TRB

TRANSPORTATION RESEARCH RECORD

Journal of the Transportation Research Board, No. 1912

Geometric Design and the Effects on Traffic Operations 2005

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Actual Driving Data Analysis for Design Consistency Evaluation

by

Prof. Salvatore Cafiso
Department of Civil and Environmental Engineering
School of Engineering, University of Catania
Viale Andrea Doria 6, I-95125 Catania, Italy
Phone: + 39 095 738 2213
Fax: + 39 095 738 2247
E-mail: dcafiso@dica.unict.it

Dr. Alessandro Di Graziano
Department of Civil and Environmental Engineering
School of Engineering, University of Catania
Viale Andrea Doria 6, I-95125 Catania, Italy
Phone: + 39 095 738 2215
Fax: + 39 095 738 2247
E-mail: adigraziano@dica.unict.it

Dr. Grazia La Cava
Department of Civil and Environmental Engineering
School of Engineering, University of Catania
Viale Andrea Doria 6, I-95125 Catania, Italy
Phone: + 39 095 738 2223
Fax: + 39 095 738 2247
E-mail: glacava@dica.unict.it

ABSTRACT

As many researchers have proved in recent years, it can be assumed that a consistent highway design is one which ensures successive elements coordinated in such a way as to produce harmonious and homogeneous driver performances and does not provoke unexpected events.

Knowledge and practice highlights that drivers make fewer errors in the vicinity of geometric features that conform to their expectations. On this basis, the importance of identifying inconsistencies on highways and the significant contribution to road safety that this makes is emerging as an important feature in highway design. Although several techniques and models for evaluating the consistency of a design in a quantitative way have been identified and, even if some countries have implemented the design consistency concept in their road design guidelines in a mainly qualitative way, there have been only few efforts to measure actual driving behavior.

The aim of this paper is to determine design inconsistencies on existing two-lane rural roads using actual driving behavior by means of field data measurements and to verify their agreement with a consistency evaluation model. Furthermore, suitable equipment and a procedure for surveying driving dynamics and driver workload have been developed. In particular driving behavior is assessed through direct measurements and parameters taken from data collected on a selected sample of test drivers using a purposely designed instrumented vehicle. The vehicle, named Driver Instrumented Vehicle Acquisition System (DIVAS), was driven under real traffic conditions on a two lane rural road. The design classes of consistency of the test courses were, also, evaluated using a well known Safety Criteria Model. Data collection and treatment procedures will be presented and data analysis and results from this first experiment will be given.

INTRODUCTION

While driving, the driver receives and processes a series of input (mainly visual), based on his/her own characteristics (age, sex, psycho-physical state, level of attention, threshold of subjective risk), in order to estimate the various alternatives of driving behavior (for example: operating speed, car trajectory, gap distance), and to decide and execute the most appropriate maneuvers and afterwards observe their effect through the reception and elaboration of new information. 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. Understanding the driving task and driver expectancy is a key to characterizing inconsistent and undesiderable operating speed patterns or traffic maneuvers that are common manifestations of geometric inconsistency problems.

As many researches have proved in recent years (1), it can be assumed that a consistent highway design is one which ensures successive elements coordinated in such a way as to produce harmonious and homogeneous driver performances and does not provoke unexpected events. Design consistency is also defined as the degree to which a road is designed to avoid critical driving maneuvers that can lead to a risk of collision (2) or as the ability of the highway geometry to conform to driver expectancy (3). In particular, a consistent alignment 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. Knowledge and practice highlights that drivers make fewer errors in the vicinity of geometric features that conform to their expectations. Furthermore it was found that departures from consistency lead directly to an increase in accident rates and accident cost rates.

Thus, the importance of identifying inconsistencies on highways and the significant contribution to road safety that this makes is emerging as an important feature in highway design. Techniques and models to evaluate the consistency of a design in a quantitative way refer to operating speed measures (4,5,6), alignment indices (4,7), vehicle stability (4), and driver workload (8,9,10). Moreover, even though some countries, such as Canada (11) and South Africa (12), have implemented the design consistency concept in their road design guidelines, it remains often briefly mentioned and mainly qualitatively. Although most of the research has focused on identifying measures for design consistency and evaluation and on developing models for their estimation, there have been only few efforts to measure actual driving behavior.

The aim of this paper is to determine design inconsistencies on existing two-lane rural roads using actual driving behavior by means of field data measurements and to verify their agreement with a consistency evaluation model. Furthermore, suitable equipment and a procedure for surveying driving dynamics and driver workload were developed. In particular driving behavior is assessed through direct measurements and quantities taken from data collected on a selected sample of test drivers using a purposely designed instrumented vehicle and acquisition system. The vehicle, named Driver Instrumented Vehicle Acquisition System (DIVAS), was driven under real traffic conditions on a two-lane rural road The design classes of consistency of the test courses were, also, evaluated using a well known Safety Criteria Model.

In the paper the DIVAS and data collection procedures will be briefly presented, the test course and test driver sample introduced and results from this first experiment will be given.

THE DRIVER INSTRUMENTED VEHICLE ACQUISITION SYSTEM

The DIVAS is a standard medium class car (Fiat Brava 1600) equipped with high accuracy instruments (GPS double frequencies, optical odometer, inertial gyroscope, triaxial accelerometer, web camera), all synchronized using a multifunction DAQ Card controlled by a specific software for data acquisition and geo-referencing (figure 1) (13, 14).

A hardware and software system was designed and home built for synchronised dynamic and human data acquisition and the subsequent elaboration of analogical and digital information coming from the various devices. In point of fact, all data collected must have a common time reference (ID). The acquisition of analogical and digital signals is carried out by means of the multifunction DAQ Card which was programmed to acquire differential data from 4 analogical channels at an interval of 50 ms (20 Hz) between the various acquisition bursts. An acquisition burst relates to the sampling and the digitizing of the four analogical channels at a fixed speed equal to 10000 Hz.

The instant that acquisition begins is synchronized with an interrupt signal (PPS) coming from the GPS receiver at 1 second intervals. In this way, 20 sets of information from each channel are memorized each second, in this time interval the first (time t) and the last set of information (time t+1 sec) are geo-referenced.

Moreover, DIVAS is able to acquire and collect field data related to driving behaviour, while travelling under actual traffic conditions. Specifically, the system is able to measure data depending on driving behaviour, driving dynamics and road-vehicle interaction (Dynamic Data, DD) such as Vehicle Speed, Vertical, Longitudinal and Lateral Acceleration, Car positioning, distance, yaw angle and driver's Visual Field. These data are significant of driving modes and of the dynamic effects directly related to driving comfort and road-vehicle interaction. In effect, the four analogical channels of the multifunction DAQ Card were programmed to acquire the yaw angle, the longitudinal speed Vx and the accelerations along two axes of the reference system (vertical az and transverse ay). The acquisition was synchronised with a digital video camera and the Varioport® system. Varioport® permits several psycho-physiological parameters (Human Data, HD) to be recorded, such as Electrocardiogram (ECG), Electrooculogram (EOG), Electrodermal activity (EDA) and Electromyography (EMG) which proved to be suitable for evaluating changes in the driver's behavioural aspects and therefore in driver performance, that can be related to sudden changes in road characteristics.

EXPERIMENTAL DESIGN

To carry out this first experiment it was necessary to select test drivers and to choose test courses having characteristics of interest to the research. Analogously, data acquired from the DIVAS system had to be treated and elaborated to locate all the information with respect to the exact position of the vehicle along the test course and to obtain further evaluation parameters.

Test Driver Selection

Since a totally representative sample of all drivers does not exist, it was decided to define one from the driver population on the basis of homogeneity (all students aged 24-32, with equal driving experience) and validity also in terms of psycho physiological parameter responses. The first phase of the test driver selection, called pre-selection, was carried out using a form containing information relating to age, sex, health conditions and driving experience. On the basis of the collected data all the people who showed particular characteristics as compared to the defined standard were discarded. The second phase of selection was carried out on the basis of an appropriate protocol to check on the psycho-physiological characteristics, previewing the use of specific psychological tests and a PC driving simulation, in order to obtain groups of test drivers that were as homogenous as possible and suitable in terms of psycho- physiological parameters and driving reactions. During the tests, subjects were opportunely monitored with the electro medical equipment Varioport®, purposely designed for the requirements of the tests on road, which recorded specific psycho-physiological parameters (ECG, EMG, EOG, EDA).

