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Safety performance functions incorporating design consistency variables

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ABSTRACT

Highway design which ensures that successive elements are coordinated in such a way as to produce harmonious and homogeneous driver performances along the road is considered consistent and safe. On the other hand, an alignment which requires drivers to handle high speed gradients and does not meet drivers' expectancy is considered inconsistent and produces higher crash frequency.

To increase the usefulness and the reliability of existing safety performance functions and contribute to solve inconsistencies of existing highways as well as inconsistencies arising in the design phase, we developed safety performance functions for rural motorways that incorporate design consistency measures. Since the design consistency variables were used only for curves, two different sets of models were fitted for tangents and curves. Models for the following crash characteristics were fitted: total, single-vehicle run-off-the-road, other single vehicle, multi vehicle, daytime, nighttime, non-rainy weather, rainy weather, dry pavement, wet pavement, property damage only, slight injury, and severe injury (including fatal). The design consistency parameters in this study are based on operating speed models developed through an instrumented vehicle equipped with a GPS continuous speed tracking from a field experiment conducted on the same motorway where the safety performance functions were fitted (motorway A16 in Italy).

Study results show that geometric design consistency has a significant effect on safety of rural motorways. Previous studies on the relationship between geometric design consistency and crash frequency focused on two-lane rural highways since these highways have the higher crash rates and are generally characterized by considerable inconsistencies. Our study clearly highlights that the achievement of proper geometric design consistency is a key design element also on motorways because of the safety consequences of design inconsistencies.

The design consistency measures which are significant explanatory variables of the safety performance functions developed in this study are: (1) consistency in driving dynamics, i.e., difference between side friction assumed with respect to the design speed and side friction demanded at the 85th percentile speed; (2) operating speed consistency, i.e., absolute value of the 85th percentile speed reduction through successive elements of the road; (3) inertial speed consistency, i.e., difference between the operating speed in the curve and the average operating speed along the 5 km preceding the beginning of the curve; and (4) length of tangent preceding the curve (only for run-off-the-road crashes).

1. Introduction

Highway design which ensures that successive elements are coordinated in such a way as to produce harmonious and homogeneous driver performances along the road is considered consistent and safe. On the other hand, an alignment which requires drivers to handle high speed gradients and surprising events and does not meet drivers' expectancy is considered inconsistent and produces higher crash frequency (Anderson et al., 1999; Awatta et al., 2006; Cafiso et al., 2007; Camacho-Torregrosa et al., 2013; Lamm et al., 1999; Montella, 2005, 2009, 2010; Montella et al., 2008, 2012). As a consequence, the identification of proper design consistency measures and the development of quantitative relationships between design consistency and crash frequency are crucial for several steps of the highway safety management process, such as the design of new highways, the hotspots identification, the design

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of improvements of existing highways, and the evaluation of the safety effects of the design decisions.

Several design consistency measures have been successfully used as explanatory variables in safety performance functions fitted on two-lane rural highways (Anderson et al., 1999; Awatta et al., 2006; Cafiso et al., 2010; Camacho-Torregrosa et al., 2013; de Oña et al., 2014; Ng and Sayed, 2004). Design consistency measures are generally related to the operating speed profile and the speed differential from an approach tangent to an horizontal curve (Montella et al., 2014a,b; TRB, 2011). The best known consistency criteria are those proposed by Lamm et al. (1995, 1999), that defined three design classes (good, fair, and poor) basing on three consistency measures: (1) ΔV_d, design speed consistency (absolute value of the difference between design speed and operating speed); (2) ΔV_{85}, operating speed consistency (absolute value of the 85th percentile speed reduction through successive elements of the road); and (3) Δf_r, consistency in driving dynamics (difference between side friction assumed with respect to the design speed and side friction demanded at the 85th percentile speed).

