Ramp/Mainline Speed Relationships and Design Considerations

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Great care must be exercised in selecting the design speed of ramps, particularly off-ramps from high-speed freeways, to ensure that drivers slow down from the mainline freeway speed to the design speed of the ramp. The AASHTO Green Book provides guidance on the selection of ramp design speeds that are appropriate for specified mainline highway design speeds. The process of selecting an appropriate design speed for a ramp, the operational and safety problems that may arise from selecting a ramp design speed that is too low, and the geometric design and traffic control techniques that may be used to alleviate such problems are addressed. Where problems are anticipated, geometric design changes may be appropriate to increase the ramp design speed or the deceleration distance available to drivers. Traffic control devices, including advisory speed signing, may be used to communicate to drivers the need to reduce speed. Further evaluation of the effectiveness of speed-control measures is needed.

One of the difficult challenges facing designers of freeway interchanges is the development of ramp geometrics that are consistent with the mainline freeway speeds and geometrics. If a ramp has horizontal curves with design speeds much lower than the mainline freeway design speed, operational and safety problems may be created for vehicles traversing the ramp. Designers would often like to use relatively high ramp design speeds, but ramp geometrics are often strongly influenced by physical constraints in the interchange area. It may be especially difficult in a rehabilitation situation to identify feasible methods to increase the radius of a ramp curve at reasonable cost without the need for major realignment of other interchange elements. Similar issues arise in the design of ramps on arterials and collectors, although arterials and collectors often have lower speeds than freeways. The issues inherent in selection of appropriate ramp design speeds and geometrics to avoid interchange operational and safety problems are reviewed.

GEOMETRIC DESIGN POLICIES FOR FREEWAY RAMPS

The AASHTO Green Book (*1*) presents guidelines for the selection of the design speed for a ramp as related to the design speed of the mainline highway. The guidelines are summarized in Table X-1 of the Green Book, which is reproduced as Table 1.

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AASHTO policy states that ramp speeds should, desirably, approximate the low-volume running speeds of the intersecting highways. Since such high design speeds for ramps are not always practicable, lower design speeds may be necessary. Table 1 presents three speed ranges for ramp design speed—identified in the table as the upper, medium, and low ranges. The AASHTO policy also states that only the design speeds over 50 mph in Table 1 are applicable to freeway and expressway exits (i.e., off-ramps).

The upper-range values for ramp design speeds in Table 1 are generally 5 to 10 mph less than the design speed of the mainline highway. The middle-range values are generally 15 to 20 mph less than the mainline highway design speed. The lower-range values are generally 25 to 35 mph less than the mainline highway design speed. The AASHTO policy states that ramp design speeds should not be less than the lower-range design speeds given in Table 1.

The ramp design speeds in the table apply to the sharpest or controlling ramp curve, usually on the ramp proper. The geometrics of ramp curves—as a function of design speed and maximum superelevation rate—are determined in accordance with AASHTO policy that applies to all horizontal curves, presented in Chapter III of the Green Book. For freeway ramps, the horizontal curve design criteria should be determined by reference to Table III-6 of the Green Book (see the next section for a discussion of horizontal curve design on arterials and collectors). Some elements of ramp curve design, such as superelevation runoff distances, are governed by the design guidelines for turning roadways in Chapter IX of the Green Book.

The following guidelines are given in Chapter X of the Green Book for selection of design speeds on specific types of ramps:

- For ramps that serve right-turn movements, upper-range design speeds are often attainable and the lower range is usually practicable. For diamond interchange ramps, a design speed in the middle range is usually practical.
- For loop ramps that serve left-turn movements, the upper-range values are not attainable. Loop ramps with design speeds above 30 mph require large areas of land and are, therefore, more costly to construct and maintain and require left-turning drivers to travel increased distances. The large land area requirements may make loop ramps with high design speeds infeasible in developed areas.
- For semidirect connection ramps, ramp design speeds in the upper and middle ranges can generally be used. Design speeds less than 30 mph should not be used.

