ANALISIS OF SPEED PREDICTION FOR DESIGN CONSISTENCY OF TWO-LANE RURAL HIGHWAYS

Topic area: Design consistency

Leandro Cardoso Trentin – Professor MSc
Av. Professor Ascendino Reis, 725 – Vila Clementino
CEP: 04027-000 – São Paulo/SP
UNIP – Universidade Paulista – São Paulo / Brasil
Planservi Engenharia Ltda - São Paulo / Brasil
trentin@planservi.com.br
Phone: +55 (11) 3304-1435
Fax: +55 (11) 3304-1401

Felipe Issa Kabbach Junior – Professor PhD
EPUSP – Escola Politécnica da Universidade de São Paulo – São Paulo / Brasil
Planservi Engenharia Ltda - São Paulo / Brasil
felipe@planservi.com.br
Phone: +55 (11) 3304-1406
Fax: +55 (11) 3304-1419

Carlos Yukio Suzuki – Professor PhD
EPUSP – Escola Politécnica da Universidade de São Paulo – São Paulo / Brasil
FEI – Faculdade de Engenharia Industrial – São Bernardo do Campo / Brasil
Planservi Engenharia Ltda - São Paulo / Brasil
suzuki@planservi.com.br
Phone: +55 (11) 3304-1404
Fax: +55 (11) 3304-1419

ABSTRACT

Two of the mostly used models for the analisis of highway design consistency are: the safety criteria method established by Lamm et al. (1) and the one proposed by Fitzpatrick et al. (2) incorporated in the Design Consistency Module (DCM) of the Interactive Highway Safety Design Model (IHSDM) developed by the Federal Highway Administration (FHWA).

The methods presented in this paper to determine the design consistency on two-lane rural highways are based on the design speed and the observed 85th percentile speed. The speed profile is used to evaluate the design consistency of two-lane highways utilizing both methods.

The objective of this paper is to develop a speed-prediction model for two-lane rural highways in Brazil, especially in the State of São Paulo. To develop the prediction equation, regression models based on the geometry of the curves were used.

Highway speeds were obtained for vehicles travelling on curves at three bidirectional two-lane roads in State of São Paulo. With these results, a speed prediction equation was developed.

Upon comparison of the results obtained in the case study, it was verified that on curves with radius of curvature larger than 100m, the observed speeds in the Brazilian two-lane roads are similar to those predicted by Fitzpatrick's (3) equation. However, on roads whose radius is shorter than 100m, the observed speeds are closer to those yielded by the equation elaborated by Lamm (1).

INTRODUCTION

Most two-lane rural roads in the state of Sao Paulo were built in the 1960´s and 1970´s, during a time when most projects aimed to minimize development and construction costs, therefore the existing topography and roads were used to set the alignment of the two-lane rural roads. For this reason, the design of these highways contained, in certain sections or in their whole, a restrictive geometry and/or design inconsistency.

The safety and comfort that the roadway provides to users are linked to a number of factors that involve the roadway features and driver behavior; therefore, the design consistency is important because of its relationship with safety.

Until the beginning of the 1970's, Switzerland and Germany used methods which were based on speed profiles in order to analyze the consistency design of highways. In the United States, many speed profiles were developed, however they weren't used in geometric design, Fitzpatrick et al (4).

To elaborate a speed profile, it should be considered that the highway user speeds depends on many factors that can be generically grouped in terms of geometric design, environmental and surrounding conditions, driver, vehicle and operational conditions. (5)

Inconsistency problems occur when the characteristics of a section of the road suffers continuous modifications to consecutive segments. These problems can be verified when speed changes are observed, sudden change of vehicle course and high accident rates occur on certain highway segments. From the driver's point of view, the inconsistency is noticed when maneuvers do not turn out as expected.

In this case study, the speed in fourteen curves and a tangent of the Tamoios Highway (SP-99) was investigated. The objective was to establish an equation that could predict speeds. Additional data from previous speeds studies by Tsu (6), conducted on highway SP55 between km 241,5 and km 220,4, and Osorio (7), on highway SP-360, between the cities Jundiaí and Morungaba, districts in the state of Sao Paulo were also used.

MODELS STUDIED

The models used to evaluate the geometric consistency based on operating speeds focus mainly on vehicle behavior and on horizontal and vertical curve alignments.

However, studies done in Switzerland have also shown excessive speed on tangents. Thus, it is recommended that tangent sections be considered as "dynamic elements" and be observed as acceleration and deceleration movements.

