Freeway design consistency evaluation - a case study on driving simulator

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ABSTRACT

This paper shows the results of an experimental survey carried out using an advanced full scale interactive driving simulator with the aim of: evaluating design inconsistencies on existing multi-lane freeway road in mountainous area; define predicting models for operating speed (V85) and mean speed with respect to combined horizontal and vertical curvature from the date collected. A sample freeway section was selected from a real road in yunnan mountainous area as a test course and was modeled graphically and implemented in the driving simulator. 30 drivers were selected as test drivers who performed the simulation driving on the course. Dynamic data were collected from the simulation system and the analysis of data highlighted inconsistencies of the sample road using a well known Safety Criteria Model. Combined models predicting operation speed and mean speed versus grade and CCR were aggressed from test date and the speed profile from which shows a good agreement with test one.

1 INTRODUCTION

Highway design consistency implies that the design or geometry of a road does not violate either the expectation of the motorist or the ability of the motorist to guide and control a vehicle in a safe manner(1). Accordingly it becomes one of the considerations regarding road design assessment or road safety issues. The expectation here means drivers' subjective operating tendence during diving processing. It relates to a driver's readiness to respond to coming situations, events, and information in predictable and successful ways(1). Thus, the driver plays the major role in determining success or failure within the highway system. Inappropriate driving behavior results from deficiencies in human-vehicle interaction and/or from a misunderstanding of upcoming driving conditions with respect to the roadway, which can produce dangerous situations(2).

Among observable or measurable features of driver's maneuver the speeds of vehicles at free-flow condition is used as one of the significant measurements to represent the driver's operational expectancy responding to highway geometry(3). A consistent alignment, according to the definition, would allow most drivers to operate safely at their own speed along the road, whereas an alignment with inconsistencies requires drivers to handle speed gradients in order to drive safely on certain alignment elements. Practice indicates that drivers make fewer errors in the vicinity of geometric features that conform to their expectations, and departures from consistency lead directly to an increase in accident rates and accident cost rates.

According to this concept of expectative diving, a well known safety evaluation process based on quantitative consistency measurements has been proposed which gives three safety Criterions as following with Good (sound), Fair (tolerable), and Poor three levers (4).

• Design consistency (Criterion I), related to the difference between the operating speed, represented by the 85th percentile speed (V85), and the design speed (Vd) of observed roadway section;

• Operating speed consistency (Criterion II), related to the difference in V85, between two successive geometric elements;

• Driving dynamic consistency (Criterion III), determined by the difference between side friction assumed (fRA) and demanded (fRD).

In the paper, experiments based on Driving Simulator were conducted to measure the speed profiles and dynamic data of simulated vehicles. Analysis and models from process of collected data will be given.

2 DRIVING SIMUALTOR SYSTEM

The experimentation was carried out using the KMRTDS driving simulator set up in the simulation laboratory at Faculty of Transportation, Kunming University of Science and Technology (5), Outlook of the simulator is shown in figure 1. In order to create a driving environment similar to the actual one, a full scale car with real steering wheel and pedals is used as an operation cab, and the visual scenes or scenario is generated from the computers and projected onto the screens in the front of the cab. Driver's operation information from the cab and vehicle behavior data from the vehicle dynamic model can be logged as you wish.

The simulator provides researchers a scientific tool to study road traffic and transportation under controlled test conditions. It allows researchers to create any roadway or scenario to study design or traffic problems. Graphics-based imagine modeling methodology allows precise reproduction of the road horizontal and vertical alignments, cross-section elements as well as traffic facility and roadside obstruction. All vehicle response data can be collected from a sophisticated vehicle dynamic model for the further process.

3 EXPERIMENTAL DESIGN

To carry out the experiments on the Driving Simulator, first of all it was necessary to create a virtual test course exactly based on sample road section. Afterward, subjects (test drivers) were selected and trained to fit to the simulator. Before starting, preliminary test and calibration are required to make the rig work well and the parameters of the vehicle dynamical model be matching with actual ones. Finally, formal experiments were carried out and the data were collected. For further analysis and evaluation all data acquired from the KMRTDS had to be treated and elaborated to be located with respect to the exact position of the vehicle along the test course.

3.1 Virtual Test Course

The sample roadway was selected from a section of multi-lane freeway GZ65 (The National Road in China) in Yunnan mountainous area. It starts from K38 to K58 which has 20km long and with complicated alignments. If characterizing the alignment with curve and tangent as showing in Figure 2, there were 22 single curves and 16 tangents in whole road. Figure 3 shows the geometric features of the sample with radius, grade and altitude versus locations, and Figure 4 gives the combined curvature and grade rate along the road.