TABLE 1 Guide Values for Ramp Design Speed as Related to Highway Design Speed (*1*)

Highway design speed (mph)	30	40	50	60	65	70
Ramp design speed (mph)						
Upper range	25	35	45	50	55	60
Middle range	20	30	35	45	45	50
Lower range	15	20	25	30	30	35
Corresponding minimum radius (ft)	See Table III-6					

- For direct connection ramps, ramp design speeds in the middle and upper ranges should also be used. Ramp design speeds should generally be 40 mph or more and should in no case be less than 35 mph.

Ramps that connect highways with different design speeds should be designed to provide a smooth speed transition between these highways. In general, the highway with the higher design speed should be the control in selecting the design speed for the ramp (i.e., the higher of the two highway design speeds should be used to enter Table 1). However, the transition to or from the highway with the lower design speed also needs to be considered. On an exit ramp from a high-speed freeway to a lower-speed arterial, the design speed of the ramp proper (including the sharpest or controlling curve) should be determined from the freeway design speed using Table 1. It may also be appropriate to use a lower design speed for the final curve before the arterial ramp terminal to assist in creating an appropriate speed transition. On an entrance ramp from a lower-speed arterial to a high-speed freeway, the first curve that the driver encounters on the ramp after leaving the arterial may be based on the arterial design speed. However, the design speed of most of the ramp—and especially the final curve before entering the freeway—should be determined from the freeway design speed using Table 1.

The design speeds in Table 1 do not apply to ramp terminals, which should be properly transitioned and provided with speed-change facilities adequate for the roadway speeds involved. Speed-change lanes are usually provided at free-flow ramp terminals. Speed-change lanes are classified in AASHTO policy as auxiliary lanes and are more commonly referred to as acceleration and deceleration lanes. Ramp terminals that do not have free-flow connections are referred to as at-grade ramp terminals. Such terminals function as at-grade intersections and are typically found at the junction of a ramp with an arterial or collector facility. A complete explanation of AASHTO policies concerning the design of at-grade ramp terminals is provided by Plummer et al. in this Record.

GEOMETRIC DESIGN CRITERIA FOR RAMPS ON ARTERIALS AND COLLECTORS

The ramp design speeds given in Table 1 for the upper, middle, and lower ranges of ramp design speed as a function of the mainline highway design speed are applicable to ramps on arterials and collectors as well as freeway ramps. For arterials and collectors, Table 1 is entered using the design speed of the arterial or collector as the highway design speed. Thus, the main body of Table 1 is not used any differently on arterials and collectors than on freeways, except that urban arterials and collectors are likely to involve design speeds below 50 mph, which are not used on freeways.

However, the final line of Table 1, which indicates the minimum radii for horizontal curve design, does not fully explain the AASHTO policy as it applies to the design of horizontal curves on arterial and collector ramps and turning roadways. The table implies that the horizontal curve design criteria in Table III-6 apply to all horizontal curves on ramps. Whereas this is clearly true for freeway ramps, the table should make clear that the AASHTO policy provides two sets of design criteria for horizontal curves on arterials and collectors: (*a*) the high-speed design criteria based on Table III-6 of the Green Book, which are used on freeways and higher-speed arterials and collectors, and (*b*) the low-speed design criteria based on Table III-17 of the Green Book, which are used on lower-speed arterials and collectors. The low-speed design criteria for horizontal curves are based on higher net lateral acceleration or *f*-values than the high-speed criteria. The "high-speed" and "low-speed" horizontal curve design criteria should not be confused with the high, middle, and low ranges of ramp design speeds in Table 1.

AASHTO policy states that the low-speed design criteria for horizontal curves are applicable to arterials with design speeds of 30 mph or less and collectors with design speeds of 40 mph or less. State highway agencies operate few roads of this type, and those roads seldom have ramps. However, it is more common for local agencies to design ramps or turning roadways under these low-speed conditions. Since the AASHTO Green Book is used by many local agencies, it would be desirable if Table 1 (i.e., Table X-1 of the Green Book) made clear that the low-speed horizontal curve design criteria may be used on some ramps.