To increase the usefulness and the reliability of the existing safety performance functions incorporating design consistency variables, there is the need of further studies not limited to two-lane rural highways (Montella et al., 2008) as well as of studies taking into account the location of any geometric element in relation to the overall road alignment and the distance from the other geometric elements (Camacho-Torregrosa et al., 2013; Findley et al., 2012). Aim of the paper is to fill these research gaps developing safety performance functions for rural motorways that incorporate design consistency measures and take into account the location of any geometric element in relation to the overall road alignment. The design consistency parameters in this study are based on operating speed models developed in previous research through an instrumented vehicle equipped with a GPS continuous speed tracking (Montella et al., 2014a) from a field experiment conducted on the same motorway where the safety performance functions were fitted. These operating speed models are more accurate than models based on spot speed studies since they are not based only on spot speed data collected at the centre of the horizontal curve and at the midpoint of the preceding tangent.

The remainder of paper is organized as follows: Section 2 describes the study data; Section 3 describes the methodology used to develop the safety performance functions and the variables introduced in the models; Section 4 explains and discusses the results, with a specific focus on the comparison with results of previous studies; finally, conclusions are drawn in the last Section.

2. Data description

2.1. Geometric data

The study site is the section Naples–Candela of the motorway A16 Naples–Canosa (L = 255.0 km, i.e., 127.5 km per carriageway). It is part of the Trans European Road Network (Road E841), is located in the south of Italy and links up west coast (Motorway A1) and east coast (Motorway A14). It is a divided highway with two lanes for each direction (lane width = 3.75 m, right shoulder width = 0.50–3.50 m, median width = 2.00 m), access control, and interchanges. Median safety barriers include w-beam, double w-beam, thrie-beam, and concrete New Jersey shaped barriers. Because of the topographical constraints and the mountainous terrain, the freeway is characterised by a bending alignment, with several low radius curves and many design inconsistencies, and by sections with high longitudinal grades (Table 1). It is worthwhile to point out that, because of the presence of numerous mountains, in Italy several motorways have geometric characteristics similar to the study site.

The corridor is connected to the road network by 11 interchanges, with 21 exit ramps (13 on curves, 8 on tangents) and 20 entrance ramps (11 on curves, 9 on tangents). Part of the route is in mountainous terrain with 11 tunnels (L = 4.03 km) and 38 bridges (L = 8.11 km). Two climbing lanes are located in east direction (L = 10.48 km) and one climbing lane is located in west direction (L = 3.83 km). Statutory speed limit is 130 km/h but posted speed limits equal to 80 km/h are installed in both travel directions (L = 50.25 km in east carriageway, L = 26.60 km in west carriageway).

Segmentation was carried out to obtain homogeneous segments with respect to average annual daily traffic and curvature. First, all horizontal curves and tangents were separated. Then, segments with homogeneous curvature were further separated when changes in traffic volumes occurred inside the segment due the presence of an interchange. Based on the horizontal alignment characteristics and the traffic flow volumes, a segmentation into 652 homogeneous sections (326 for each carriageway) was carried out.

Length of the segments varies between 62 and 3509 m. Radius of the horizontal curves varies between 245 and 4000 m. Spiral transitions are not present. Deflection angle varies between 5 and 109 gon. Superelevation mean is equal to 3.25%. Radius of the vertical curves varies between 3000 m (sag curve) and 30,000 m (crest curve). Maximum longitudinal grade is equal to 6.35%. Sight distance is often less than the stopping sight distance and ranges between 62 and 840 m.

Table 1
Summary statistics of geometric data.

Parameter	Mean	Standard deviation	Minimum	Maximum
Length[a] (m)	394.10	348.12	61.51	3.509,58
Radius of horizontal curves[b] (m)	790.77	575.09	245.00	4.000,00
Deflection angle (gon)[c]	34.57	20.75	4.88	109.07
Superelevation (%)	3.25	1.09	1.30	6.42
Radius of sag vertical curves[d] (m)	9,000.00	3,233.58	3,000.00	20,000.00
Radius of crest vertical curves[e] (m)	10,888.89			30,000.00
Longitudinal grade (%)	2.41	1.70	0.00	6.35
Sight distance (m)	342.87	173.53	62.27	840.00
Right shoulder width (m)	2.10	0.89	0.50	3.50

[a] 652 segments.
[b] 332 horizontal curves.
[c] The dimension gon corresponds to 400 angle units in a circle instead of 360 degrees.
[d] 92 sag curves.
[e] 76 crest curves.