/dX'$ at $X'_{vj})$.

In determining which HA and VA segment contains a certain wheel position, first the coordinate of the intersection between each HA segment centerline and the normal to it through the wheel position X'_{ci} is determined. The HA segment containing the wheel is the one satisfying the condition

$$X'_{h(i-1)} < X'_{Ci} \leq X'_{hi} \tag{1}$$

where $X'_{h(i-1)}$ is the X' coordinate at the end of the $(i-1)$th HA segment. Then, the VA segment containing the wheel is found by the condition

$$X'_{v(j-1)} < X'_C \leq X'_{vj} \tag{2}$$

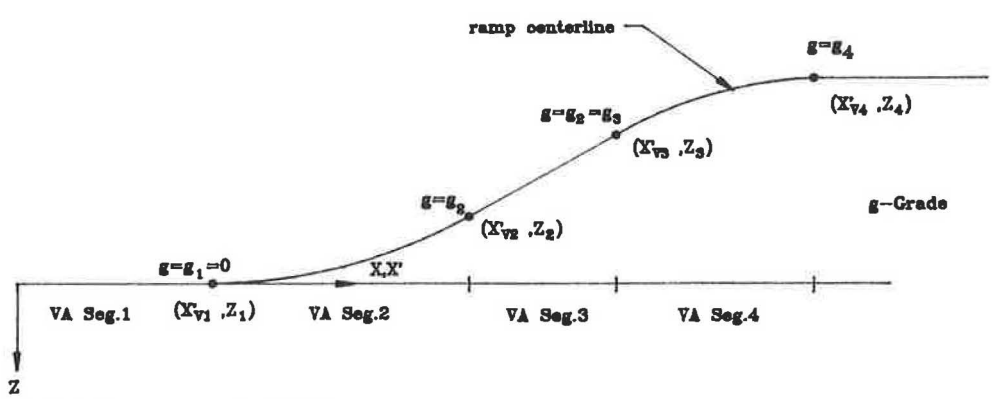

FIGURE 6 Parameters of vertical alignment (VA) segments.

where $X'_{v(j-1)}$ is the X' coordinate at the end of the $(j-1)$th VA segment, and X'_C is equal to X'_{Ci} satisfying Condition 1.

On determining the VA segment the wheel is on, elevation Z_C at the point with the ramp coordinates $(X'_C,0)$ is found as follows, depending on whether the segment is at constant grade or parabolically shaped. If $(X'_C - X'_{vj})$ and $[X'_C - X'_{v(j-1)}]$ are denoted X'_{Cvj} and $X'_{Cv(j-1)}$, respectively, for (a) a constant-grade segment,

$$Z_C = Z_{j-1} - X'_{Cv(j-1)} g_j \tag{3}$$

(b) a symmetric parabolic curve (*4*),

$$Z_c = Z_{j-1} - X'_{Cv(j-1)} \left[g_{j-1} + \frac{(g_j - g_{j-1}) X'_{Cv(j-1)}}{2L_{vj}} \right] \tag{4}$$

and (c) an asymmetric parabolic curve (*4*),

$$Z_c = Z_{j-1} - X'_{Cv(j-1)} \left[g_{j-1} + \frac{(g_j - g_{j-1}) X'_{Cv(j-1)} L_{2vj}}{2L_{vj} L_{1vj}} \right] \tag{5}$$

for $X'_{Cv(j-1)} \le L_{1vj}$, and

$$Z_c = Z_j - X'_{Cvj} \left[g + \frac{(g_j - g_{j-1}) X'_{Cvj} L_{1vj}}{2L_{vj} L_{2vj}} \right] \tag{6}$$

for $X'_{Cv(j-1)} > L_{1vj}$,

where

L_{vj} = vertical curve length,
L_{1vj} = first vertical curve length for an asymmetric curve, and
L_{2vj} = second vertical curve length for an asymmetric curve.

The gradient dZ/dX' at $(X'_C,0)$ is found by taking the derivative of the Equations 3, 4, 5, or 6 with respect to X'_C.

Next, it is determined whether the wheel is on a (a) superelevation transition, (b) superelevated section, or (c) nonsuperelevated section. If X'_c corresponding to the wheel position satisfies the condition

$$X'_{sk} - L_{sk} < X'_C \le X'_{sk} \tag{7}$$

where L_{sk} and X'_{sk} are the length and X' coordinate at the end of the kth superelevation transition, respectively, then the wheel is on the kth superelevation transition. If X'_C satisfies the condition

$$X'_{sk} < X'_C \le X'_{s(k+1)} - L_{s(k+1)} \tag{8}$$

the wheel is on a superelevated section or a nonsuperelevated section depending on whether the kth transition is a beginning or an ending transition, respectively.