Test Course Characteristics

The test courses for field experiments were selected from the local rural network (two-lane rural roads) in Sicily (Italy) and all belong to one road (SS 385). In particular each test course was at least 2 km long (max. 7 km), with a reasonably low AADT (2860 vehicles per day), since otherwise it would be difficult to arrive at an unhindered test ride. Each test course was selected as running between junctions in order to remove driver behavioural adaptation relating to the presence of a junction, leaving a stretch of 150m before and after it. For this paper the data collected along test courses numbers 6 and 7 (figure 2), 1873 m and 2134 m long, respectively, were selected.

At the beginning of the test, a long enough ride was needed, for the driver to become familiar with the test vehicle and to allow him or her to adapt to the HD recording system. Moreover the total length of the test had to avoid problems of fatigue for the test driver. An important requisite was that test drivers did not know, when the test course started and when it ended. Along each test course Static Data (SD), which represent the infra-structural features that do not change during the test but are important with respect to driving behaviour, were collected. These features were identified as being: alignment, roadside environment, cross section, available sight distance, traffic signs, presence of junctions and surface characteristics.

The design consistency of test courses were evaluated using a well known safety evaluation process based on quantitative consistency measurements according to Good (sound), Fair (tolerable), and Poor (dangerous) design practices. (4,15) which allows the quantified measurements of the following:

- design consistency, related to the difference between the operating speed, represented by the 85th-percentile speed (V85), and the design speed (Vd) of the observed roadway section (Safety Criterion I);
- operating speed consistency, related to the difference in V85, between two successive geometric elements (Safety Criterion II);
- driving dynamic consistency, determined by the difference between side friction assumed (f_{RA}) and demanded (f_{RD}), (Safety Criterion III).

As the differences between the two factors, that characterize the various safety criteria increase, there is a progressive decrease in the degree of consistency and thus a probable increase in dangerous situations. All the evaluation parameters of the three criteria depend on the Curvature Change Rate of the single curve (CCRs), which has been demonstrated to be the most successful parameter in explaining much of the variability in operating speeds and accident rates (4,15).

In Tables 1 and 2 and in Figures 3 and 4, the safety classification of test courses 6 and 7, related to different consistency measurements is shown.

A specific research was conducted to define the correlation between V_{85} and CCRs for roads with geometric characteristics similar to the test courses: two-lane rural roads with a pavement width of about 8,5 m. From this study (16) the following linear regression equation was obtained:

$$V85 = 107{,}8 - 0.053\ CCRs \quad (R^2=0.83) \quad \text{(Eq. 1)}$$

The formula for determining the curvature change rate of the single curve with transition curves is given by the following equation [4,15]:

$$CCR_S = \frac{\left(\frac{L_{Cl1}}{2R} + \frac{L_{Cr}}{R} + \frac{L_{Cl2}}{2R}\right)}{L} \times \frac{200}{\pi} \times 10^3 = \frac{\left(\frac{L_{Cl1}}{2R} + \frac{L_{Cr}}{R} + \frac{L_{Cl2}}{2R}\right)}{L} \times 63{,}700 \qquad \text{(Eq. 2)}$$

where:

CCR_S = curvature change rate of the single circular curve with transition curves [gon/km],
L = $L_{Cl1} + L_{Cr} + L_{Cl2}$ = overall length of unidirectional curved section [m],
L_{Cr} = length of circular curve [m],
R = radius of circular curve [m],
L_{Cl1}, L_{Cl2} = lengths of clothoids (preceding and succeeding the circular curve), [m].

Data Collection And Treatment

The tests were carried out in daylight and good weather conditions (no rain). In the end all HD and DD (17) related to 15 valid test drivers were collected

Referring to the Dynamic Data (DD), DIVAS permits the collection, for each test, of the longitudinal speed v_y and the accelerations along vertical and transverse axes (a_z and a_x), which can be used to define driving behaviour parameters. At the same time the digital video camera registers spot event occurrences, which could influence the driving mode, acquiring a frame each second.

First of all it was necessary to locate all these data along the test course, using the GPS reference system, transferring DD from time to metric series. In order to accurately locate the DIVAS GPS position along the road alignment, a procedure was developed using reference points in fixed position on the road (14).

The data collected for each test were used to define driving evaluation parameters, such as speed profile, longitudinal and transversal acceleration profile and curvature of driving path.

In effect, from the data collected only speed and transversal acceleration profiles could be directly used for the evaluation of driving behaviour, whilst for longitudinal acceleration and curvature car path a process to obtain evaluation parameters more directly correlated to driving behaviour is necessary. For example, the information derived from a_x and v_y measurements were combined in order to obtain information about the vehicle trajectory. More specifically, the ratio a_y/v_x^2 represents the instant curvature (1/R) of the vehicle trajectory and was therefore used to evaluate the actual curvature car path as compared to the horizontal alignment.

The profiles of each test were, first of all, cleaned of spot event occurrences that condition the driving modes (i.e. queuing and/or overtaking manoeuvres). More specifically, by means of camera image analysis, the starting and finishing points of DIVAS during the spot event were located along the alignment. Then, the stretch of road run by the test during the period influenced by the spot event was removed and not used in the data evaluation process.

In Figure 5, the data collected and used for test 34 on test course 6 are presented. The first part of the path was eliminated as it was involved in queuing and subsequent overtaking manoeuvres. Using the images it was possible to identify the traffic flow conflicts which determine such manoeuvres leading the test driver to change his or her driving behaviour.

DATA EVALUATION AND ANALYSIS OF RESULTS

Even if the number of elements (8 curves and 4 tangents) in the two test courses are limited, allowing only general considerations to be drawn, an analysis of the data gives rise to several interesting considerations regarding driving behaviour with respect to horizontal alignment consistency.

In the graphical elaboration of the mean speed profile, the influence of curvature on operating speed of drivers (figures 6 and 7) is highlighted. On the same test road (16), a set of spot speed measurements were conducted on selected sections (middle point of curve and tangent length) with different values of CCRs, in order to compare the results obtained from the test sample with a wider sample of road users. For each section a sample of, at least, 300 vehicles travelling under free flow conditions were surveyed to obtain statistics relating to operating speed. Regression analysis of mean speed versus CCRs showed a good linear correlation (figure 8). The comparison between the expected mean speed, obtained from the linear correlation, and the mean speed of test drivers on curve and tangent shows a good agreement. This result confirms the representativeness of the test sample.

In order to analyse driving behaviour consistency, it is also useful to study the speed gradients and therefore the longitudinal acceleration (figure 6 and 7). The longitudinal acceleration profile shows a maximum deceleration (transition from tangent to curve) of less than 0.5 m/s^2 where a good consistency exists in horizontal alignment (sequence of curves with similar radius between short tangents). Values in the range of 0.6÷0.5 m/s^2 can be obtained just by the release of the gas pedal, as checked with the DIVAS driving on a test track with starting speed in the range of 100÷40km/h. This consistency is, also, highlighted by a “good” level as defined by safety Criterion II (figures 3 and 4). Deceleration values of about 1 m/s^2 were observed approaching curves n. 4 test course 7 and n. 10 test course 6, with a fair level of Criterion II. Where Safety Criterion II gives a poor level (element 2 - test course 6) a maximum speed deceleration of about 2 m/s^2 was observed. These values, compared to the first, can be obtained with a braking manoeuvre and not only by the release of the gas pedal. Such driving behaviour shows that the driver is forced to adapt his/her speed to the alignment curvature even in the presence of traffic signs for dangerous curves and speed limits located on the road. On the two test courses, along the transitions from curve to tangent, the acceleration phase is usually more gradual with speed gradients of 0.5 – 0.9 m/s^2.

The maximum value of deceleration is always reached at the beginning of the curve while the acceleration phase starts near the middle of the curve. This behaviour is probably due to the absence of transition elements (clothoids) between tangents and curves. The need of the driver to correct this incorrect horizontal alignment becomes evident also looking at the curvature of car path (figure 9 and 10). The entry steering manoeuvre usually starts 50 ÷ 70 meters before the beginning of the curve with a progressive increase of curvature that continues inside the curve reaching a minimum value approximately equal to the inverse of the curve radius, with the exception of elements 2 and 10 in test course 6 where the driver has to correct his manoeuvre using a very low steering radius due to the unexpected curvature of the alignment. The steering manoeuvre to come out of the curve starts inside the curve lasting until the straight trajectory at the beginning of the successive tangent is reached. This behaviour confirms that test drivers tend to reach the curvature they perceive in their front visual field shifted respect to the vehicle location. These aspects evidence the usefulness to introduce the transition curves to adapt the alignment to real driving trajectory.