In the following analysis, speed-prediction equations proposed by Lamm et al (1) and those used by the FHWA (Federal Highway Administration) IHSDM (Interactive Safety Design Model) program , which was based on the studies done by Fitzpatrick et. al. will be investigated.

Methods of Safety Criteria

The method proposed by Lamm (1) is similar to that developed in Germany. After studying 270 horizontal curves in the state of New York, a speed prediction model was developed using the curve change rate (CCR) as the main variable to predict the 85^{th} percentile operating speeds.

TABLE 1 Speed prediction models proposed by Lamm in the United States

Table 2 presents some examples of speed prediction models for the conditions present in other countries considering the CCR parameter.

TABLE 2 Speed prediction models proposed by in others countries

IHSDM Method

Initial studies done by Fitzpatrick et al (3), based on Lamm (1), consisted of defining an operating speed prediction model (V85) using horizontal and vertical alignment along the highway and the validation of the speed profile to be included in the consistency model program IHSDM.

In the present study, the speed prediction model was developed for different conditions of horizontal and vertical alignments. Models to predict acceleration and deceleration rates were also developed considering the effect of combining horizontal and vertical alignments.

It can be noticed that the equations proposed by Fitzpatrick (2) were elaborated for specific sections; that is, each horizontal and vertical alignment combination will have a particular equation to predict speed.

TABLE 3 Speed prediction equations for passenger vehicles

CASE STUDY

In order to compare each previously discussed predictive speed model, the observed speeds on the Tamoios Highway, between km 64 and km 83 located in the state of Sao Paulo were surveyed. The speed limit is

Moreover, in order to be able to compare the practiced speeds in Brazil to those practiced in other countries as determined by the prediction equations of Lamm (1) and Fitzpatrick (3), a highway speed study was undertaken, between March and April 2007, utilizing the following criteria:

- Curves between tangents or successive curves;
- Absence of access ramps and intersections;
- Absence of obstacles that could cause a decrease in speed;
- Grades with slopes of 6% or less;
- Annual average daily traffic volumes of 12,000 vehicles per day;
- Lane width equal to 3.60 m;
- Posted speed limit of 60 km/h to 100 km/h.

Another aspect that was considered was the size of the sample collected in each location. A minimum of 100 vehicles per location was set, as in other studies. All locations near of an intersection and urban zone were eliminated from the study. (1) (3)

In addition, a minimum interval of 3 seconds between vehicles was also established. The goal was to discard vehicles that drive in platoon, keeping only those who drive in free flow.

Equipment Used for Measuring

To collect speed data, the portable Nu-Metrics counter, model NC-97, which works with a magnetic sensor, was used.

The equipment consists of a plate-like unit which is placed on the pavement and fixed with pressure screws. Speed and interval between vehicles and length of vehicles that pass over or next to the units are collected using the IMV (Magnetic Image of Vehicle) technology, which measures the interference that the vehicle mass exerts on the magnetic field.

This counter was chosen because it does not interfere with road traffic, allowing speeds practiced in real traffic to be obtained. The usage of mobile radars could have caused a situation in which drivers travel in compliance with the legal speed limits on the sections studied.

Determining Research Locations

Using the studies of Fitzpatrick (3), the speed data collection was defined in four ranges of radius curvature, presented in table 4.

TABLE 4 Curvature Radius Matrix

Following the directives and the distribution of radius of curvature, 14 curves and 1 tangent were then chosen for the study. For each location, the value of the curve radius, superelevation, grade, slope and speed were compiled. Table 5 describes the characteristics of each location.

Voigt expanded the equation by Krammes et al. to include superelevation, the length of the curve, the deflection angle, and the superelevation have shown some effect in estimating operating speeds. Care must be employed when interpreting these results because of the collinearity among the independent variables. (3)

TABLE 5 Description of researched locations on Tamoios Highway

These roads were renovated as part of the Road Renovation Program sponsored by the Interamerican Development Bank (BID), and horizontal and vertical road signs were considered good; so were the conditions of the pavement and shoulder. Therefore, these factors did not interfere with practiced speeds.

The counters were placed on each location for a minimum of two hours in order to obtain a sample of more than 100 vehicles in free flow; it was also ensured that they were placed at the midpoint on circular curves and in the center of the lane, on both directions of the traffic, as illustrated below:

FIGURE 1 Disposition of counter in the surveyed curve

The disposition of the counter is similar to the one utilized by Lamm (1) and Fitzpatrick (3) in their study about speed in curves.

