Consistency of Horizontal Alignment for Different Vehicle Classes

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The objective of this study was to develop guidelines for evaluating the consistency of horizontal alignment of two-way two-lane highways. A number of simple and continuous horizontal curves were selected for this purpose. Roadway geometric design variables were obtained from design plans and field measurements. The speed of passenger cars, light trucks, and trucks was measured on tangent and horizontal curves. In the analysis, the speed reduction between tangent and curve or successive curves was considered the inconsistency indicator. The results of the analysis indicate that the degree of curve, length of vertical curve, gradient, and pavement condition have a significant effect on consistency of simple horizontal curves. For successive curves separated by a short common tangent, the speed reduction was found to be highly affected by the radii of curves. Also, the results reveal that a good consistent design can be achieved if the radii of successive curves are equal. Finally, the speeds on a common tangent between successive curves are investigated. For each type of vehicle, the results indicate that the degree of successive curves and the tangent length significantly influence the speed on the common tangent.

Roadway consistency may be defined as the degree to which highway systems are designed and constructed to avoid critical driving maneuvers, which can lead to unnecessary accident risk. A common case of geometric inconsistency is the existence of a sharp horizontal curve after a long tangent highway section. Studies indicate that half of the total accidents on two-lane rural highways may be indirectly attributed to improper speed adaptation (*1*). Most errors due to excessive speed may be related to inconsistency in horizontal alignment. Therefore, achieving geometric consistency is vital in the design and redesign of two-lane rural highways.

Although many studies have addressed the issue of roadway consistency, most have focused on the operating speed of passenger cars on simple curves. Therefore, more research is needed on highway sections with different types of curves and vehicle classes.

PURPOSE AND SCOPE OF RESEARCH

The purpose of this study is to develop guidelines that will help highway designers and decision makers evaluate and select the best alignment alternatives. The scope of this study is limited to two-way two-lane rural highways. Multi-lane highways are not included because inconsistency in the geometric design of these highways does not lead to hazardous conditions similar to those of two-lane highways. Although traffic accidents are a necessary component in the development of consistent design guidelines, the unavailability of reliable accident information precluded including this variable in the analysis.

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METHODOLOGY

Four primary rural roads were selected. The availability of geometric design plans in the Jordan Ministry of Public Works and Housing was the sole criterion for selection. The following criteria were adopted to select a roadway section:

1. The selected section should be far from the influence of intersections or any physical features that may create abnormal hazards, such as narrow bridges.
2. The pavement and shoulder widths should be constant for both tangent and curve sections.
3. The tangent and subsequent curves should have the same pavement conditions.

These criteria are recommended in several studies (*2*). Based on these criteria, 57 simple horizontal curve sections and 36 continuous horizontal curves were selected. In this study, a simple horizontal curve is a circular curve preceded by a straight tangent section with a length of at least 800 m. The curve may or may not be accompanied by transition curves. A continuous curve consists of two successive horizontal curves separated by a short tangent with a maximum length of 300 m. Lamm et al. (*3*) indicated that a tangent length of up to 260 m (850 ft) may be considered a nonindependent tangent if the traffic speed is approximately 80 km/hr (52 mph). For nonindependent tangents, the sequence between curves controls the design process.

Different methods have been proposed for evaluating horizontal alignment consistency. These methods include the graphic speed-profile technique proposed for use in the United States, the theoretical speed model used by the Swiss Highway Design Community, and a German procedure using a design parameter known as the curvature change rate (*1*). In this study, the inconsistency indicator is defined in terms of speed reduction, expressed by the 85th percentile, between tangent and curve or successive curves. The effects of geometric design and traffic variables on the speed reduction were investigated using multiple regression analysis.

DATA COLLECTION

Roadway geometric elements were obtained from the design plans of the Ministry of Public Works and Housing, Jordan. Field measurements were conducted to determine some geometric elements.

The geometric elements included degree of curve, deflection angle, length of horizontal curve, length of vertical curve within the horizontal curve, gradient, superelevation, length of spiral, and widths of the lane and shoulder.

The data also included the length of common tangent for continuous curves. as well as prevailing terrain, pavement conditions and posted speed limits. Prevailing terrain was evaluated for each section and described as mountainous, rolling, or level. Pavement conditions for each roadway section were evaluated by a panel of raters. The pavement condition was expressed in terms of Present Serviceability Rating (PSR). Posted speed limits for passenger cars and trucks were obtained from a field survey.