Finally, with respect to transversal acceleration (Ta) in the curve (figures 9 and 10), dynamic data show comfortable values, less than 0.2 g, adopted by drivers on curves with large radius (R>300 m) or in curvilinear alignment (sequence of elements 8, 6 and 4 – test course 6). When drivers are surprised by an unexpected curve radius (e.g. a sharp curve after a long tangent) they are forced to reach Ta values of about 0.3 g (elements 2 and 10 – test course 6). These values are due both to high speeds and to real curvature paths lower than the centreline alignment of the curve. Therefore, criterion III related to radial friction assumed and demanded can be influenced by the deviation between real and conventional path.

Comparing the behavioural considerations with the results coming from the safety criteria, it can be noted that in test course 6 for element 2 safety criteria I and II assume fair and poor levels and for element 10 safety criteria I and II assume good and fair levels, respectively. Safety criterion III gives poor levels for all the curves in test course 6. Instead, the comparison with the Ta values highlights the worst conditions still at element 2 and 10.

CONCLUSION

An instrumented vehicle, named DIVAS, was driven under real traffic conditions to evaluate design inconsistencies on existing two-lane rural roads using actual driving behavior by means of field data measurements. The experimental test was conducted with 15 test drivers, collecting the Dynamic Data (DD) of vehicle position, longitudinal speed, vertical and transversal accelerations, digital video camera frames which were used to define driving behaviour parameters.

The experiment confirmed that a coordinate sequence of curves does not produce an unexpected driving event even if short bending radius are adopted. Geometric inconsistency produced by a sharp curve following a long tangent produces tense driving behaviour as was observed on elements 2 (R=120 m) and 10 (R=80 m) in test course 6. Driving inconsistencies are highlighted by high speed gradients of about 2 m/s^2, transversal accelerations of 0.3 g and local maximum curvature of the car path higher than those required by horizontal alignment. These values of deceleration reached with a light braking action are higher than $0.80 \div 0.85$ m/s^2 generally assumed regarding driving behaviour in speed profiles diagrams. These manoeuvres are caused by the driver's need to suddenly correct his/her driving behaviour due to an unexpected alignment and can produce a dangerous situation if bad pavement conditions or unexpected events occur. The lack of transition curves is another contributing factor in geometric inconsistency.

The comparison of driving inconsistencies with the design level (good, fair, poor) expressed by the safety criteria, confirmed the worth of this safety evaluation approach. From this point of view the criteria that were better able to describe consistency between driver expectancy and horizontal alignment were criterion II and partially criterion I. Since also criterion III gives useful information above all if they are compounded with the ones coming from the other two criteria, an overall consistency evaluation using all three criteria improve the safety analysis.

Although, the experiment is still in progress, the results have shown interesting correlations between Dynamic Data and geometric consistency. DIVAS system have permitted also the collection of psycho-physiological parameters (Human Data, HD) during the tests. Human Data evaluation will give original information about the mental workload of the driver and its correlation with road features.

It is foreseen that these experimental results will provide useful information regarding the interaction existing between road environment and road user behaviour in order to design safer roads.

ACKNOWLEDGMENT

The research project was financed by the Italian Minister of Research and by the University of Catania with the scientific contribution of prof. Ruediger Lamm (University of Karlsruhe) and Dipl. Eng. Ralf Heger (University of Dresden).

The car used to prepare the DIVAS was on free loan from the Province of Catania.

REFERENCES

1. Fitzpatrick K., Wooldridge M., Tsimoni O., Collins J., Green P., Bauer K., Parma K., Koppa R., Harwood D., Anderson I., Krammes R., Poggioli B.. Alternative Design Consistency Rating Methods for Two-Lane Rural Highways. Federal Highway Administration Report FHWA-RD-99-172, Springfield, VA, 2000
2. Al-Masaied H. R., Hamed M., Albul-Ela M. and Ghannam A.G. Consistency of Horizontal Alignment for Different Vehicle Classes. Transportation Research Record 1500, Transportation Research Board, Washington D.C., pp 178-183, 1994
3. Nicholson A. Superelevation Side Friction and Roadway and Roadway Consistency. Journal of Transportation Engineering, American Society of Civil Engineering, ASCE, Vol. 124(5), pp. 411-418, 1998
4. Lamm R., Psarianos B., Mailaender T. Highway Design and Traffic Safety Engineering Handbook. McGraw-Hill, Professional Book Group, New York, N.Y., U.S.A., 1999, 932 pages, ISBN 0-07-038295-6, Language Editors: J.C. Hayward, E.M. Choueiri, and J.A. Quay.
5. Morall, J. Talarico M.J. Side friction demanded and margins of Safety on Horizontal Curves. Transportation Research Record 1435, Transportation Research Board, Washington D.C., pp 145-152, 1994
6. Polus A., Fitzpatrick K., Fambro D.B. Predicting Operating Speeds on Tangent Sections of two lane Rural Highways. Transportation Research Record 1737, Transportation Research Board, Washington D.C., pp 145-152, 2000
7. Anderson I. B., Bauer K., Harwood D., Fitzpatrick K, Relationship to Safety of Geometric Design Consistency Measures for Rural Two-lane Highways. Transportation Research Record 1658, Transportation Research Board, Washington D.C., pp 43-51, 1999
8. Wooldridge M., Bauer K.,Green P., Fitzpatrick K.Comparison of driver visual demand in test track, simulator, on-road environments. Proceedings of the 79th Annual Meeting of the Transportation Reasearch Board, National Research Council, Washington D.C., CD ROM. Natioanl Academy Press, Washington D.C.2000
9. Messer C.J. Methodology for evaluating geometric design consistency. Transportation Research Record 757, Transportation Research Board, Washington D.C., pp 7-14, 1980
10. Heger R., (1995), Driving Behavior and Driver Mental Workload as Criteria for Highway Geometric Design Quality. International Symposium on Highway Geometric Design Practices, Boston Massachussets, U.S.A.,
11. Transportation Association of Canada – ACT “Geometric Design Guide for Canadian Roads – Part 1” September 1999
12. South African National Roads Agency “Geometric Design Guidelines”. January, 2003
13. S. Cafiso & G. La Cava, R. Heger, R. Lamm Integrating Human Factor Evaluation in the Design Process of Roads – A Way To Improve Safety Standards For Rural Roads XXII WORLD ROAD CONGRESS, PIARC , 19-25 October 2003, Durban, South Africa.
14. S. Cafiso, A. Di Graziano, G. La Cava, R. Lamm, R. Heger In Field Data Collection for Driving Behaviour Analysis using the DIVAS Instrumented Car. XIV International Congress SIIV 27/29 Ottobre 2004, Florence, Italy
15. R. Lamm, B. Psarianos, S. Cafiso. Safety Evaluation Process of Two-Lane Roads. A 10-Year Review. Transportation Research Record 1796, 2002, pp 51-59. ISBN: 0309077214.
16. Francesco Scuderi “Experimental research of operating speed on local rural roads”. Master thesis, School of Engineering, University of Catania, Italy. April 2004.
17. Giovanni Lo Bianco “Experimental research of Driving Behaviour Consistency”. Master thesis, School of Engineering, University of Catania, Italy. In progress.

LIST OF TABLES AND FIGURES

TABLE 1 SAFETY EVALUATION PROCESS FOR TEST COURSE 7

Element	**Design Element**	**Length Li**	**CCRSi**	**e**	**Vd ≈ ∅V85**	$V85_i$[1)]	**Safety** Criterion I **|V85i - Vd|**	**Safety Criterion II |V85i - V85i+1|**	**Safety2) Criterion III fRA - fRD**
no.	[m]	[m]	[gon/km]	[%]	[km/h]	[km/h]	[km/h]	[km/h]	[-]
1	R = ∞	160	0	2,5	100	102,30	2,30 (good)	5,90 (good)	-
2	R = 298	105	213	5,0	100	96,40	3,60 (good)	4,99 (good)	- 0,028 (fair)
3	R = ∞	80	0	2,5	100	101,40	1,40 (good)	3,90 (good)	-
4	R = -330	215	193	5,1	100	97,50	2,50 (good)	10,30 (fair)	- 0,011(fair)
5	R = ∞	1090	0	2,5	100	107,80	7,80 (good)	7,85 (good)	-
6	R = 433	482	147	4,5	100	99,95	0,05 (good)	9,95 (good)	0,029 (good)

Legend:

1) $V85_i$ is based on Equation (1).
2) n = utilization ratio of side friction. For existing alignments: n = 0.6.

$$\varnothing CCR_S = \frac{\sum_{i=1}^{i=n} (CCR_{Si} \times L_i)}{\sum_{i=1}^{i=n} L_i} \qquad \text{(Eq. 6)}$$

where:

$\varnothing CCR_S$ = average curvature change rate of the single curves across the section under consideration without regarding tangents [gon/km] ,

CCR_{Si} = curvature change rate of the i-th curve [gon/km] ,

L_i = length of the i-th curve [m].