The text that accompanies Table X-1 (see pp. 965–966 of the 1990 Green Book) states that the maximum superelevation rates for ramps are those given in Table IX-12 of the Green Book. (As discussed above, this is an apparent contradiction of Table X-1.) The superelevation rates in Table IX-12 are based directly on the low-speed horizontal curve design criteria in Table III-17 of the Green Book. Thus, the Green Book appears to sanction the use of low-speed horizontal curve design for all horizontal curves on ramps for which the ramp design speed is 40 mph or less. However, the authors of this paper do not believe that this is what was intended.

Figure 1 shows what the authors believe was intended as AASHTO policy. The figure indicates that the choice between horizontal curve design criteria based on high-speed design (Table III-6) and low-speed design (Table III-17) for a specific ramp on a specific highway should be based on the highway functional classification and highway design speed (not the ramp design speed). Once either the high- or low-speed design criteria have been selected, the ramp design speed should be used in designing the horizontal curve in accordance with either Table III-6 or Table III-17.

Figure 1 indicates that all horizontal curves on freeway ramps should be designed in accordance with the high-speed horizontal curve design criteria in Table III-6 of the Green Book. For arterials, the low-speed design criteria would apply to situations

Functional Classification	Highway Design Speed (mph) 30	35	40	45	50	55	60	65	70
Freeway or Expressway	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6
Arterial	Use Table III-17	Minimum: Use Table III-17; Desirable: Use Table III-6	Minimum: Use Table III-17; Desirable: Use Table III-6	Minimum: Use Table III-17; Desirable: Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6
Collector	Use Table III-17	Use Table III-17	Minimum: Use Table III-17; Desirable: Use Table III-6	Minimum: Use Table III-17; Desirable: Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6	Use Table III-6

FIGURE 1 AASHTO horizontal curve design criteria for ramps as a function of the design speed and functional classification of the mainline highway.

in which the arterial design speed (and thus the ramp design speed) was 30 mph or less. The high-speed design criteria in Table III-6 would apply to arterials with design speeds of 50 mph or more. For arterials with highway design speeds of 35, 40, and 45 mph, the low-speed horizontal design criteria in Table III-17 would be minimum acceptable values, and the high-speed criteria in Table III-6 would be desirable values for ramp design. A similar interpretation would apply to ramps and turning roadways on collectors, except that low-speed design for collectors applies to highway design speeds of 40 mph or less.

In summary, Table X-1 of the Green Book and its accompanying discussion do not clearly state the AASHTO policy concerning the design of horizontal curves on ramps. The table and its accompanying text need clarification. Figure 1 is our attempt to present what we think was intended by AASHTO.

OPERATIONAL AND SAFETY CONSIDERATIONS IN SELECTING RAMP DESIGN SPEED

Clearly, ramp design speeds are often dictated by physical design constraints. Designers would often prefer to use ramp design speeds higher than those they find it necessary to use. The following discussion examines the situations in which reduced ramp design speeds may lead to operational or safety problems and possible methods of avoiding such problems.

Over the years, highway agencies have found some ramp curves with concentrations of run-off-road and rollover accidents, particularly accidents involving trucks. Such problems are more prevalent on off-ramps than on-ramps because of the higher travel speeds of vehicles exiting from a freeway; speeds of vehicles entering a freeway from the arterial street system are likely to be lower. Both operational experience and a recent analysis of horizontal curve design criteria suggest that these safety problems are more related to vehicles traveling faster than the design speed than to any basic flaw in the AASHTO horizontal curve design policy.