The virtual test course was modeled based on graphic method from the CAD database of the sample road. In effect, the Driving Simulator provides researcher with specific software to transfer the data from road design database to a kind of visual data used in the simulator system. In this way exact geometric shape of roads can be presented in the virtual scenario of the simulator visual system. Besides road alignments, traffic marking, signs, road side guardrail, side terrain and decorated side hill along the road as well as other facilities were all created as visual scenes. The completed geometric model and its virtual scenario of the test course are showed in Figure 5 and Figure 6 separately.

3.2 Vehicle Models

Since a totally representative sample of all vehicles does not exist, it was decided to define three classes of vehicle model from the car population on the basis of engine power capacity and their physical parameters, the power of the model engine defined by 1litre cylinder capacity (lcc), 1.5 lcc and 2.0 lcc engines separately. Accordingly they represented three kinds of vehicle driving performance with homogeneous accelerations and highest speeds.

3.3 Subjects

The experiments were required to represent normal driving situation as actual ones, 30 experienced drivers were selected from text drivers aged between 27 and 50, with male 23 and female 7, at least five years of driving experience and average 14 years. Speed limit signs of 110km/h were located on the test road as same as actual situation, but test drivers were asked to drive at the speeds as they expected to. No traffic flow on test lane in experiments in order to achieve free-flow speeds of test vehicles.

3.4 Data Collection and Treatment

Experiments were carried out in the Diving Simulator. For each test, driving from K58 to K38, the data were collected from the vehicle dynamical model in which the speeds of the vehicle, longitudinal and transverse accelerations along the road were significant for the study. Since the all collected parameters came with respect to the time, they need to be transferred into locate-based data so as to analyze a site at the road, more specifically, to study on the speeds at a single curve, tangent, up or down hill. The data transformation can be figured out by locating every position of the moving vehicle on the test course as a coordinate system. Consequently the speed and other parameters of traveled vehicle were accurately located along the test course (speeds versus location). Figure 7 shows the speed and acceleration profiles of drivers on one of segments (K43-K38).

Using Curvature Change Rate of the single curve (CCRs) and grade rate described the road section, the detail of alignments are shown in Table 1.

The formula for determining the curvature change rate of the single curve with transition curves is given by the following equation (6):

$$CCRs = \frac{(\frac{L_{C11}}{2R} + \frac{L_{Cr}}{R} + \frac{L_{C12}}{2R}}{L} \times 63700 \qquad (1)$$

Where:

CCRs: Curvature change rate of the single circular curve with transition curves [gon/km],
L = LCl1 + LCr + LCl2 : overall length of unidirectional curved section [m],

LCr : length of circular curve [m],

R : radius of circular curve [m],

LCl1, LCl2 : lengths of clothoids (preceding and succeeding the circular curve), [m].

The mean speed and 85% percentile speed were adopted from simulated data on selected sections (middle point of curve and tangent length) versus the value of CCR and grade. The operation speed and relative index by Criterion and are also shown in the table.

The side friction assumed is a fraction of tangential friction (ft) and is taken as being (2)

$$f_{RA} = 0.925 \times 0.6 \times f_T \qquad (2)$$

Where:

$$f_T = 0.59 - 4.85 \times 10^{-3} \times V_d + 1.51 \times 10^{-5} \times V_d^2$$

The side friction demanded is expressed by AASHTO (7) as follow:

$$f_{RD} = \frac{V_{85}^2}{127 \times R} - e \qquad (3)$$

Where:

R = radius of curve [m]

e = superelevation rate [%]

The Table 1 shows transversal friction index by Criterion .

4 DATA ANALYSIS AND EVALUATION

Based on 38 elements (22 curves and 16 tangents) in the test course, an analysis of the data gives rise to some results regarding the sample free way consistency and relationship of operating speeds regarding road alignment geometry.

In the table 1, the consistence of each element in test section are highlighted by "good", "fair" and "poor" lever as defined by Criterion , and separately. It can be noted that Criterion assumed good and fair for all elements except element 8. Actually, if considering horizontal curvature only respect to radius, the sample road as free way was designed in a high standard with an average radius of 1000km and minimum radius of 405km, therefore the each element has a good homogenous with successive ones. But as built in mountainous area the grades of road (up or down) frequently appear which have obviously impact on the speed as it was shown in figure 7. In the sample course, there are 16 segments with grade bigger than 2%, the maximum reach to 5%. This is the limited value of permitted grade in specific terrain for design speed over 100km/h in China. The great change of speed between element 8 and element 7 is just due to a great change of grade (from -3.5% up to 3.9% down).