If the wheel is on a superelevation transition, cross slope dZ/dY' and gradient dZ/dX' (denoted by $Z_{,Y'}$ and $Z_{,X'}$, respectively) at the wheel are determined by the use of expressions presented in Table 5, depending on the type of transition (see Figure 7) and whether it is a beginning or an ending transition. Expressions for transition Types 2 and 3 were derived with the use of the formulas for reverse parabolic curves (*4*). For a superelevated section, the cross slope is equal to the superelevation, and the gradient is the same as that at the ramp centerline. If the section is not superelevated, the cross slope is zero and the gradient is equal to that at the ramp centerline.

Elevation Z at the wheel is then determined from the expression

$$Z = Z_C + Y' Z_{,Y'} \tag{9}$$

and the gradients $Z_{,X}$ and $Z_{,Y}$ are

$$Z_{,X} = Z_{,X'} \cos \alpha_C - Z_{,Y'} \sin \alpha_C$$
$$Z_{,Y} = Z_{,X'} \sin \alpha_C - Z_{,Y'} \cos \alpha_C \tag{10}$$

TABLE 5 EXPRESSIONS USED TO DETERMINE THE GRADES AND CROSS SLOPES OF SUPERELEVATION TRANSITION SECTIONS

transition type	beginning transition	ending transition
1	$Z_{,X'} = Z_{C,X'} + eY'/L_s$ $Z_{,Y'} = eX'_s/L_s$	$Z_{,X'} = Z_{C,X'} - eY'/L_s$ $Z_{,Y'} = e(1 - X'_s/L_s)$
2	$g_{,Y'} = -e/[L_s - (L_1+L_2)/2]$	$g_{,Y'} = e/[L_s - (L_1+L_2)/2]$
	(a) $X'_s \le L_1$ $Z_{,X'} = Z_{C,X'} - X'_s Y' g_{,Y'}/L_1$ $Z_{,Y'} = -g_{,Y'} X'^2_s/(2L_1)$	(a) $X'_s \le L_1$ $Z_{,X'} = Z_{C,X'} - X'_s Y' g_{,Y'}/L_1$ $Z_{,Y'} = e - g_{,Y'} X'^2_s/(2L_1)$
	(b) $L_1 < X'_s \le L_s - L_2$ $Z_{,X'} = Z_{C,X'} - Y' g_{,Y'}$ $Z_{,Y'} = -g_{,Y'}(X'_s - L_1/2)$	(b) $L_1 < X'_s \le L_s - L_2$ $Z_{,X'} = Z_{C,X'} - Y' g_{,Y'}$ $Z_{,Y'} = e - g_{,Y'}(X'_s - L_1/2)$
	(c) $X'_s > L_s - L_2$ $Z_{,X'} = Z_{C,X'} - Y' g_{,Y'} X'_{sL}/L_2$ $Z_{,Y'} = e - g_{,Y'}[L_2 - X'_{sL} - (L_2 - X'_{sL})^2/(2L_2)]$ $g_{,Y'} = 2e/L_s$	(c) $X'_s > L_s - L_2$ $Z_{,X'} = Z_{C,X'} - Y' g_{,Y'} X'_{sL}/L_2$ $Z_{,Y'} = -g_{,Y'}[L_2 - X'_{sL} - (L_2 - X'_{sL})^2/(2L_2)]$ $g_{,Y'} = -2e/L_s$
3	(a) $X'_s \le L_s/2$ same as for type 2(a) with $L_1 = L_s/2$	(a) $X'_s \le L_s/2$ same as for type 2(a) with $L_1 = L_s/2$
	(b) $X'_s > L_s/2$ same as for type 2(c) with $L_2 = L_s/2$	(b) $X'_s > L_s/2$ same as for type 2(c) with $L_2 = L_s/2$

Note:
L_s = transition length
e = rate of superelevation
$X'_s = X'_C - X'_{s(k-1)}$
$X'_{sL} = X'_{sk} - X'_C$
L_1 = first vertical curve length
L_2 = second vertical curve length