Free-flow speeds were determined by measuring the time required to traverse a 40-m trap length. The measurements were taken for individual vehicles with a minimum gap of 6 sec (*4*). For simple horizontal curves, the measurements were taken along the central part of the curve, and on the preceding tangent about 250 m from the start of the curve section (*2*). Different studies reported that the minimum value of free-flow speed occurred near the curve center (*5–7*).

For continuous curves, measurements were taken at three locations. Two measurements were taken along the central part of each curve and the third on the common tangent. For each location and type of vehicle, the speed distribution was found to be normal. Previous studies by Mclean (*8*) reported similar results. Therefore, the 85th percentile driver in the tangent speed distribution would be the 85th percentile driver in the curve speed distribution. Thus, the speed reduction between tangent and curve or successive curves was estimated as the difference between the 85th percentile speeds.

DEVELOPMENT OF CONSISTENCY MODELS

The information included in the data base was used to develop statistical models that express the speed reduction as a function of geometric, pavement condition, prevailing terrain, and posted speed variables. For each type of vehicle, separate analyses were conducted for simple and continuous curves. The results are presented in the following sections.

Consistency Models for Simple Curves

For each type of vehicle, a correlation matrix was established between speed reduction and the variables included in the data base. The analysis indicated that speed reduction is highly correlated with the degree of horizontal curve, length of vertical curve within horizontal curve, gradient, and pavement condition (*9*). It was also found that the radius of curve and deflection angle are highly correlated with the degree of curve. In addition, the analysis revealed that lane and shoulder widths, superelevation rate, prevailing terrain, and posted speed for passenger cars and trucks had no effect on the speed reduction. Although posted speeds for cars and trucks are important variables, their variances in this study were very low and they did not significantly affect the speed reduction.

Based on stepwise regression analysis, the degree of horizontal curve was the most important variable for predicting the estimated speed reduction. The speed reduction for passenger cars, light trucks, trucks, and for all vehicles are presented, in the following equations:

$$\Delta V_P = 3.64 + 1.78DC \quad (1)$$

$$\Delta V_L = 2.0DC \quad (2)$$

$$\Delta V_T = 4.32 + 1.44DC \quad (3)$$

$$\Delta V_A = 3.30 + 1.58DC \quad (4)$$

where ΔV_P, ΔV_L, ΔV_T, and ΔV_A represent the speed reduction (km/hr) between tangent and curve for passenger cars, light trucks, trucks, and all vehicles, respectively, and DC is the degree of curve (angle in degrees, subtended at the center by an arc of 30 m in length).

The coefficients of multiple determination values were 0.51, 0.69, 0.42, and 0.62 for passenger cars, light trucks, trucks, and all vehicles, respectively. Based on the preceding equations, the estimated speed reductions associated with a curve having a degree of curve of 8 degrees (radius = 215 m) are 17.9, 16.0, and 15.8 km/hr for passenger cars, light trucks, and trucks, respectively. The corresponding speed reduction for all vehicles is 16 km/hr. By inspection, the estimated speed reduction for each type of vehicle is not significantly different from the speed reduction of all vehicles.

Further improvement in prediction precision was achieved when other significant variables were considered. These variables included length of vertical curve within the horizontal curve, gradient, and pavement condition. The length of vertical curve was found to be highly correlated with gradient. Therefore, separate models were developed to show the effects of vertical curve and gradient separately. The resulting equations for all vehicles were as follows:

$$\Delta V_A = 1.84 + 1.39DC + 4.09PC + 0.07G^2 \quad (5)$$

$$\Delta V_A = 1.45 + 1.55DC + 4.00PC + 0.00004V_C^2 \quad (6)$$

where

PC = pavement condition (for PSR ≥ 3, $PC = 0$, otherwise $PC = 1$),
G = gradient (in percent, average slope between the points of speed measurements on the tangent and the curve center), and
V_C = the length of vertical curve within the horizontal curve (m).

Both models and their parameters were statistically significant at the 95 percent confidence level. The coefficients of multiple determination values were 0.77 and 0.76 for Equations 5 and 6, respectively. Similar equations were developed for each vehicle type. Most of the data included high gradients, which are associated with up-grade and crest curves.