For evaluation of Criterion , It can be found that at the elements of 3, 10, 20, 21, 23, 24, 25, the differences between 85% percentile speed and design speed were bigger than 20 km/h which highlight the inconsistency of those elements by "poor" lever. From the features of alignment of the sample in Table 1, all these spots located on the long tangent or curvature with radius over 700m and connecting with tangents in two ends. In addition the elements of 20, 21, 23, 24 and 25 are still on the slope over 3% (down hill). Accordingly, this behavior confirms drivers tend to fast the speed consciously or unconsciously when driving on tangent or down roads.

From the data collected speed and transversal acceleration profiles could be directly used for the evaluation of road alignment consistence. More specifically, the ratio ay/vx^2 represents the instant curvature (1/R) of the vehicle trajectory and is therefore used to evaluate the actual curvature car path as compared to the horizontal alignment. From transversal acceleration and mean speed profile of simulated results, the curvature of the car trajectory was calculated. Comparison with horizontal curvature is shown in Figure 8.

Considering operation speed and mean speed versus CCR at reasonable horizontal situations (grade rate < 2%) a correlation of operation speed and mean speed versus CCR was obtained separately by regressing the data adopted from the test result as showed in Figure 9 and Figure 10, the expression of the model were given as:

$$V_{85} = 122 - 0.378 \times CCR \qquad (4)$$
$$R^2 = 0.782$$

$$V_m = 104 - 0.345 \times CCR \qquad (5)$$
$$R^2 = 0.825$$

Analogously, the relationship between speed and grade rate at tangent or gentle curvature (radius > 700m) was regressed from test data, it was shown in Figure 11. The equation was given as:

$$V_{85} = 124 - 2.915 \times grade \times 100 \qquad (6)$$
$$R^2 = 0.75$$

As most of alignments is the combination of horizontal and vertical curve in the sample section. It is necessary to merge equation (4) and equation (6) for operation speed prediction, and merge equation (5) and equation (6) for mean speed prediction.

For down grade expected speed will increase with grade rate, and once more the actual speed will slow down with horizontal curvature. Provide that the expected speeds variance by the rate of equation (6) with grade, and the variance caused by curvature makes no diversity with equation (4) or (5), the combined equations can be expressed as:

$$V_{85} = 122 - 2.915 \times grade \times 100 - 0.378 \times CCR$$
$$V_m = 104 - 2.915 \times grade \times 100 - 0.344 \times CCR \qquad (7)$$

When speed slows down with up grade, it is not necessary to decrease the speed as same rate as in the flat topography at a curve. Because the speed rates regarding curvature in equation (4) and (5) are respect to expected speed. Accordingly when entering up hill and speed slows down to a limit no more decreasing speed at all regarding some curve. Two consequent equations by this concept were given by:

$$V_{85} = 122 - \left|2.915 \times grade \times 100, \quad 0.378 \times CCR\right|_{\max}$$
$$V_m = 104 - \left|2.915 \times grade \times 100, \quad 0.344 \times CCR\right|_{\max} \qquad (8)$$

The equation (8) implies that for the alignment with combination of horizontal curves and up grade the maximum between the speed decrease caused by grade and the decrease caused by CCR will be adapted as a decrement from expected speed.

The operation and mean speed profile by equation (7) and (8) were presented in Figure 12 and Figure 13, and comparison with test data shows a good agreement.

5 CONCLUSION

An evaluation of design consistence on existing multi-lane free way has been conducted by specific Driving Simulator experiments. The experiments were implemented with 30 test drivers (subjects), the data of vehicle positions, speeds, longitudinal and transversal accelerations and other relative parameters were collected from the simulation system.

Analysis of the experiments confirmed that a sequence of curves does not produce an unexpected driving event even if the combined horizontal curve and grade is adopted. The differences over 20km/h between operation speed (85% percentile speed) and design speed were observed on element 3, 10, 20, 21, 23, 24, 25 and alignments of these elements are found to be long tangent or small curvature (radius >700m), more specifically most of the elements(20, 21, 23, 24, 25) combined with down hill (3%-4%).