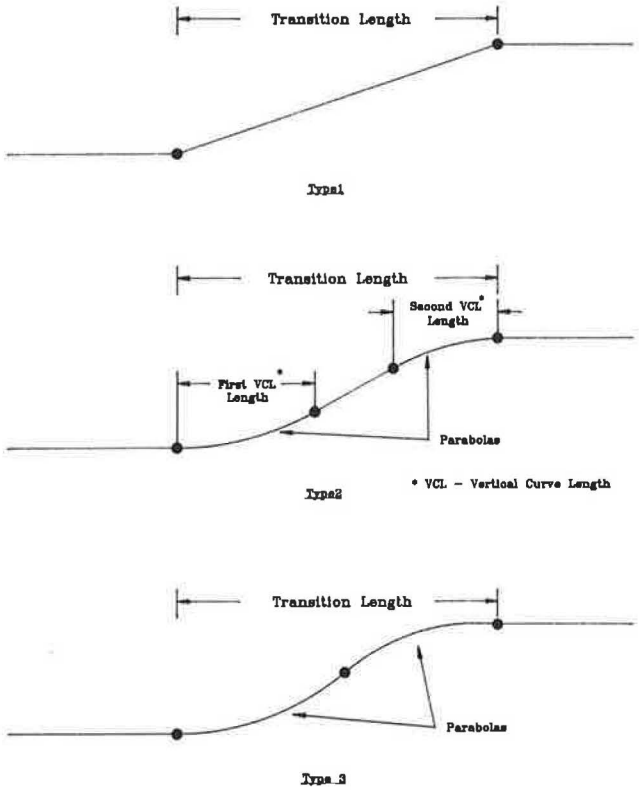

FIGURE 7 Types of superelevation transitions.

where α_C is the angle between the tangent to the ramp centerline at X'_C and the inertial X axis. If only the gradients are required (i.e., at axle centers), the step of computing Z by Equation 9 is bypassed.

PARAMETERS NEEDED FOR TRAJECTORY CONTROL

In order to control the trajectory of the tractor-trailer, the PHASE-4 program uses a path-follower, closed-loop driver model (2). For these computations, the program requires the deviation Y_p (see Figure 8) of the ramp centerline from a given point on the line through the origin of inertial coordinate system X, Y and parallel to the vehicle heading direction. If this point is X_p distance away from the origin of the X, Y coordinate system, X_p and Y_p can be expressed in terms of X, Y, and the yaw angle ψ as

$$X_p = X \cos \psi + Y \sin \psi$$

$$Y_p = -X \sin \psi + Y \cos \psi \tag{11}$$

In order to find Y_p for a given X_p, first the deviation Y_{pi} to each segment is determined. Initially, a straight line segment is considered unbounded and the full circle is considered for a circular segment. Hence, for a straight line segment,

$$Y_{pi} = \frac{(Y_{hi} - m_i X_{hi}) - X_p (\sin \psi - m_i \cos \psi)}{(\cos \psi + m_i \sin \psi)} \tag{12}$$

and for a circular segment,

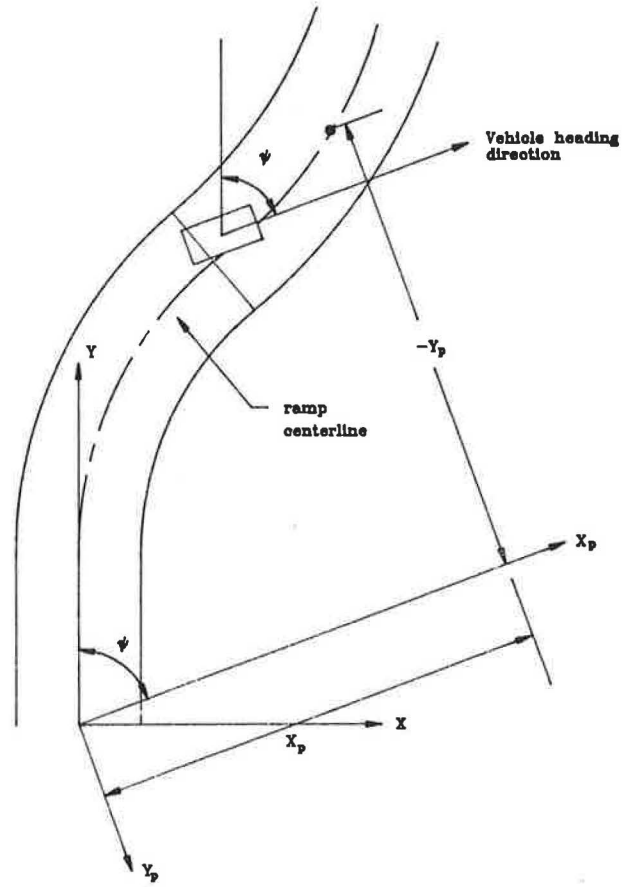

FIGURE 8 Parameters needed for trajectory control.

$$Y_{pi} = \pm\sqrt{R_i^2 - [X_p - (X_{oi} \cos \psi + Y_{oi} \sin \psi)]^2} - X_{oi} \sin \psi + Y_{oi} \cos \psi \tag{13}$$

where R_i is the radius of curvature of the segment. Then it is checked whether the point on the segment centerline represented by the values X_p and Y_{pi} is within the bounds of that segment. In case of a circular segment, there are two such points given by the two values of Equation 13. If it is within bounds, the required value of Y_p is given by Y_{pi}. All segments are checked until a value for Y_p is found.