$\varnothing CCR_S = \frac{164 \cdot 272 + 1274 \cdot 80 + 185 \cdot 260}{272 + 80 + 260} \approx 318$ gon/km ➚ ∅V85 = 85 km/h (Eq. 4)

➚ V_d = 90 km/h (selected).

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

$$f_{RA} = 0.925 \times n \times f_T \qquad \text{(Eq. 7)}$$

where

$$f_T = 0.59 - 4.85 \times 10^{-3} \times V_d + 1.51 \times 10^{-5} \times V_d^{\;2} \qquad \text{(Eq. 8)}$$

The side friction demanded is expressed as

$$f_{RD} = \frac{V85^2}{127 \times R} - e \qquad \text{(Eq. 9)}$$

where

R = radius of curve [m]

e = superelevation rate [% / 100]

TABLE 2 SAFETY EVALUATION PROCESS FOR TEST COURSE 6

Element	**Design Element**	**Length Li**	**CCRSi**	**e**	**Vd ≈ ∅V85**	$V85_i$ 1)	**Safety** Criterion I **|V85i - Vd|**	**Safety Criterion II |V85i - V85i+1|**	**Safety2) Criterion III fRA - fRD**
no.	[m]	[m]	[gon/km]	[%]	[km/h]	[km/h]	[km/h]	[km/h]	[-]
1	R = ∞	754	0	2,5	80	107,80	27,80 (poor)	42,22(poor)	-
2	R =-80	63	791	7,0	80	65,58	14,42 (fair)	38,76 (poor)	- 0,157 (poor)
3	R = ∞	456	0	2,5	80	104,34	24,34 (poor)	18,18(fair)	
4	R = 157	100	405	6,4	80	86,16	6,16 (good)	1,55 (good)	- 0,115 (poor)
5	R = ∞	69	0	2,5	80	87,71	7,71 (good)	7,48 (good)	-
6	R = -123	65	516	6,9	80	80,23	0,23 (good)	6,32 (good)	- 0,149 (poor)
7	R = ∞	60	0	2,5	80	86,55	6,55 (good)	1,54 (good)	-
8	R = 149	73	427	6,5	80	85,01	5,01 (good)	2,95 (good)	- 0,123 (poor)
9	R = ∞	86	0	2,5	80	87,96	7,96 (good)	8,31 (good)	-
10	R = -120	76	527	6,9	80	79,65	0,35 (good)	10,35 (fair)	- 0,151 (poor)
11	R = ∞	68	0	2,5	80	n.r	n.r.	n.r.	-