From evaluation of driving consistence with design lever (good, fair, poor) expressed by the Safety Criteria, the sample freeway in mountainous terrain is good in horizontal alignment which make a homogenous curvatures, both Criteria and give the lever of "good" or "fair". But as combined horizontal and vertical alignments frequently appear the bigger difference of operation speed respect to design speed can produce a dangerous situation if bad pavement conditions or unexpected events occur. This can be confirmed by mountainous free way accident history data in which most accidents happened at the bottom of down hill of long tangents.

Based on the data of speeds with respect to CCR and grade separately, the regressive models regarding operation and mean speed prediction were obtained. To combine these two linear models, a predicted speed profile was given and the comparison with the speed from the tests shows a good agreement.

ACKNOWLEDGMENT

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Figure 1 Driving Simulator used in the test

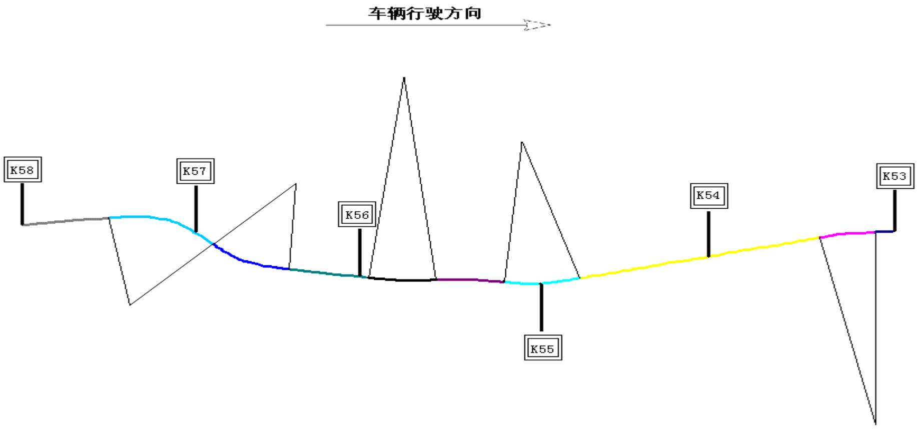
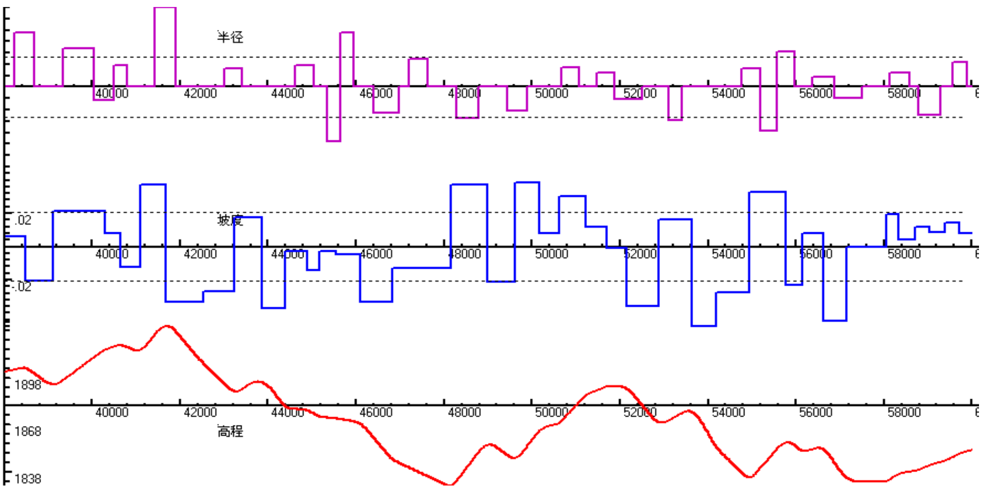
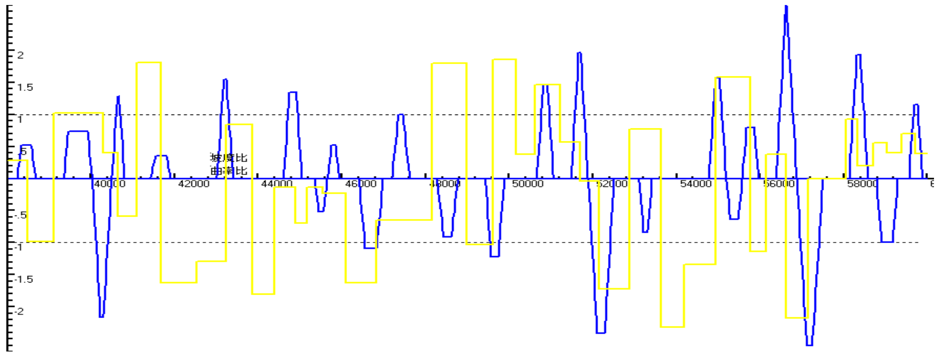