A recent analysis by Harwood et al. (*2*) assessed the AASHTO high-speed design policy for horizontal curves as presented in Table III-6 of the Green Book. The study concluded that the current AASHTO design policy provides an adequate margin of safety for both passenger cars and trucks on horizontal curves as long as the design assumptions on which the AASHTO policy is based are not violated. In particular, it is important that trucks not travel faster than the design speed on curves with relatively low design speeds. Harwood et al. concluded that the current AASHTO horizontal curve design policy was adequate for both passenger cars and trucks traveling at or below the design speed of the highway. However, in some cases, a vehicle with very poor tires on a poor wet pavement could skid, or a vehicle with a worst-case rollover threshold could roll over, at only a few miles per hour above the design speed. Furthermore, the research found that skidding or rollover was most likely to be critical for curves with lower design speeds, such as ramps.

Table 2 summarizes vehicle speeds at impending skid and impending rollover for several critical scenarios. The table represents the following conditions:

- A minimum-radius AASHTO curve with a maximum superelevation rate of 0.08 ft/ft designed in accordance with Table III-6 of the Green Book,
- Wet-pavement friction levels equivalent to those assumed in AASHTO stopping sight policy,
- A passenger car rollover threshold equal to 1.2 *g*, and
- A truck rollover threshold of 0.30 *g*, which is representative of the worst-case trucks currently on the road.

TABLE 2 Vehicle Speed at Impending Skid and Rollover Under Critical Conditions (*2*)

		Passenger car speed (mph)		Truck speed (mph)	
Design speed (mph)	Maximum e	At impending skid (wet)	At impending rollover	At impending skid (wet)	At impending rollover
20	0.08	32.5	45.3	26.8	24.7
30	0.08	47.1	69.6	39.0	37.9
40	0.08	61.8	94.8	51.3	51.6
50	0.08	76.8	121.1	63.9	66.0
60	0.08	95.2	152.2	79.3	82.9
70	0.08	118.0	191.5	98.5	104.3

Table 2 indicates that the most critical design conditions for horizontal curves occur at the lower design speeds, particularly at design speeds of 20 to 30 mph. Under the assumed conditions (an extremely rare combination of worst-case conditions), a truck on a curve with a 20-mph design speed can roll over when traveling at about 25 mph and may skid off the road under critical wet-pavement conditions at about 27 mph. A truck on a curve with a design speed of 30 mph could roll over when traveling at a speed of about 38 mph and could skid off the road at 30 mph. It is important to note in Table 2 that passenger cars are less critical than trucks and that higher design speeds are less critical than lower design speeds.

Table 2 indicates the importance of ensuring that ramps have realistic design speeds. In other words, there is no problem in using a 30-mph design speed on a ramp, but we must be able to ensure that drivers—and, in particular, truck drivers—travel at or below 30 mph. However, safety problems may arise if designs are overly optimistic about how much speed reduction can be expected from drivers on an exit ramp from a high-speed freeway.

The study by Harwood et al. (*2*) did not address the AASHTO low-speed design criteria for horizontal curves presented in Table III-17 of the Green Book. These criteria are used only on turning roadways at ramps or intersections on low-speed arterials and collectors. Two key factors distinguish the low- and high-speed designs. First, horizontal curves designed in accordance with the low-speed criteria are based on higher *f*-values, so they may be more critical for skidding or rollover, especially by trucks. On the other hand, such curves are found only on lower-speed roadways, where it is less likely that vehicles will attempt to traverse the ramp at speeds substantially higher than the design speed. The issue of safety of passenger cars and trucks on curves designed in accordance with Table III-17 of the Green Book merits further investigation to fully evaluate the implications of current policy.

CONSIDERATION OF EXPECTED OPERATING SPEED IN DESIGN

Design policy for horizontal curves should ensure an adequate margin of safety against both rollover and skidding at the travel speeds actually used by vehicles on a particular horizontal curve. In other words, it is not enough just to select a design speed for a ramp to fit the physical constraints of the site. There is also a need to determine an anticipated operating speed for the ramp. If a substantial percentage of vehicles are expected to travel faster than the design speed, there is a need to change to a higher design speed or to incorporate effective speed-control measures in the design. The following discussion presents guidelines for selecting an appropriate ramp design speed and incorporating speed-control measures where needed.