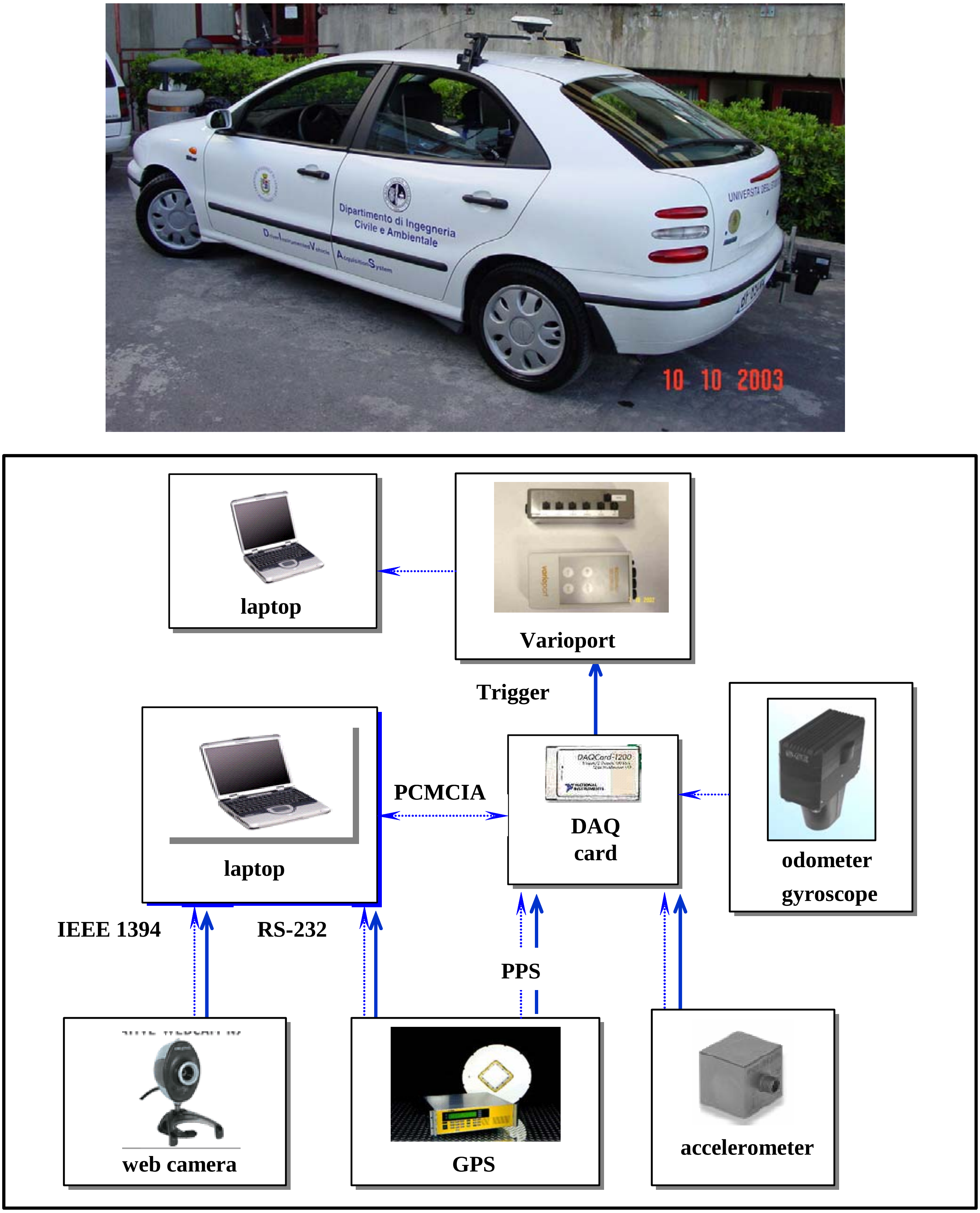


FIGURE 1 - DIVAS: vehicle and instrumentation connection scheme

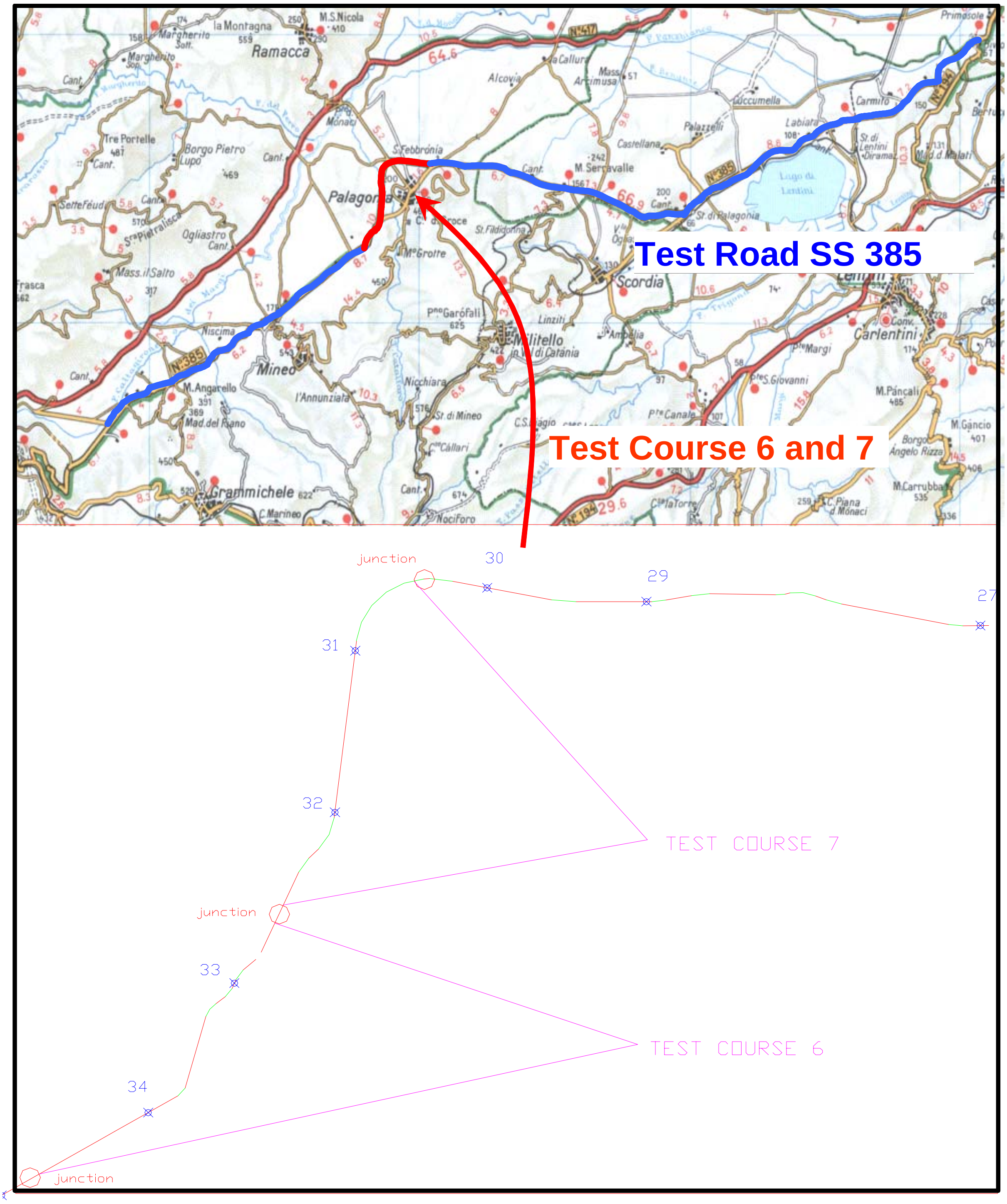
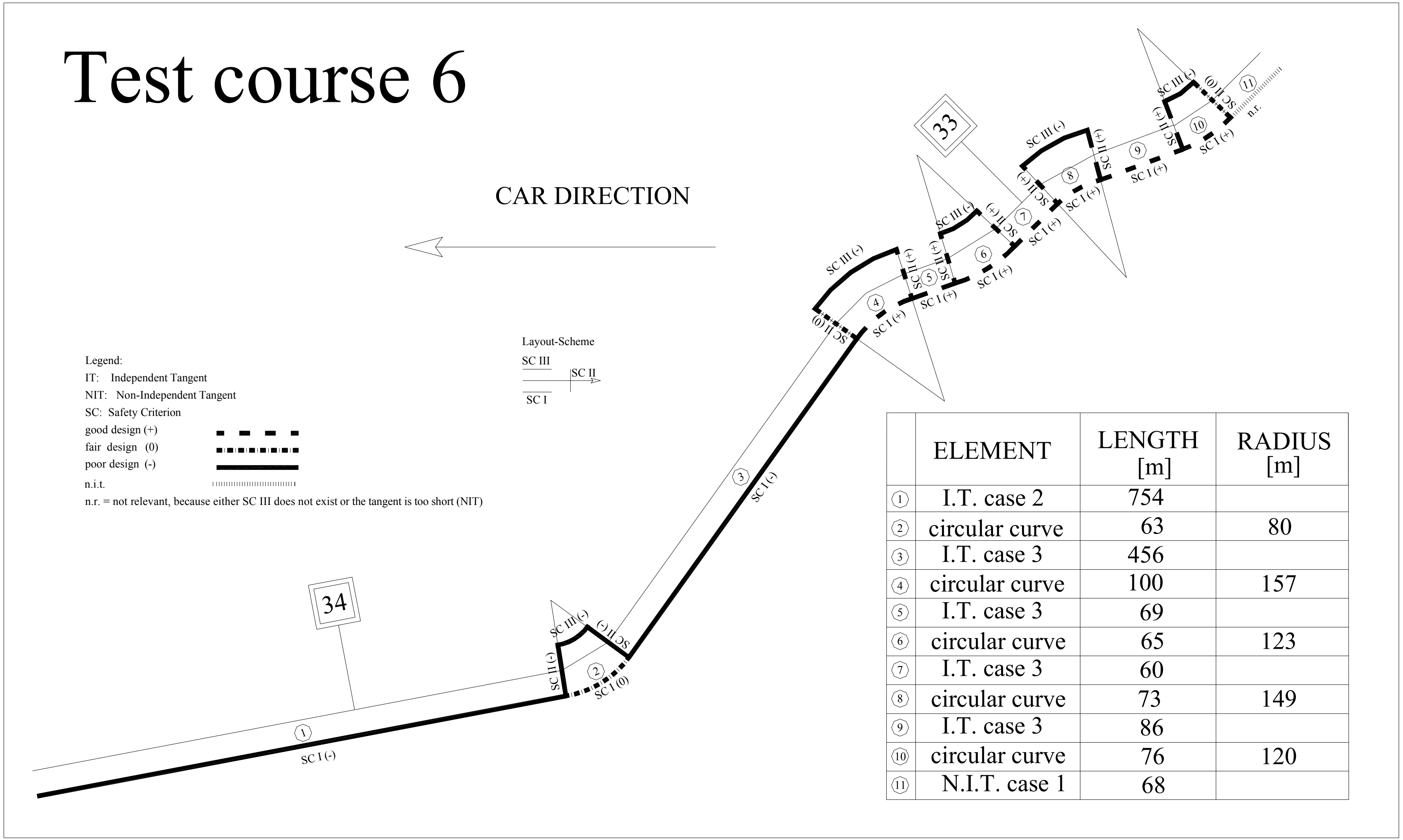
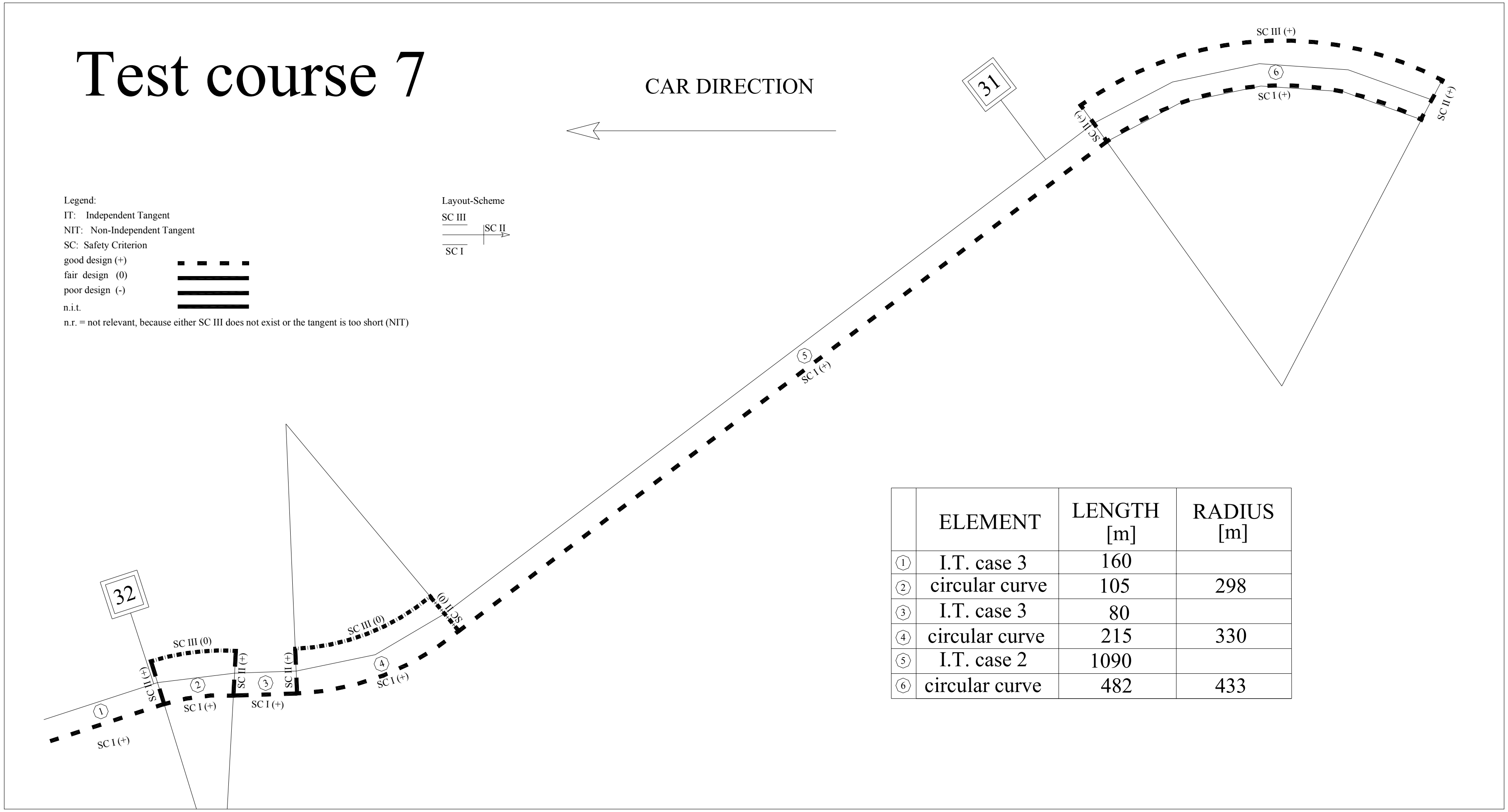