The data obtained by the survey using the portable counter in each section were then analyzed. First, commercial vehicles were excluded and only vehicles measuring 5m or less were kept, since they were assumed to be passenger vehicles. After that, vehicles that travel in platoon (i.e., vehicles with an interval inferior to 3 seconds) were also excluded.

For each section studied, a cumulative frequency distribution curve indicating the 85^{th} percentile of the distribution was determined.

FIGURE 2 Speed distributions in curve 01

Table 6 presents the data obtained in each surveyed location in Tamoios Highway. The table shows the value of curvature change rate, number of vehicles, minimum and maximum operating speeds, and average operating speed for each curve and direction.

TABLE 6 Values for each curve on both direction on Tamoios highway

Speed Prediction Models

The observed speeds practiced by drivers in the road were correlated to the curvature change rate by determining a regression curve as shown in Figure 4.

FIGURE 3 Speed operation in function of CCR – Tamoios Highway

The equation produced based on the tendency curve is presented below; it correlates the operating speed and the curve rate on each curve studied.

$$V_{85} = \frac{10^6}{10.238 + 5{,}9754 \times CCR_s}$$

$$R^2 = 0{,}8132$$

The equation presented above was determined by using the data obtained on Tamoios Highway and is, therefore, valid for this particular road only.

In order to obtain an equation that is valid for other roadways, the data obtained in (other) studies done in the state of Sao Paulo were also analyzed.

The Table 7 presents the data obtained by Tsu (6) on Highway SP55, between km 241,51 and km 220,37.

TABLE 7 Values obtained in the study of Highway SP55

It was also included in this study the speeds observed by Osorio (7), on Highway SP360, between Jundiai and Morungaba. Both highways are currently under the jurisdiction of the Department of Roadways of the State of Sao Paulo. The operating speeds, curve radius, and curvature change rate of the study are presented in Table 8.

TABLE 8 Values obtained in the study of Highway SP360

After adding the speeds observed by Tsu (6) and Osorio (7) to the observed values in the present study, a linear regression was used to correlate operating speeds and curvature change rate. Figure 5 shows the tendency curve that best fits the obtained data.

FIGURE 4 Speed operation in function of CCR

Using the speed data of these highways combined another equation that correlates operating speeds and curvature change rate was produced:

$$V_{85} = \frac{10^6}{9.672{,}2 + 6{,}4135 \times CCR_s} \quad \textbf{(4)}$$

$$R^2 = 0{,}8232$$

Most speed prediction equations were elaborated according to the horizontal alignment and the different design speeds, except the study done by Fitzpatrick (3), which combines the horizontal and vertical alignment.

The speed prediction equations of the main existing methods were then compared (equation 4). For the IHSDM equation, the 0% to 4% slope equation (equation 3) was used. For Lamm (1), the two equations used were based on studies done in the United States (equation 1) and Germany (equation 2).

FIGURE 5 Comparison between speed prediction equations in function of CCR

FIGURE 6 Comparison between speed prediction equations in function of radius of curvature

CONCLUSION AND CRITICAL ANALYSIS

Based on the correlation between the operating speeds estimated by the speed prediction equations of the two methods and the speeds practiced on the roads studied, it is possible to affirm that, in the curves with curve change rate up to 650 gon/km, (i.e., curves whose radius of curvature is larger than 100m), the speed practiced by drivers, in the same conditions, were similar to the those observed by Fitzpatrick (3). However, when CCR is greater than 650 gon/km (i.e., curves whose radius of curvature is shorter than 100m), the speeds verified were closer to ones observed by Lamm (1) in Germany.

When elaborating speed profiles, the major difference between the methods is how the spiral curve is treated. In the method proposed by Lamm (1), the spirals transitions are used in the calculation of the curvature change rate and are, therefore, taken into consideration when operating speeds are estimated.

In the DCM model of the IHSDM, program, spiral curves are not considered in the estimation of the operating speeds because, according to the findings of the Fitzpatrick (2), the operating speeds in curves with and without spiral transition are similar and do not yield meaningful differences.

The analysis of the results of this case study permits us to conclude that, in the projects developed in Brazil for radius of curvature larger than 100m, it is possible to use, with certain caution regarding legal speed limits, the design consistency analysis of DCM model, contained in the IHSDM program.

This study can also be used as an example to be followed whenever the speed prediction equations of the two methods of design consistency analysis are used to analyze roads with specific characteristics.

Whenever measuring speeds is not possible, as mentioned earlier, the speed prediction equation of the DCM model for curves whose radius of curvature is larger than 100 m can then be used.