Figure 2 Part of sample road (K53-K58)



Above: radius, middle: grade rate, bottom: altitude

Figure 3 Geometric feature of the sample road



1 yellow: grade, 2) blue: curvature rate

Figure 4 Combined curvature rate and grade rate

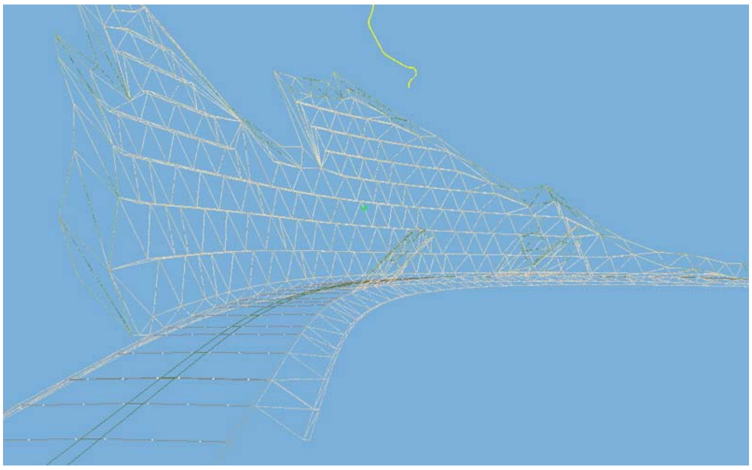


Figure 5 Geometric model of sample road

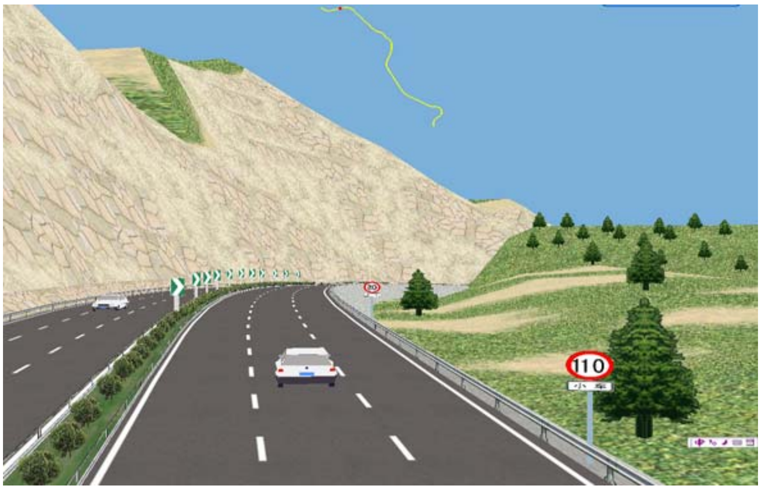


Figure 6 Virtual scenario of sample road

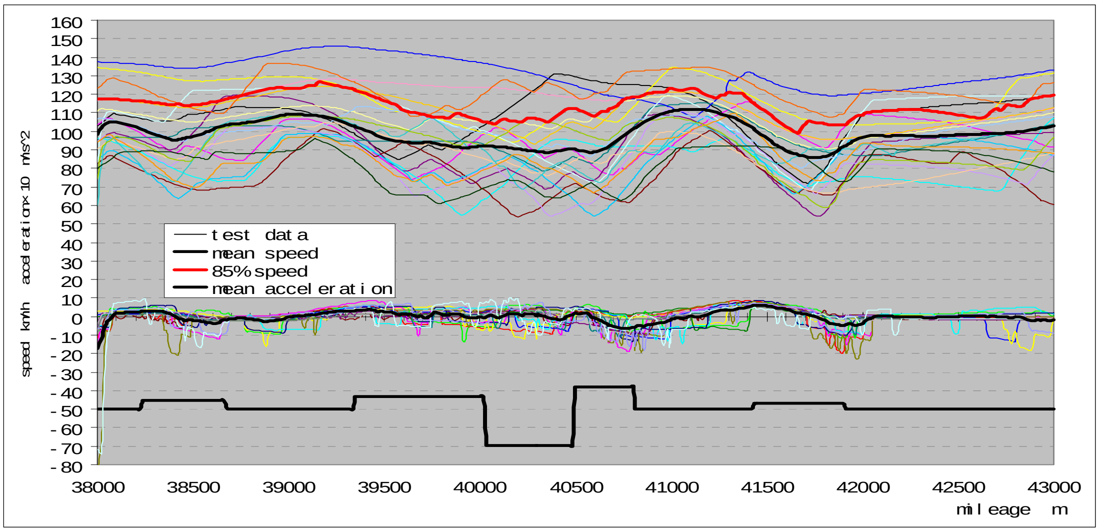


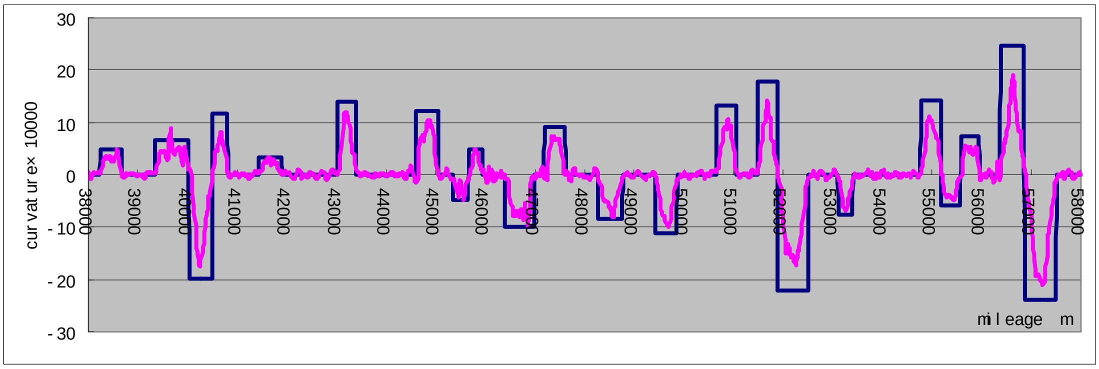
Figure 7 Speed and acceleration profiles of drivers

Table 1 Safety Evaluation Process for Sample Road

E	Radius (m)	Length (m)	CCR deg/ km	e %	Grade %(1)	Vd Km/h	V85 Km/h	Safety Criterion I **|V85i - Vd|**	Safety Criterion II **|V85i-V85i+1|**	Safety2) Criterion III **fRA - fRD**
1	∞	220	0	2	.6	100	117	17(fair)	--	-