FIGURE 2 – Test road location and test courses alignment



	ELEMENT	LENGTH [m]	RADIUS [m]
①	I.T. case 2	754	
②	circular curve	63	80
③	I.T. case 3	456	
④	circular curve	100	157
⑤	I.T. case 3	69	
⑥	circular curve	65	123
⑦	I.T. case 3	60	
⑧	circular curve	73	149
⑨	I.T. case 3	86	
⑩	circular curve	76	120
⑪	N.I.T. case 1	68	

FIGURE 3 – Test course 6: geometric element and safety criteria evaluation



	ELEMENT	LENGTH [m]	RADIUS [m]
①	I.T. case 3	160	
②	circular curve	105	298
③	I.T. case 3	80	
④	circular curve	215	330
⑤	I.T. case 2	1090	
⑥	circular curve	482	433

FIGURE 4 – Test course 7: geometric element and safety criteria evaluation

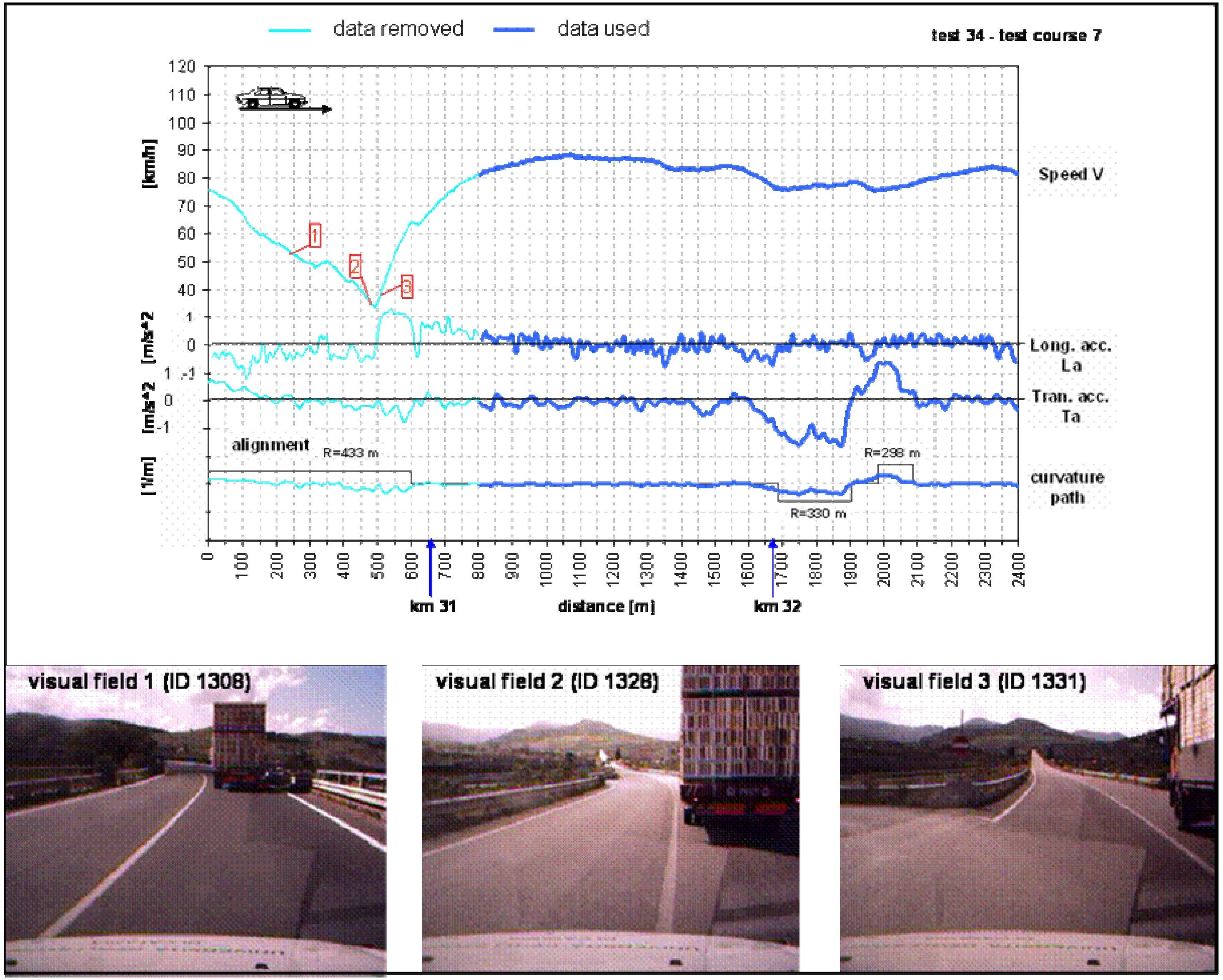


FIGURE 5 – Example of Dynamic Data report and treatment for single test driver

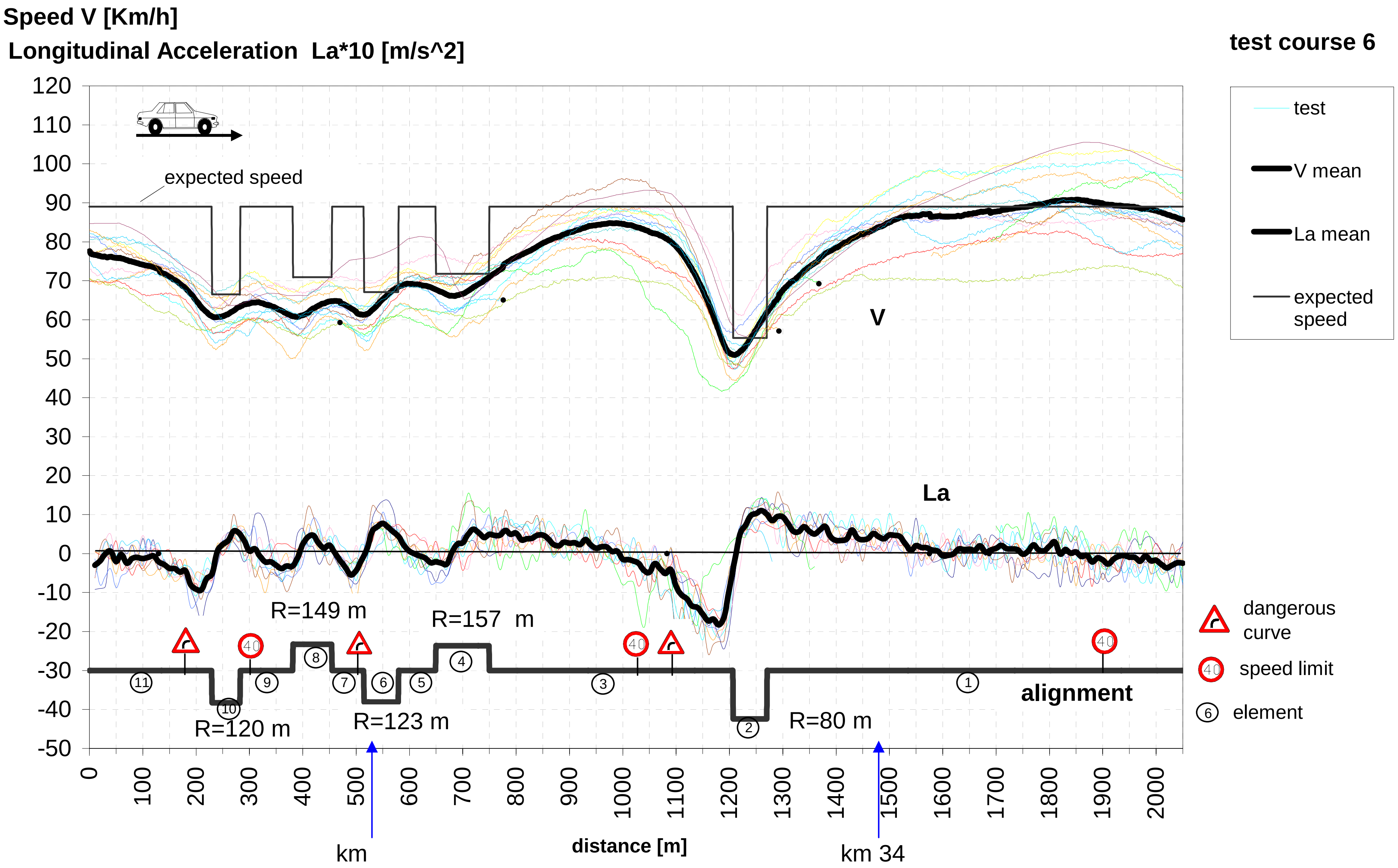


FIGURE 6 – Speed and longitudinal acceleration profiles in test course 6

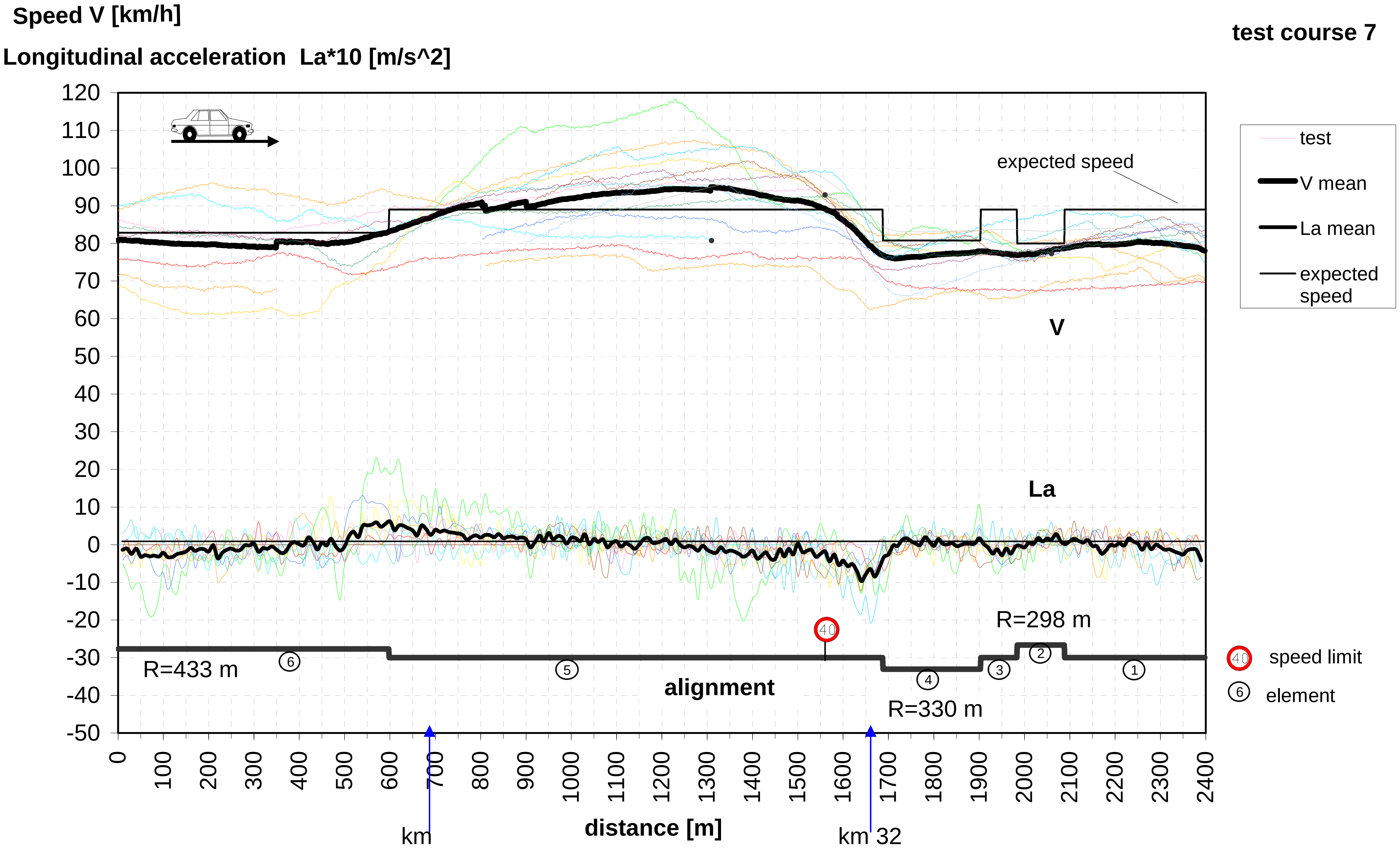