In both methods, the tangent is considered a dynamic element of the design; however, a difference in the values of acceleration and deceleration can occur, and further research is still necessary to establish values which are compatible with the Brazilian reality.

BIBLIOGRAPHY

1. Lamm, R., Psarianos, B., Mailaender, T. "Highway Design and Traffic Safety Engineering Handbook", 1998.

2. Fitzpatrick, K., Wooldridge , M., Tsimhoni, O., Collins, J., Green, P., Bauer, K., Evaluation of Design Consistency Methods for Two-Lane Rural Highways, Executive Summary – Report FHWA-RD-99-173 - Washington D.C., 2000.
3. Fitzpatrick, K., Elefteriadou, L. Harwood, D. Collins, J., McFadden, J., Anderson, I.B., Krammes, R.A., Irizarry, N., Parma, K., Bauer, K. and Passetti, K., - Speed Prediction for Two-Lane Rural Highways – Report FHWA-RD-99-171 - Washington D.C., 2000.
4. Fitzpatrick, K., Wooldridge , M., Tsimhoni, O., Collins, J., Green, P., Bauer, K., - Alternative Design Consistency Rating Methods for Two-Lane Rural Highways – Report FHWA-RD-99-172 - Washington D.C., 2000.
5. National Cooperative Highway Research Program Report 502 - Geometric Design Consistency on High-Speed Rural Two-Lane Roadways - Transportation Research Board, 2003.
6. Tsu, B.S.A., O estabelecimento de limites legais de velocidade em rodovias de pista simples. Dissertação de Mestrado. São Paulo, Universidade de São Paulo, 2003.
7. OSORIO, C.A.A.C. Avaliação da consistência de traçado em rodovias com duas faixas de tráfego. Dissertação de Mestrado. São Paulo, Universidade de São Paulo, 2000.

LIST OF TABLES AND FIGURES

TABLE 1 Speed prediction models proposed by Lamm in the United States

Lane width (m)	Equation	R^2
3,0	$V_{85} = 89{,}034 - 0{,}045 \times CCR_S$	0,753
3,3	$V_{85} = 93{,}296 - 0{,}046 \times CCR_S$	0,746
3,6	$V_{85} = 95{,}594 - 0{,}044 \times CCR_S$	0,824
Combination	$V_{85} = 93{,}850 - 0{,}05 \times CCR_S$ **(1)**	0,787

TABLE 2 Speed prediction models proposed by in others countries

Country	Equation	Speed limit (km/h)	R^2
Germany ISE (Lamm et al)	$V_{85} = \frac{10^6}{8270 + 8{,}01 \times CCR_S}$ **(2)**	100	0,73
Germany Old	$V_{85} = 60 + 39{,}70 \times e^{(-3{,}98 \times 10^3 \times CCR_S)}$	100	-
Greece	$V_{85} = \frac{10^6}{10150{,}1 + 8{,}529 \times CCR_S}$	90	0,81
France	$V_{85} = \frac{102}{1 + 346 \times \left(\frac{CCR_S}{63700}\right)^{1{,}5}}$	90	-
Australia	$V_{85} = 101{,}2 - 0{,}043 \times CCR_S$	90	0,87
Lebanon	$V_{85} = 91{,}03 - 0{,}056 \times CCR_S$	80	0,81
Canada	$V_{85} = e^{(4{,}561 - 5{,}27 \times 10^{-4} \times CCR_S)}$	90	0,63

TABLE 3 Speed prediction equations for passenger vehicles

Alignment Condition	Equation	Number of Research	R^2
Horizontal curve grade _ -9% ≤ i < -4%	$V_{85} \leq 102,10 - \frac{3077,13}{R}$	21	0,58
Horizontal curve Grade _ -4% ≤ i < 0%	$V_{85} \leq 105,98 - \frac{3709,90}{R}$	25	0,76
Horizontal curve Grade _ 0% ≤ i < 4%	$V_{85} \leq 104,82 - \frac{3574,51}{R}$ **(3)**	25	0,76
Horizontal curve Grade _ 4% ≤ i < 9%	$V_{85} \leq 96,61 - \frac{2752,19}{R}$	23	0,53
Horizontal curve combined with sag vertical curve	$V_{85} \leq 105,32 - \frac{3468,19}{R}$	25	0,92
Horizontal curve combined with limited sight-distance crest vertical curve (K≤43 m/%)	$V_{85} \leq 103,24 - \frac{3576,51}{R}$	22	0,74
Sag vertical curve on horizontal tangent.	V_{85} = Assumed desired speed	7	n / a
Vertical crest curve with non-limited sight distance on horizontal tangent	V_{85} = Assumed desired speed	6	n / a
Vertical crest curve with limited sight distance (k < 43 m/%) on horizontal tangent	$V_{85} \leq 105,08 - \frac{149,69}{K}$	9	0,60