DESIGN AND OPERATIONAL GUIDELINES

The following guidelines should be considered in selecting the design speed for an off-ramp:

- Consider physical and economic constraints in selecting a tentative design speed for the ramp. Use the upper or middle range in Table 1, if possible. It is especially important to avoid the lower range of ramp design speeds on ramps that will carry substantial volumes of truck traffic.
- Identify the most critical curve on the ramp (usually, but not necessarily, the first curve downstream of the gore area).
- Develop a forecast of operating speeds at the most critical curve on the ramp on the basis of actual speeds on existing ramps with similar mainline design speeds, mainline operating speeds, and similar geometrics for the speed-change lane and the portion of the ramp prior to the most critical curve. This forecast should be based on the mainline design and operating speeds, but not on the ramp design speed.
- If the projected ramp operating speed exceeds the design speed, raise the design speed. If the design speed cannot be raised because of physical or economic constraints, consider speed-control measures such as those discussed below.

On ramps where anticipated operating speeds exceed the maximum feasible design speed, the following speed-control measures should be considered:

- Provide signing with an appropriate advisory speed for the ramp.
- Place the advisory speed signing so that drivers have sufficient length to slow down between the signing and the most critical curve.
- Increase the length of the deceleration lane or realign the ramp to increase the distance from the gore area to the most critical curve.
- Supplement the standard advisory speed signing to make the signing more conspicuous, to increase the distance from the signing to the most critical curve, and to draw the attention of truck drivers to the signing. These objectives may be accomplished by using more than one ramp speed advisory speed sign, placing ramp speed advisory signing on the mainline highway in advance of the ramp, incorporating an Exit Speed panel in the guide signing for the off-ramp, using overhead signing, using a Truck Speed advisory sign, and using flashing beacons to call attention to the advisory speed.
- Avoid designs in which the presence of a critical curve on a ramp is not obvious (e.g., where a tight horizontal curve follows a larger-radius curve).
- Consider the use of collector-distributor roads in the interchange. Collector-distributor roads introduce an intermediate speed roadway between the mainline freeway and the ramp and, thus, may assist in reducing ramp speeds. For example, collector-distributor roads could be appropriate if design constraints necessitated the use of a loop ramp with a 30-mph design speed on a 70-mph freeway.

All of these speed-control measures have been used by highway agencies, but only limited data are available to quantify their effectiveness in reducing speeds. Highway agencies have found that traffic control devices alone are not very effective in reducing vehicle speeds on ramps, but this is not well documented, and further research is needed.

SUMMARY AND CONCLUSIONS

Current AASHTO policies for freeway ramp design are adequate so long as the drivers adjust their speed to levels th are less than or equal to the design speed. Safety problems on ramp curves are most likely for vehicles traveling faster than the design speed. Under normal and even worst-case conditions, drivers who stay within the design speed are unlikely to lose control of their vehicles. However, loss of control—due to skidding tires or vehicle rollover—is more likely for vehicles that exceed the design speed. Loss of control due to skidding or rollover is more likely for trucks than for passenger cars and is more likely for ramps with lower design speeds than for higher design speeds. Further research is needed to address the potential for skidding and rollover problems on ramp curves designed in accordance with the AASHTO horizontal curve criteria for low-speed design (see Table III-17 of the Green Book).

Where ramp designers find it necessary to use a reduced design speed for a ramp (especially for design speeds within the lower design speed range in Table 1), an assessment should be made as to whether drivers are likely to slow down to the selected design speed. If operating speeds higher than the design speed are expected, the design speed of the ramp should be increased whenever possible. If no change in ramp geometrics is possible due to physical, environmental, or economic constraints (especially in a rehabilitation project at an existing interchange), appropriate speed-control measures should be considered. Further research is needed to evaluate the effectiveness of speed-control measures, such as various forms of advisory speed signing, in reducing the travel speeds of passenger cars and trucks on ramp curves and to develop more effective speed-control methods.

REFERENCES

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