2	2100	444	20.5	2	.6 -2.1	100	114	14(fair)	3(good)	0.113(good)
3	∞	669	0	2	-.2.1 2.2	100	123	23(poor)	9(good)	-
4	1500	682	32.0	3	2.2	100	109	9(good)	14(fair)	0.160(good)
5	506	464	64.4	8	2.2	100	107	7(good)	2(good)	0.013(good)
6	851	311	37.0	5	0.8 -1.2	100	110	11(fair)	3(good)	0.049(good)
7	∞	622	0	2	-1.2 3.9	100	121	22(fair)	11(fair)	-
8	3086	480	14.3	2	3.9 -3.5	100	98	1(good)	23(poor)	0.137(good)
9	∞	1105	0	2	-3.5 -2.7	100	110	10(good)	12(fair)	-
10	710	382	46.9	6	-2.7 1.8	100	121	21(poor)	11(fair)	-0.0003(fair)
11	∞	1207	0	2	1.8 -3.9 -0.3	100	107	7(good)	14(fair)	-
12	820	441	47.7	5	-0.3 -1.5	100	108	8(good)	1(good)	0.048(good)
13	∞	302	0	2	-1.5 -0.3	100	110	10(good)	2(good)	-
14	2100	306	18.3	2	-0.3 -0.5	100	106	6(good)	4(good)	0.120(good)
15	2113	289	17.7	2	-0.5	100	107	7(good)	1(good)	0.119(good)
16	∞	455	0	2	-0.5	100	102	2(good)	5(good)	-