Font: Fitzpatrick (2000)

TABLE 4 Curvature Radius Matrix

Horizontal Alignment Curvature radius (m)				
<119	120 - 219	220 - 399	> 400	Total
7	3	2	2	14

TABLE 5 Description of researched locations on Tamoios Highway

Number of site	Location km	Radius of curvature (m)	Grade (%)	Superelevation (%)
Curve 01	65,5	615	1,25	2,0
Curve 02	66,3	410	1,63	2,0
Curve 03	68,4	185	2,55	5,5
Curve 04	69,2	120	3,80	6,0
Curve 05	69,5	50	6,00	5,0
Curve 06	70,0	56	5,22	7,5
Curve 07	77,9	143	5,90	6,0
Curve 08	80,2	226	6,00	6,5
Curve 09	67,6	360	2,25	5,5
Curve 10	68,6	85	4,25	3,0
Curve 11	68,7	70	2,20	6,0
Curve 12	70,5	90	4,06	5,0
Curve 13	72,1	77	4,85	8,0
Curve 14	72,3	75	4,27	6,2
Tangent	65,0	n/a	6,00	2,0

TABLE 6 Values for each curve on both direction on Tamoios highway

Curve	Direction	CCR_S (gon/km)	Number of observation	V_{85} (km/h)	$V_{média}$ (km/h)	$V_{máx}$ (km/h)	$V_{mín}$ (km/h)
1	increase	103	400	104,00	85,56	127	18
1	decrease	104	268	100,50	84,98	124	19
2	increase	156	387	96,00	80,47	158	19
3	increase	341	402	80,00	70,13	114	21
3	decrease	348	111	79,50	69,34	108	34
4	decrease	523	122	78,00	61,27	142	10
5	increase	1320	248	56,00	48,20	98	19
5	decrease	1231	239	62,00	53,82	85	18
6	increase	1174	397	57,00	50,68	109	21
6	decrease	1103	104	56,50	49,06	134	23
7	increase	451	395	71,50	59,67	127	10
7	decrease	440	265	70,00	60,75	97	27
8	increase	283	389	78,50	68,17	117	10
8	decrease	279	145	74,50	61,52	122	19
9	increase	178	254	89,50	71,57	127	18
9	decrease	176	271	96,50	83,34	124	18
10	increase	766	193	76,00	65,15	174	18
10	decrease	734	342	68,50	60,72	155	18
11	increase	887	429	62,50	54,68	121	18
11	decrease	934	127	69,00	67,04	111	23
12	increase	722	163	73,00	54,19	124	26
12	decrease	694	213	63,50	54,16	82	18
13	increase	803	294	55,00	46,82	162	10
13	decrease	841	392	65,50	55,81	157	10
14	increase	829	365	64,00	56,29	111	10
14	decrease	870	454	72,00	60,60	135	10
Tangent	increase	n/a	978	93,00	78,60	136	10
Tangent	decrease	n/a	1.288	105,00	87,30	147	18

TABLE 7 Values obtained in the study of Highway SP55

Curve	Direction	Radius of curvature (m)	CCR_S (gon/km)	Number of observation	V_{85} (km/h)
1	Decrease	230,00	277	397	90
1	Increase	230,00	277	387	87
2	Decrease	245,00	260	244	99
2	Increase	245,00	260	489	82
3	Decrease	495,00	129	503	93
3	Increase	495,00	129	438	97
4	Decrease	144,00	442	423	82
4	Increase	144,00	442	433	77
5	Decrease	312,00	204	409	93
5	Increase	312,00	204	549	97
6	Decrease	288,00	221	367	92
6	Increase	288,00	221	528	97
7	Decrease	250,50	254	555	97
7	Increase	250,50	254	463	95
8	Decrease	400,00	159	521	98
8	Increase	400,00	159	409	90

Font: Tsu (6)