CRITICAL SPEED

Two types of hazardous situations are considered in computing the critical speed of a given ramp for a given tractor-trailer type: rollover and wheels running off the ramp. The critical speed for rollover is defined as the lowest speed at which a wheel would lift off the ramp surface. In the latter case, the critical speed is the lowest speed at which a wheel runs off the ramp. Overall critical speed is the minimum of these two speeds. In order to determine critical speed, first the tractor-trailer dynamic response is simulated starting with a given lower-bound speed. If the simulation is completed without any wheels lifting off the ground or running off the ramp, the simulation is repeated for 5-mph speed increments until a wheel is predicted to do so. On encountering a speed at which

a wheel lifts off or runs off the ramp, the simulation is repeated with 1-mph increments starting from the previous 5-mph increment. The critical speed found in this manner is accurate to 1 mph. The vehicle is assumed to be in a coast mode during the simulation. Hence, the actual speed at which a wheel is predicted to lift off or run off the ramp is slightly different from the starting speed. This actual speed rather than the starting value is considered as the critical speed.

In order to give an indication of how close the vehicle came to each critical condition at each speed increment, a rollover factor and an offtrack factor are calculated.

Rollover Factor

At each time step during the simulation, the wheel with the minimum normal force is found. Then, the ratio of this force to the steady-state tire normal force is determined. The rollover factor is the minimum value of this ratio over the duration of the simulation for each speed. If offtracking is predicted, the duration is from the beginning to the point where the wheel runs off the road. When this factor equals zero, the corresponding wheel lifts off the ground.

Offtrack Factor

At each time step during the simulation, the wheel farthest from the ramp centerline is found. Then the ratio of the offset of this wheel from the centerline to the half-width of the ramp is determined. The offtrack factor is the maximum value of this ratio over the duration of the simulation for each speed. If a wheel lift-off is predicted, the duration is from the beginning to the point where the wheel lifts off the ground. When this factor equals 1, the corresponding wheel runs off the ramp.

The rollover factor and the offtrack factor for each speed, the wheel that lifted off the ground or ran off the ramp, the inertial coordinates of the wheel position, and the time at which it occurs are listed by the ramp analysis computer program as the table of stability factors. Tables 6 and 7 present stability factors for the baseline and high-cg vehicles, respectively, for the example ramp shown in Figures 1–4.

TABLE 6 STABILITY FACTORS ON EXAMPLE RAMP FOR BASELINE VEHICLE

Speed (mph)	Roll-over Factor	Off-track Factor	Vehicle Unit	Suspen-sion	Axle	Side	X coord. (ft.)	Y coord. (ft.)	Time (sec.)
45.0	.400		tractor	Rear	Second	Left	213.98	-17.61	3.4451
		.401	tractor	Front		Right	606.01	-553.82	14.0841
50.0	.280		tractor	Rear	Second	Left	231.01	-21.70	3.3426
		.439	tractor	Front		Right	606.59	-554.83	12.8194
55.0	.053		tractor	Rear	Second	Left	249.45	-26.68	3.2801
		.449	trailer	Rear	Second	Right	606.74	-533.45	12.1370
56.0	.008		tractor	Rear	Second	Left	320.11	-53.93	4.1626
		.466	trailer	Rear	Second	Right	606.99	-528.01	11.8820
57.0	0.0*		tractor	Rear	Second	Left	232.90	-22.09	2.9575
		.420	tractor	Front		Left	153.66	-9.23	1.8175

* Rear suspension, Second axle, Left tire of the tractor comes off the road at X = 232.90 ft.; Y = -22.09 ft.; U = 56.48 mph & T = 2.9575 s.

TABLE 7 STABILITY FACTORS ON EXAMPLE RAMP FOR HIGH-cg VEHICLE

Speed (mph)	Roll-over Factor	Off-track Factor	Vehicle Unit	Suspen-sion	Axle	Side	X coord. (ft.)	Y coord. (ft.)	Time (sec.)
45.0	.065		tractor	Rear	Second	Left	237.22	-23.26	3.8126
		.370	tractor	Front		Left	149.72	-8.06	2.2400
46.0	.013		tractor	Rear	Second	Left	230.44	-21.43	3.6251
		.375	tractor	Front		Left	150.29	-8.18	2.2000
47.0	0.0*		tractor	Rear	Second	Left	219.29	-18.72	3.3801
		.379	tractor	Front		Left	150.57	-8.28	2.1575

* Rear suspension, Second axle, Left tire of the tractor comes off the road at X = 219.29 ft.; Y = -18.72 ft.; U = 46.76 mph & T = 2.1575 s.