					-3.5					
17	1000	588	41.7	4	-3.5 -1.4	100	105	5 (good)	3(good)	0.076(good)
18	∞	208	0	2	-1.4	100	108	8(good)	3(good)	-
19	1100	421	32.3	4	-1.4	100	111	11(fair)	3(good)	0.074(good)
20	∞	657	0	2	-1.4 3.9	100	126	26(poor)	15(good)	-
21	1200	498	32.4	4	3.9	100	124	24(poor)	2(good)	0.061(good)
22	∞	652	0	2	3.9	100	117	16(fair)	7(good)	-
23	900	452	43.9	5	4.0	100	125	25(poor)	8(good)	0.025(good)
24	∞	781	0	2	4.0 0.8 3.2	100	130	30(poor)	4(good)	-
25	750	406	46.3	6	3.2	100	120	20(poor)	10(fair)	0.011(good)
26	∞	413	0	2	3.2 1.2	100	109	10(fair)	11(fair)	-
27	560	405	56.8	7	1.2 -0.1	100	101	1(good)	8(good)	0.089(good)
28	453	621	81.6	9	-0.1 -3.7	100	100	0(good)	1(good)	-0.013(fair)
29	∞	605	0	2	-3.7 1.7	100	115	15(fair)	15(fair)	-
30	1300	302	29.5	3	1.7	100	112	12(fair)	3(good)	0.086(good)
31	∞	1361	0	2	1.7 -5 -2.9	100	107	7(food)	5(good)	-
32	700	416	50.4	6	-2.9 3.4	100	116	16(fair)	9(good)	0.010(fair)
33	1712	384	24.8	2	3.4	100	112	12(fair)	4(good)	0.114(good)
34	1377	382	30.7	3	3.4 -2.5	100	99	1(good)	13(fair)	0.106(good)
35	∞	423	0	2	-2.5 0.8	100	99	1(good)	0(good)	-
36	405	493	72	10	0.8 -4.7	100	83	17(fair)	15(fair)	0.107(good)
37	420	632	84	10	-4.7 0	100	89	11(fair)	6(good)	0.013(good)
38	∞	625	0	2	0 2.0	100	104	4(good)	15(fair)	-

Note (1): we define element number from K38 (1) to K58 (38), and up hill with positive grade, down hill with negative grade. But test driving was from K58 to K38 (reverse direction), in the case negative grade means up hill to driver and positive grade means down hill.