TABLE 8 Values obtained in the study of Highway SP360

Curve	Location	Radius of curvature (m)	CCR_S (gon/km)	Number of observation	V_{85} (km/h)
1	km 65,8	190,98	334	129	90
2	km 68,2	1011,12	63	151	93
3	km 68,8	435,20	146	135	95
4	km 74,2	480,00	133	119	89
5	km 75,3	400,00	159	340	89
6	km 75,8	190,98	334	353	87
7	km 78,0	200,00	319	119	87
8	km 78,9	300,00	212	299	90
9	km 100,8	170,00	375	80	97
10	km 101,0	140,00	455	143	82
11	km 101,2	150,00	425	150	79
12	km 101,4	230,00	277	127	101
13	km 107,6	114,63	556	170	79
14	km 110,1	119,92	531	166	84

Font: Osorio (7)

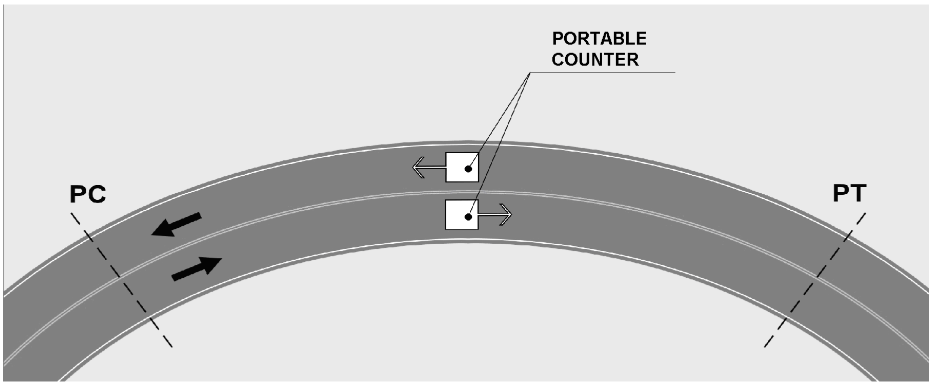

FIGURE 1 Disposition of counter in the surveyed curve

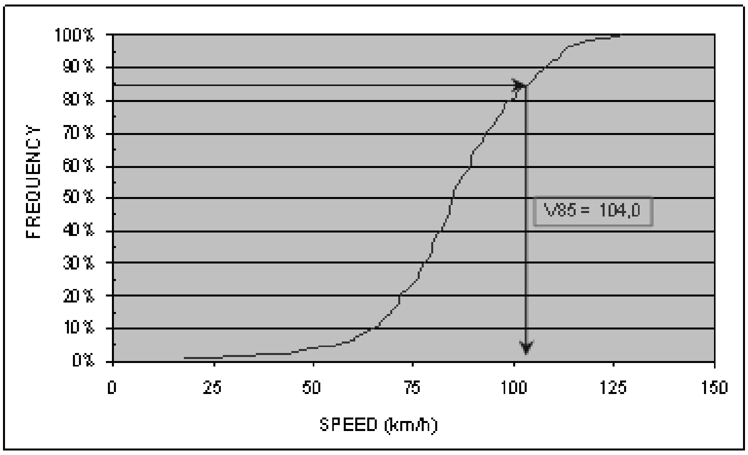

FIGURE 2 Speed distributions in curve 01

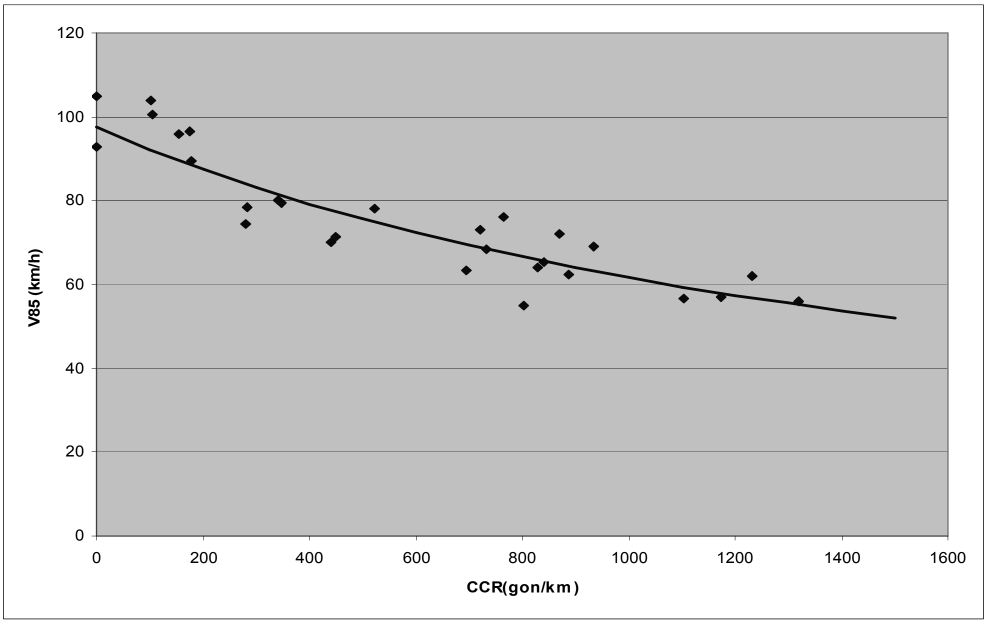