Consistency Models for Continuous Curves

The reduction in the 85th percentile speeds between the first and second curve as the dependent variable was modeled as a function of curve geometric variables. The analysis indicated that the radii of the continuous curves had the most significant effect on speed reduction. The direction of the second curve with respect to the first one was introduced as a dummy variable. However, the analysis revealed that this variable had no effect on speed reduction. Similarly, Mintsis (*10*) reported that the direction of the curve did not affect vehicle speeds. The speed reductions for passenger cars, light trucks, trucks, and all vehicles are presented in the following equations:

$$\Delta V_P = \frac{5{,}708}{R_2} - \frac{5{,}689}{R_1} \quad (7)$$

$$\Delta V_L = \frac{4{,}957}{R_2} - \frac{4{,}888}{R_1} \quad (8)$$

$$\Delta V_T = \frac{5{,}463}{R_2} - \frac{5{,}463}{R_1} \quad (9)$$

$$\Delta V_A = \frac{5{,}081}{R_2} - \frac{5{,}081}{R_1} \quad (10)$$

where R_1 and R_2 represent the radius of the first (preceding) and the second curve, respectively. The models and their parameters in Equations 7–10 were statistically significant at the 95 percent confidence level. The coefficients of multiple determination values were 0.72, 0.77, 0.66, and 0.81 for Equations 7, 8, 9 and 10, respectively. Based on these models, the speed reduction could be estimated for each vehicle type. The estimated speed reduction might be negative. This occurs if the radius of the first curve is smaller than the radius of the second one. For example, if the radii of the first and second curve are 150 and 200 m, respectively, the estimated speed reductions would be −9.4, −7.8, −9.1, and −8.5 km/hr for passenger cars, light trucks, trucks, and all vehicles, respectively. This example demonstrates that the speed reduction for all vehicles is not significantly different from the speed reduction for each type of vehicle. The relationship between speed reduction and radii of continuous curves for all vehicles is shown in Figure 1.

Consistency Models for Common Tangent

The length of the common tangent between successive curves (non-independent tangent) is considered one of the important geometric design consistency variables. For each type of vehicle, the results indicate that the speed on the common tangent was found to be strongly correlated with the length of common tangent, degree of successive curves, and the deflection angles. However, the degrees of curves were also found to be positively correlated with their deflection angles. Therefore, separate models were established with the aim of developing geometric design guidelines for highway planners.

Based on the length of common tangent and deflection angles, speed on the common tangent can be estimated from Equations 11, 12, 13, and 14 for passenger cars, light trucks, trucks, and all vehicles, respectively.

$$V_P = 115.0 - \frac{3{,}722}{LT} - 0.70\left(\frac{DF_1 * DF_2}{DF_1 + DF_2}\right) \quad (11)$$

$$V_L = 106.0 - \frac{3{,}391}{LT} - 0.73\left(\frac{DF_1 * DF_2}{DF_1 + DF_2}\right) \quad (12)$$

$$V_T = 99.3 - \frac{3{,}099}{LT} - 0.75\left(\frac{DF_1 * DF_2}{DF_1 + DF_2}\right) \quad (13)$$

$$V_A = 108.3 - \frac{3{,}498}{LT} - 0.71\left(\frac{DF_1 * DF_2}{DF_1 + DF_2}\right) \quad (14)$$

where

V_P, V_L, V_T, and V_A = 85th percentile speed of passenger cars, light trucks, trucks, and all vehicles (km/hr), respectively;
L_T = length of common tangent (m); and
DF_1 and DF_2 = deflection angles of first and second curve (in degrees), respectively.