ESTIMATION OF SAFE OPERATING SPEED

Safe operating speed V_S for a heavy truck or a combination vehicle on a certain interchange ramp is the lesser of (a) the critical speed found by the PHASE-4 simulation divided by a factor of safety F, or (b) the design speed V_D of the ramp determined in accordance with the AASHTO Green Book (*5*).

First, factor of safety F is assumed to calculate a preliminary safe speed V_{S1} as

$$V_{S1} = V_{CR}/F \tag{14}$$

where V_{CR} is the critical speed computed by the simulation. Side friction factor f given in Figure III–5 of the Green Book (*5*) corresponding to V_{S1} is then found. A second speed V_{S2} is calculated as in the Green Book from the expression

$$V_{S2} = \sqrt{15R(e + f)} \tag{15}$$

where e is the maximum superelevation on the ramp and R is the minimum radius of curvature of the ramp (ft). If $V_{S1} \leq V_{S2}$, it can be shown that V_{S1} is also less than the design speed V_D of the ramp determined according to the Green Book (*5*). Hence, safe operating speed V_S of the ramp is V_{S1}. However, if $V_{S1} > V_{S2}$, the safe speed is equal to the AASHTO design speed V_D of the ramp because it can be shown that $V_{S1} > V_D$.

Because of limited information, selection of F in Equation 14 must be based for the most part on intuition and engineering judgment. Little is known about the manner in which drivers of large trucks negotiate ramps, e.g., how well they track the curvature and how well they adhere to advisory speeds. Further research is needed in this area. For the present problem, a value of 2 was selected for F.

Table 8 presents the summary of safe operating speed calculations for the example ramp shown in Figures 1–4, considering both baseline and high-cg vehicles. In this example,

TABLE 8 SUMMARY OF THE CONVERSION OF CRITICAL SPEED TO SAFE OPERATING SPEED FOR EXAMPLE RAMP

Parameter	"Baseline" Vehicle	"High C.G." Vehicle
V_{CR}	56	46
V_{S1} [a]	28	23
f [b]	0.176	0.192
e	0.08	0.08
R	500	500
V_{S2} [c]	43.8	45.2
safe operating speed	28	23
AASHTO design speed	41.5	41.5

[a] From equation 14 with F = 2.0.

[b] From Figure III-5 of reference 5 with speed = V_{S1}.

[c] From equation 15.

V_{S1} is less than V_{S2} for both vehicles and therefore becomes the safe operating speed. The design speed according to the Green Book (*5*) is also presented in Table 8, and it is considerably larger than the estimated safe speeds. The safe operating speed calculated for the high-cg vehicle is about 5 mph lower than that for the baseline vehicle because of the greater rollover potential of the high-cg vehicle. This example underscores the need to consider large trucks in ramp design and in determining safe operating speeds.

Friction coefficients used in the simulations (i.e., in the built-in data sets) represent dry pavement conditions. As indicated in the example (see Tables 6, 7), the critical speed on dry pavements is governed by rollover as opposed to offtracking. Although wet conditions were not studied, the critical speed for trucks will generally not be governed by offtracking on a wet pavement. Design trucks overturned at a lateral acceleration between 0.25 and 0.45. Most wet pavements have an available side friction coefficient in excess of 0.3.

CONCLUSIONS AND RECOMMENDATIONS

The importance of considering truck and combination vehicle performance in the geometric design of interchange ramps has been shown by recent studies. The simplified, user friendly procedure developed using the PHASE-4 computer model (*2*) provides the highway engineer with a valuable method for estimating critical ramp speeds for heavy vehicles. A safe operating speed can then be computed by applying an appropriate factor of safety.

Further research should include improving the ramp specification of the ramp analysis computer model with additional geometric features, increasing the number of built-in tractor-trailer parameter sets to suit the nationwide trucking practice, incorporating an option to analyze the ramp under wet conditions, better quantifying the factor of safety applied to the critical speed to find the safe operating speed, and selection of speed limits for ramps with a mixture of vehicles.

Some additional geometric features to improve ramp specification are (a) transition spirals in horizontal alignment, (b) capability of specifying ramp geometry with stations numbered opposite to the traffic flow, and (c) specifying special ramp features with templates at selected stations [similar to RDS template form (*3*)].

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