1) Pink curvature of car 2) Black: curvature of test course

Figure 8 Curvature of car path in test course

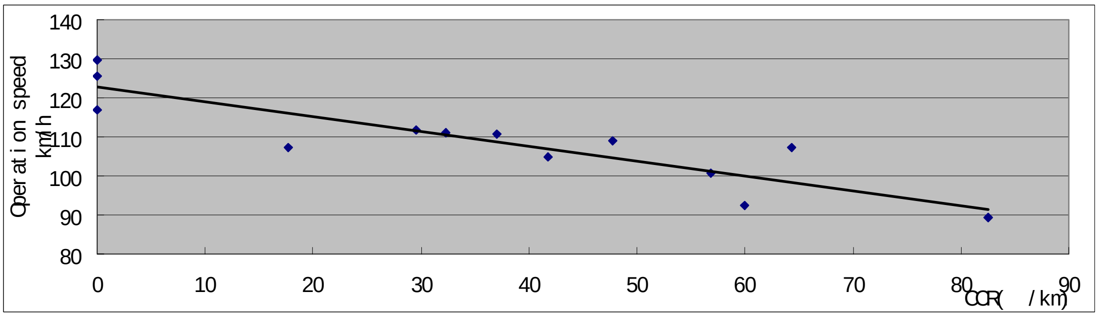


Figure 9 Regression analysis of operating speed versus CCR

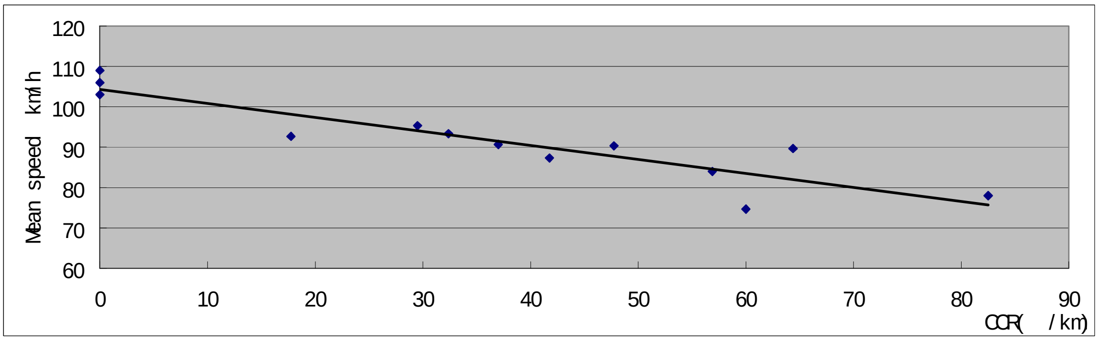


Figure 10 Regression analysis of mean speed versus CCR

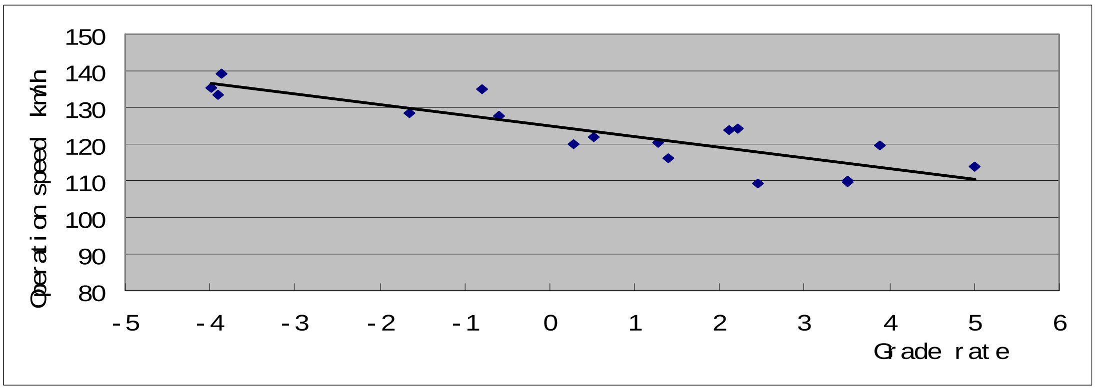
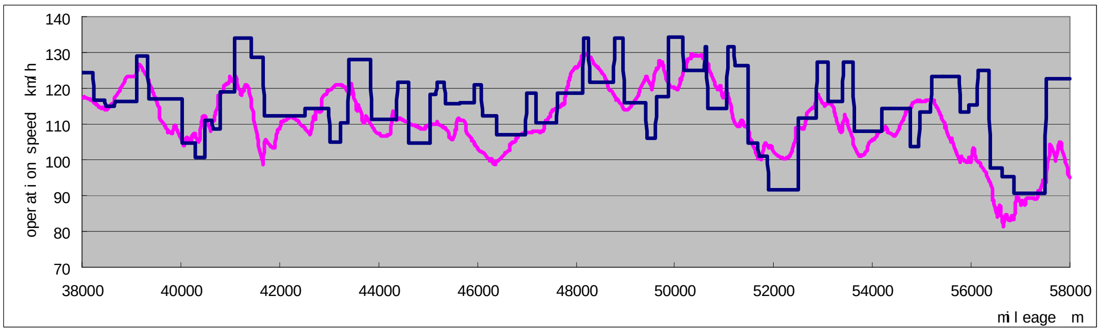
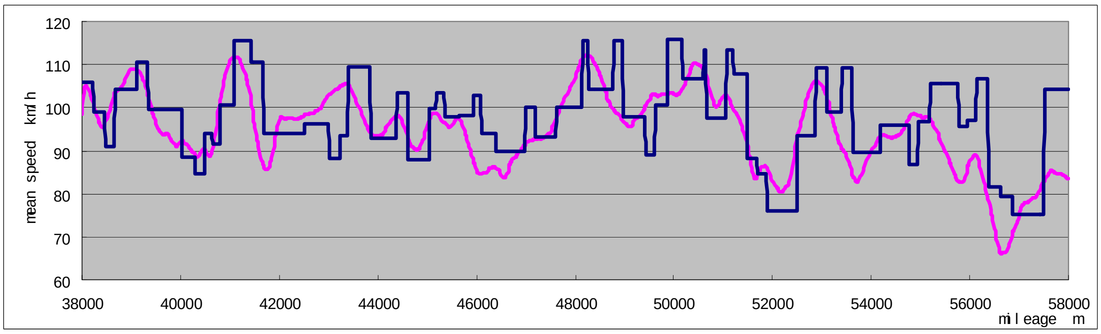


Figure 11 Regression analysis of operating speed versus grade



1) pink: tested speed 2) black: modeled speed

Figure 12 Operation speed profiles of combined linear model and tested



1) pink: tested speed 2) black: modeled speed

Figure 13 Mean speed profiles of combined linear model and tested