The parameters of the preceding models were statistically significant at the 95 percent confidence level. The coefficients of multiple determination values were 0.68, 0.71, 0.72, and 0.72 for Equations 11, 12, 13, and 14, respectively. Although each type of vehicle had its own distinct speed, the length of common tangent and deflection angles had approximately the same effects. For all vehicles, Figure 2 shows the relationship between the speed on the common tangent

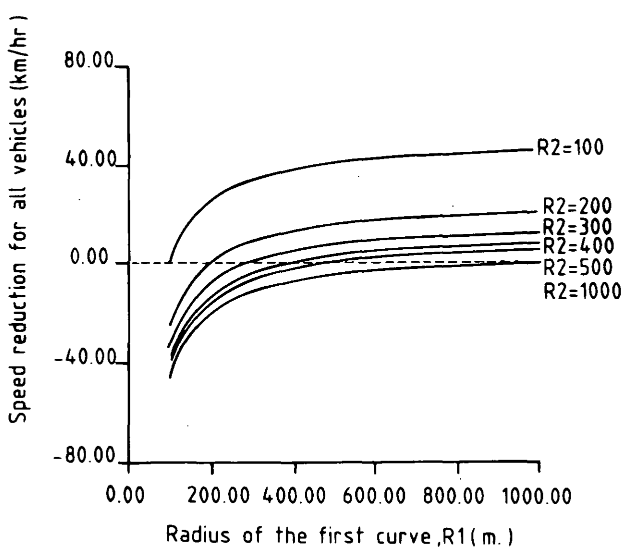

FIGURE 1 Relationship between speed reduction and radii of successive curves for all vehicles.

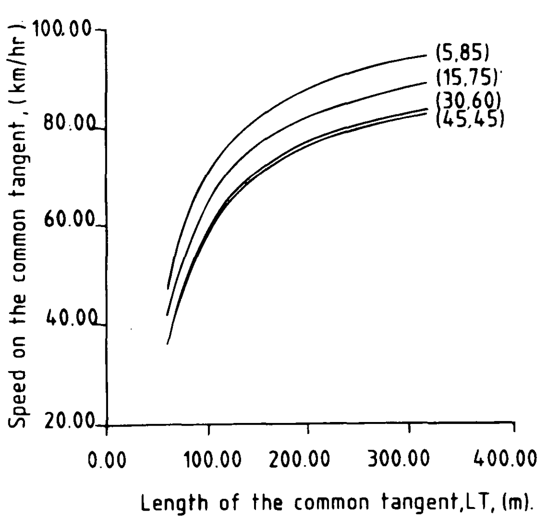

FIGURE 2 Relationship between estimated speed on tangent and both length of tangent (LT) and deflection angles (DF1, DF2) for all vehicles.

and its length for different deflection angles. This figure indicates that for the same total deflection angle ($DF_1 + DF_2$) the lowest speed can be obtained if the two angles are equal. Thus, deflection angles of successive curves should not be the same if higher speeds are desired.

Similarly, models were developed to estimate traffic speed on common tangent as a function of the length of common tangent and the degree of successive curves. For each type of vehicle, the models were similar in form. The developed model for all vehicles may be expressed as

$$V_A = 105.47 - \frac{3{,}792}{LT} - 0.27\,(DC_1 * DC_2) \qquad (15)$$

where DC_1 and DC_2 represent the degree of successive curves for the first and second curve respectively. The preceding model and its parameters were statistically significant. Compared with Equation 14, Equation 15 had lower coefficient of determination ($R^2 = 0.63$). Figure 3 shows the estimated speed for all vehicles as a function of the length of common tangent and degree of successive curves.

DISCUSSION OF RESULTS

In this study, speed reduction is considered as a quantitative measure of an inconsistent design. Several studies suggested a design criterion based on this measure (*11–14*). Previous studies have estimated speed reduction through speed-profile models (*3, 12*) or speed difference distribution (*15*). In this study, speed reduction models were developed to estimate directly the reduction in operating speed. This approach was adopted for the following reasons. First, speed reduction is the most common outcome of an inconsistent design, and it is easier to estimate it directly using appropriate models. Second, it was found through the course of this study that the speed reduction models provided a sound statistical characteristic specifically for continuous and reverse curves. Finally, the results of this study were found to be generally comparable with the results of previous studies. For simple curves, the overall operating speeds on tangents were approximately equal because the tangents were selected to be independent and the selected roads have approximately the same posted speed limits. For continuous curves, the speed on the second curve is dictated by the speed on the preceding one. Thus, modeling the speed reduction directly is not an unreasonable approach.