FIGURE 3 Speed operation in function of CCR – Tamoios Highway

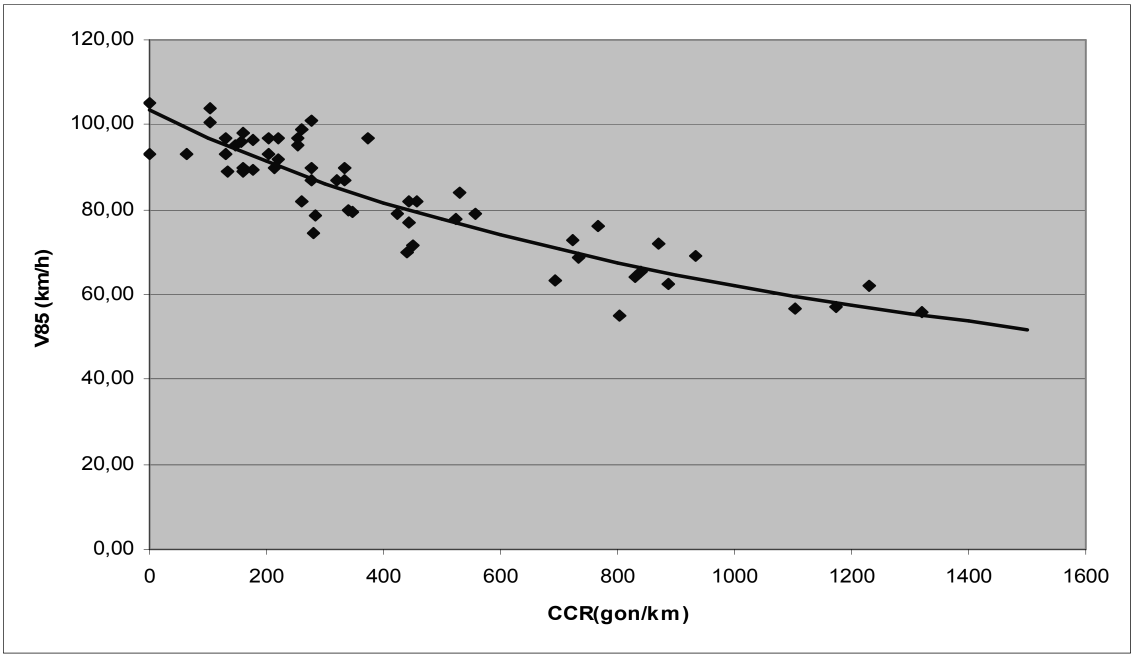

FIGURE 4 Speed operation in function of CCR

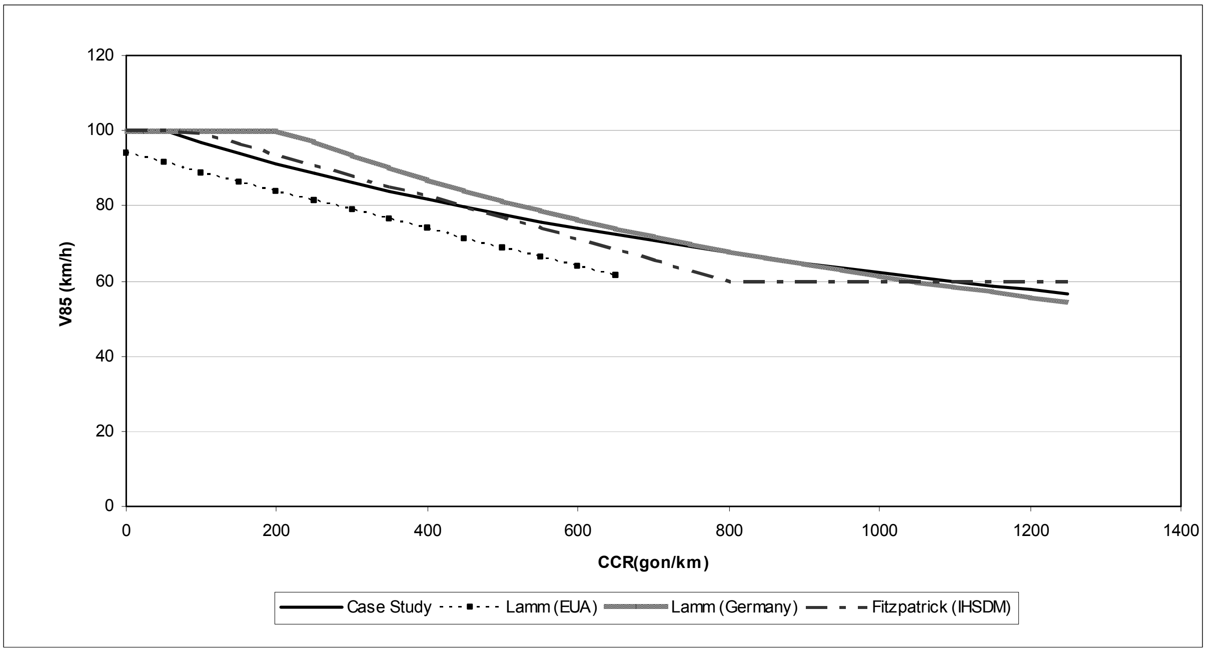

FIGURE 5 Comparison between speed prediction equations in function of CCR

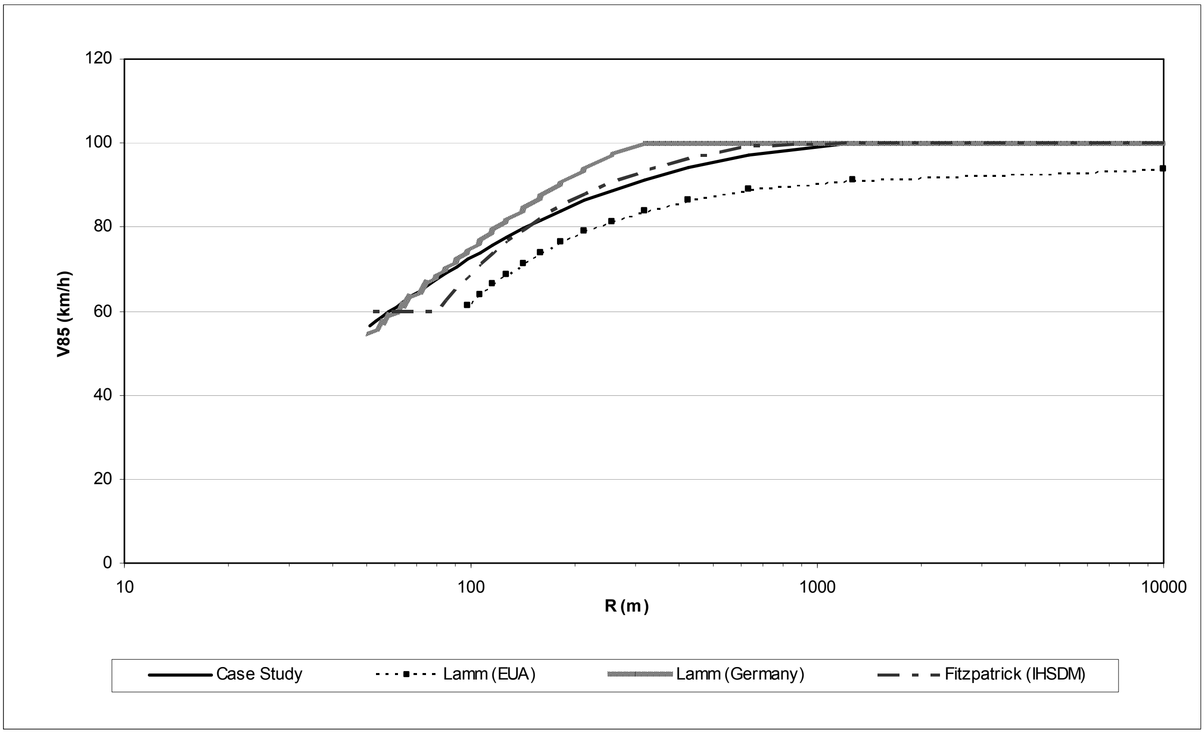

FIGURE 6 Comparison between speed prediction equations in function of radius of curvature