FIGURE 7 – Speed and longitudinal acceleration profiles in test course 7

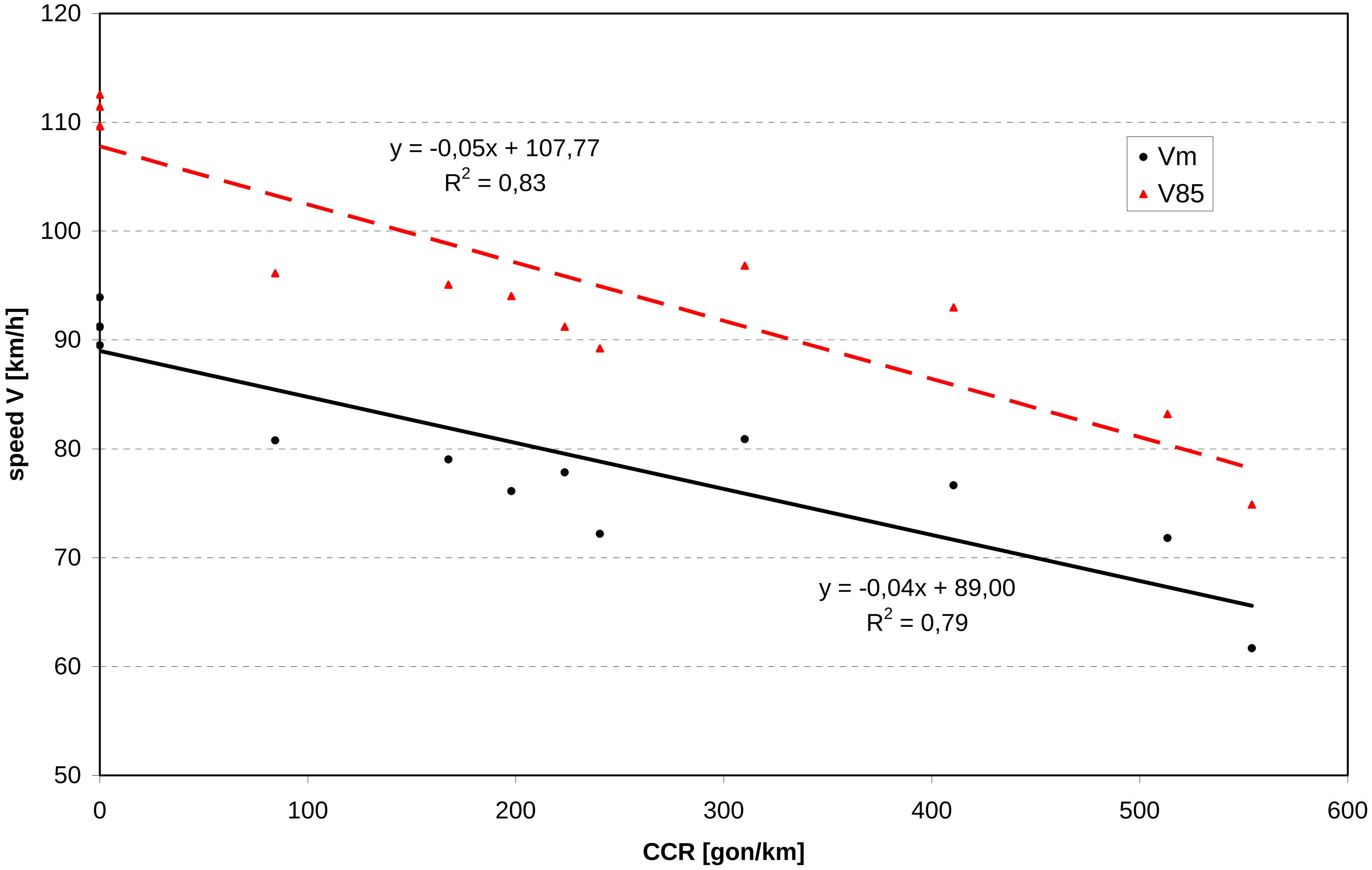


FIGURE 8 – Regression analysis of operating and mean speed versus CCR

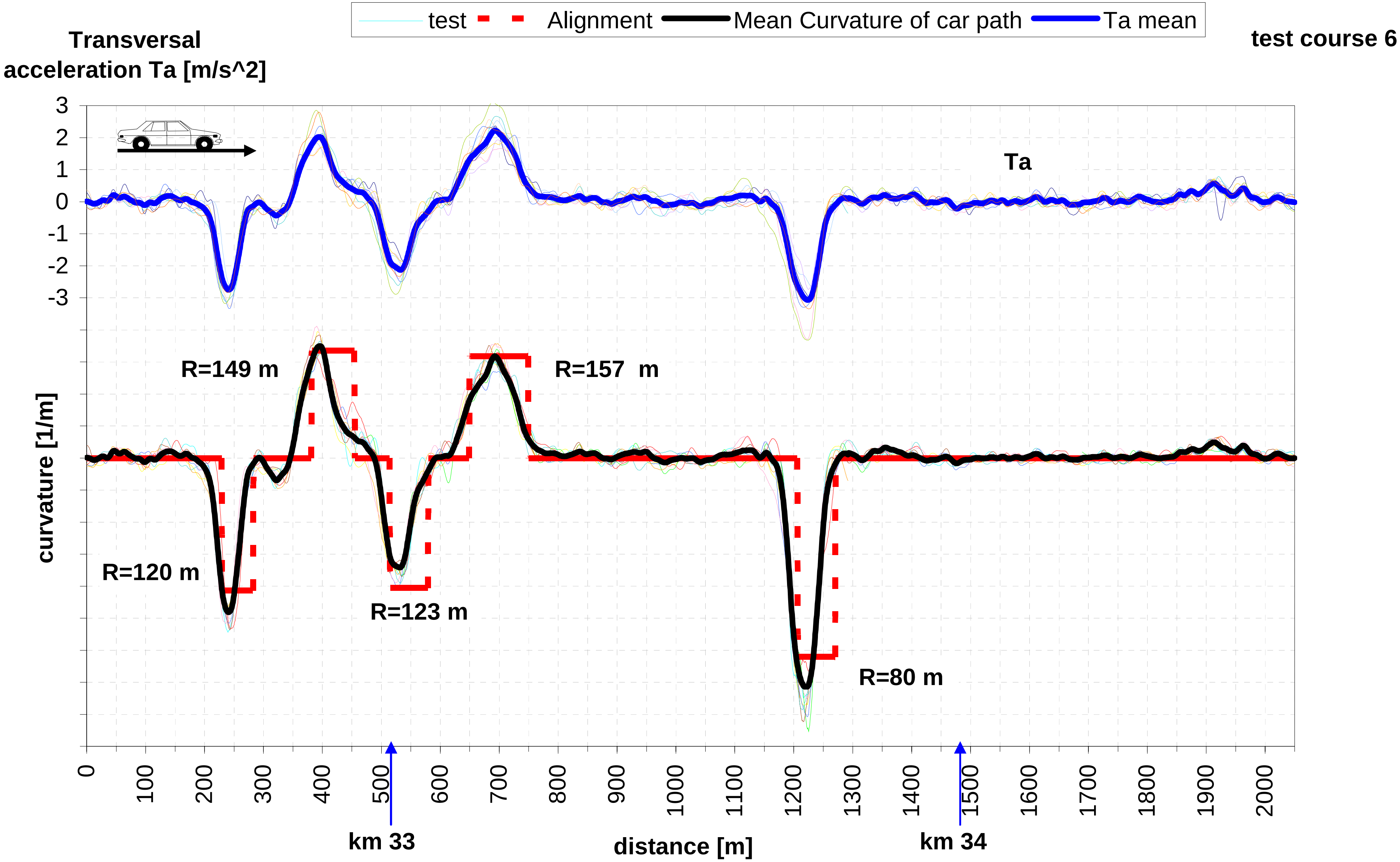


FIGURE 9 – Curvature of car path and transversal acceleration profiles in test course 6

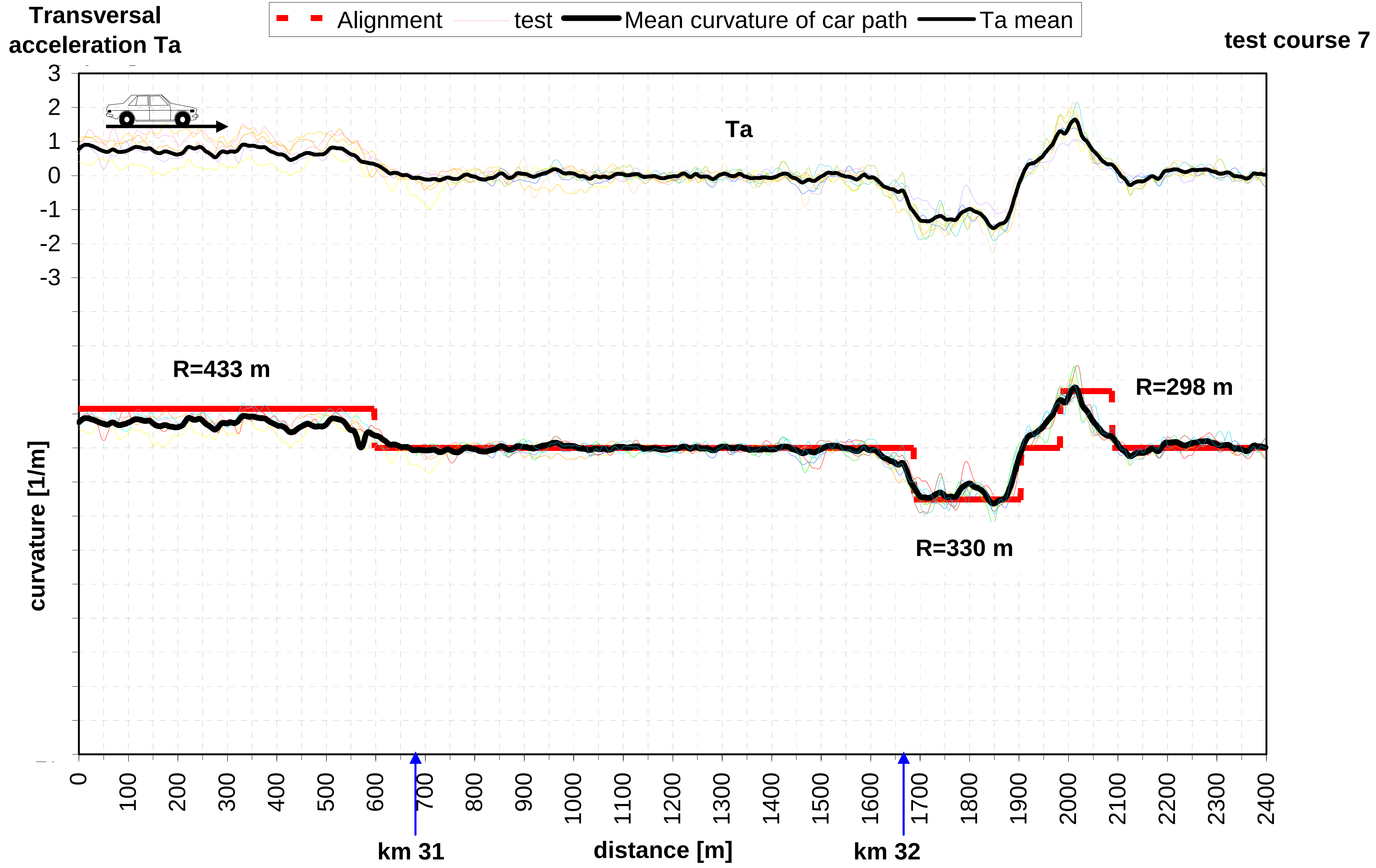


FIGURE 10 – Curvature of car path and transversal acceleration profiles in test course 7