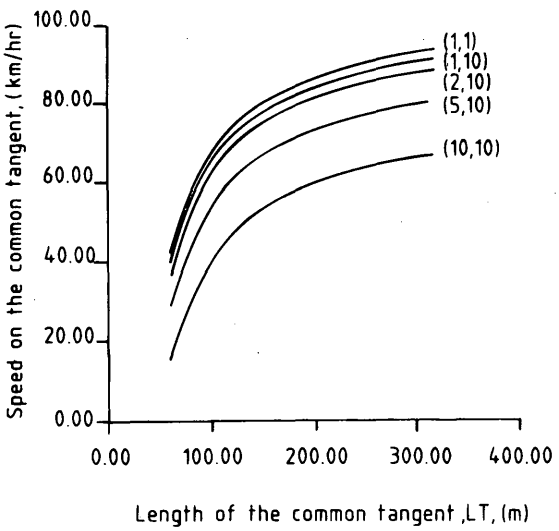

FIGURE 3 Relationship between estimated speed on tangent and both length of tangent (LT) and degree of curves (DC1, DC2) for all vehicles.

For simple horizontal curves, the analysis revealed that speed reduction is significantly affected by the degree of curves, gradient, length of vertical curve within horizontal curve, as well as pavement condition. The degree of curve was found to be the most important variable. Although previous studies did not develop speed prediction for each type of vehicle, those studies found that the degree of curve had the greatest impact on the speed of passenger cars on horizontal curves (*4, 16*). Moreover, Lamm et al. (*4*) indicated that gradient did not have a significant influence on the speed of passenger cars. The difference between these results might be attributed to the fact that Lamm et al. (*4*) did not include a gradient steeper than 5 percent, whereas this study included a gradient up to 7 percent. Kanellaidis et al. (*17*) indicated that superelevation rate, lane and shoulder widths, and grade up to 3 percent did not have a statistically significant effect on curve speed. Therefore, results of this study agree with those of previous research.

As stated, speed reduction models were developed for each type of vehicle. Investigation of Equations 1–4 reveals that the speed of passenger cars is affected to a greater extent by the degree of curve, specifically for a medium to high degree of curve. However, for a degree of curve 4 to 10 degrees, the difference between the speed reduction values for all vehicles and for each type of vehicle was not significant in this study. This result is compatible with the results of previous studies. Lamm et al. (*3*) indicated that the difference between operating speeds of passenger cars and trucks increases with increasing degree of curve, but not in a manner that could result in critical maneuvers.

Based on safety considerations, Lamm et al. (*12*) reported that the degree of simple curve should be limited to 5 degrees (radius = 345 m) and the speed reduction to 10 km/hr to achieve a good design. In this study, Equation 5 indicates that for a good pavement condition and grade of up to 4 percent, the degree of curve corresponding to a speed reduction of 10 km/hr is 5.06 degrees (radius = 340 m). Therefore, the results are comparable and the small discrepancy might be attributed to differences in driver attitudes.

For continuous curves, the speed reduction on successive curves, separated by a relatively short tangent, is highly affected by the radii of curves. An inspection of Equations 7–10 reveals that for equal radii, the speed reduction would be negligible. Furthermore, an increase in both radii would minimize the speed reduction and provide better consistency. Compared with other vehicle types, the speed of passenger cars is affected to a greater extent by the curve radii.

For comparison purposes, Equation 7 can be used to determine the radius of the second curve for a given radius of the first curve and specific level of speed reduction. Lamm et al. (*12*) indicated that a good consistent design can be achieved if the speed reduction is less than 10 km/hr. Based on this criterion, if the radius of the first curve is 100 m, then the second curve should have a radius in the range of 85 to 122 m to achieve a good consistent design for passenger cars. This value is comparable with the results of previous research. For good design, Lamm et al. (*12*) showed that a curve having a radius of 100 m can be combined with a curve having a radius in the range of 81–130 m.

The results indicate that the speed on the common tangent would be increased by increasing the length of common tangent or by reducing the deflection angles. Furthermore, the developed equations indicate that the increase in the length of the common tangent will permit the use of a large degree of curve or deflection angles. Again, one should remember that the results of this study indicate that the degree of curves was found to be strongly correlated with their deflection angles. Thus, the speed on the common tangent would be increased by reducing the degree of successive curves.

PRACTICAL APPLICATION

The ultimate objective of speed reduction models is to develop guidelines for designing or redesigning two-way two-lane highway. The literature reveals that good consistent design can be achieved if the speed reduction is less than 10 km/hr (*12*). For simple horizontal curves, Equation 4 indicates that this condition can be achieved if the degree of the curve is less than 4.24 degrees. Moreover, effect of grade, pavement condition, and the length of vertical curve can be used to determine the maximum degree of curve for a good consistent design. Considering the effects of pavement condition and gradient, Equation 5 can be used to determine the maximum degree of curve that would guarantee a good consistent design for all vehicles. Table 1 presents the maximum degree of curve for different pavement conditions and gradient. For example, if the pavement condition is good or better and the gradient is 6 percent, then a good consistent design would be achieved if the degree of simple curve is less than or equal to 4 degrees (radius = 430 m). Similarly, Table 2 presents the maximum degree of curve for different pavement condition and length of vertical curve. Table 2 was developed using Equation 6. For example, if the pavement condition is good or better and the length of vertical curve is 240 m, then the maximum degree of curve should be limited to 4 degrees (radius = 430 m) to achieve a good design.

For continuous horizontal curves, similar guidelines can be developed using curve radii instead of degree of curves. Table 3 presents the limit of horizontal curve radii that would guarantee a good consistent design. The radius of the first curve was assumed, and the minimum and maximum values of the radius of the second curve were computed using Equations 7 and 10 for passenger cars and all vehicles, respectively. In computing the minimum and maximum radius of the second curve, the speed reductions were taken to be −10 and +10 km/hr, respectively. For example, if the radius of the first curve is 300 m, the second curve should have a radius in the range of 189 to 732 m to achieve a good design for all vehicles. However, if the radius of the first curve is 500 m, then the minimum radius of the second curve is 252 m and no maximum limit (straight section) could be used.

The developed models in this study can be used to estimate the speed on a short common tangent. To achieve a desired speed, the length of the common tangent can be estimated for a given combination of curve degrees or deflection angles.

CONCLUSIONS

In addition to the degree of simple horizontal curve, the length of vertical curve within the horizontal curve, gradient, and pavement condition had a significant effect on consistency of horizontal alignment. Speed reduction, as a measure of alignment consistency, was greatly affected by the degree of curves. Considering all types of vehicles, a good consistent design can be achieved if the degree of curve is less than 4.24 degrees. The radii of successive horizontal curves separated by a short common tangent determined the speed reduction between the curves. For a good consistent design, the curves should have approximately equal radii. Although consistency models for different type of vehicles were developed, the consistency models for passenger cars provided the most conservative geometric design values. For each type of vehicle, the speed on a short common tangent was highly affected by the length of the common tangent and degree of successive horizontal curves. Also, the speed was significantly affected by the value of deflection angles.

TABLE 1 Maximum Degree of Horizontal Curve That Would Guarantee Consistent Design for Different Pavement Conditions and Gradients

Pavement Condition	Gradient (%)	Maximum Degree of Curve (degree)
Good or very Good (PSR ≥ 3)	2	5.71
	4	5.06
	6	4.00
	8	2.51
Fair or Poor (PSR < 3)	2	2.74
	4	2.11
	6	1.40
	8	0.00

TABLE 2 Maximum Degree of Horizontal Curve That Would Guarantee Consistent Design for Different Pavement Conditions and Length of Vertical Curve

Pavement Condition	Length of Vertical Curve (m)	Maximum Degree of Curve (degree)
Good or very Good (PSR ≥ 3)	320	2.85
	240	4.00
	160	4.86
	80	5.38
Fair or Poor (PSR < 3)	320	0.23
	240	1.43
	160	2.23
	80	2.69

TABLE 3 Limits of Horizontal Curve Radii That Would Guarantee Consistent Design on Continuous Curve

Radius of the First Curve (m)	Passenger Cars		All Vehicles	
	Radius of the Second Curve, R2, (m.)		Radius of the Second Curve, R2, (m.)	
	Maximum	Minimum	Maximum	Minimum
100	122	85	124	84
200	309	148	330	144
300	630	197	732	189
400	1352	236	1880	224
500	4018	267	NL*	252
600	NL	293	NL	275
700	NL	315	NL	294
800	NL	334	NL	311
900	NL	350	NL	325
1000	NL	360	NL	337

* : No Maximum Limit (straight).

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