To drive the Appropriate Speed in Curves

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Synopsis

1 Introduction / Statement of the Problem

The commercial and technical capabilities of society depend on the efficiency of the existing road network. The construction companies, as a result of the escalation of vehicle traffic and its implications for the economy, have reacted by constructing new and extending existing roads. These projects always appear to be making up for deficiencies and vary from region to region. The resulting heterogeneous road network only partly conforms to the traffic regulations and so does not fully meet todays current requirements. The greater part of the out of town traffic is carried by the federal motorways. About 6,000 out of the 8,000 road traffic deaths each year occur on out of town roads. (fig. 1)

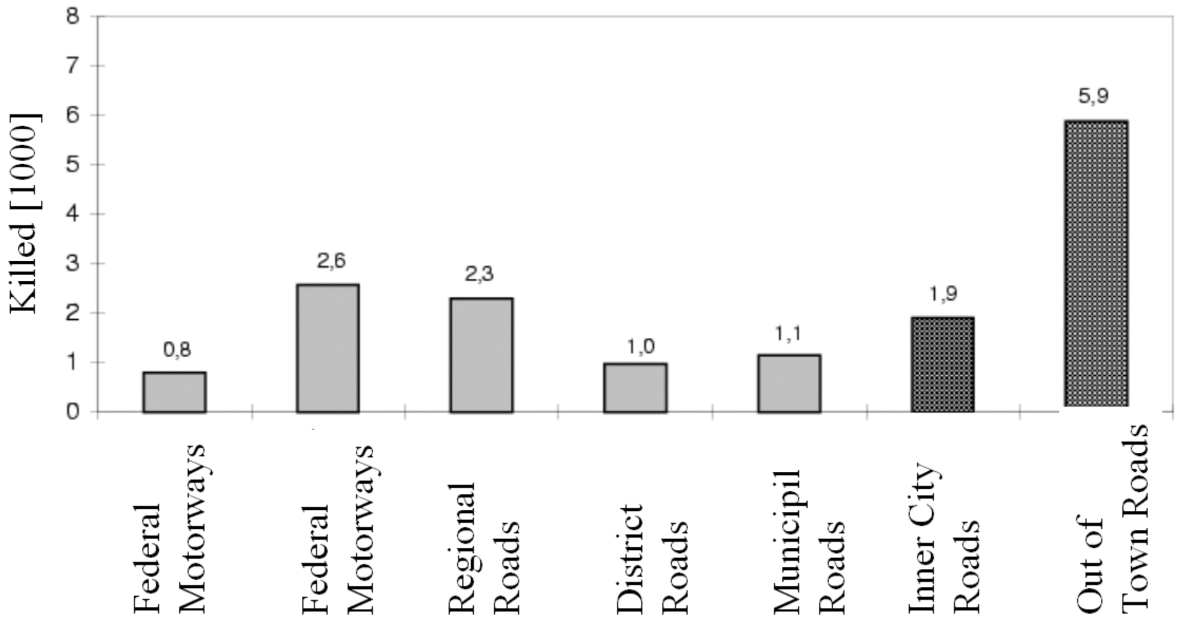

Fig. 1: Distribution of Road Deaths according to the Road Classification System in Germany in 1999

The steady decrease in road deaths and severe injuries in the last 10 years can be traced back to the safety reqirement developments in various areas (road network, road construction, road equipment and street furnishings, motor vehicle technology, traffic laws and traffic education, etc.) Marked inroads into the decrease in the percentage of deaths and severe injuries are also influenced by the introduction of seat belt regulations, more restrictive alcolhol limits and other restrictive measures. Automobile manufacturers have developed driver assistance systems which make driving safer and more efficient (ABS, ESP, DBC etc.). The distribution of accident numbers and accident costs occurring on out of town roads, shows that the most common cause of driving accidents is the loss of control of the vehicle by the driver himself, without any influencing factors from other drivers (see Fig.2)

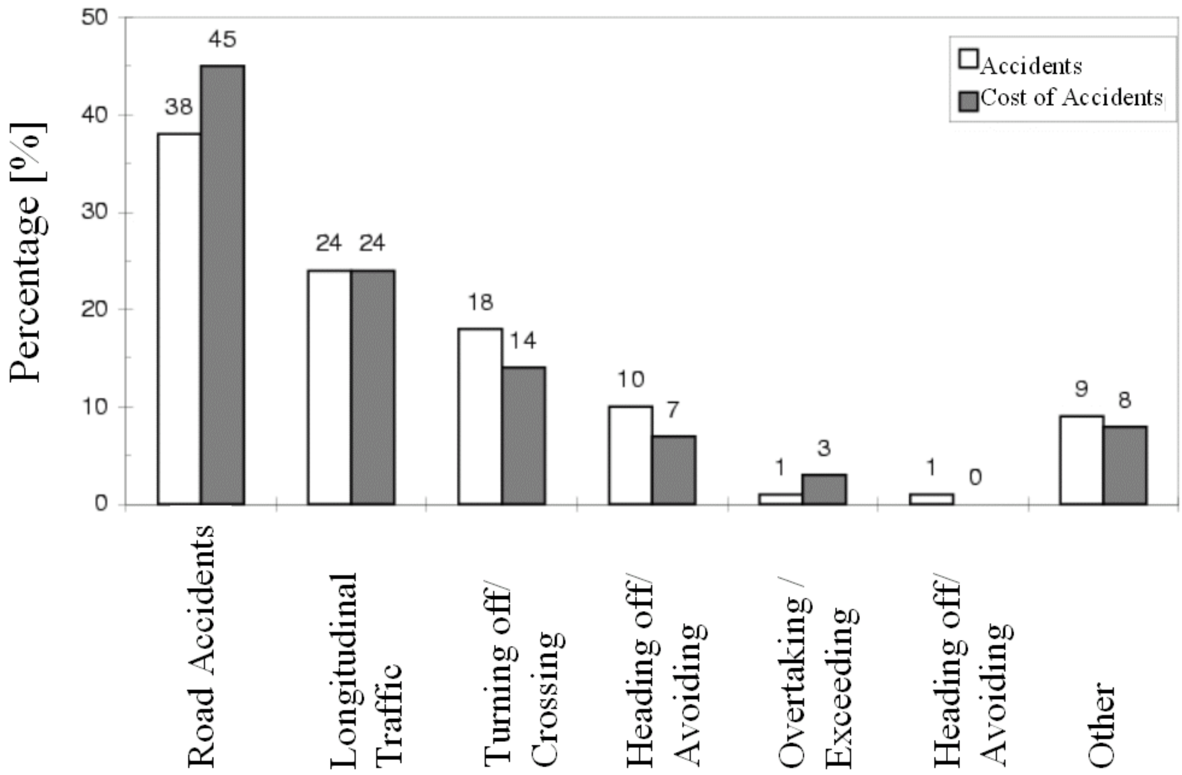

Fig. 2: Comparison of the Number of Accidents and their Costs in relation to the Type of Accidents (1995) [GDV 1996]

One of the objectives of S.A.N.T.O.S[1] was the development and evaluation of a driver assistance system known as Speed Control, which will be referred to in this document as SC, and which is designed to assist the vehicle driver in his choice of speed and to warn him of difficulties in the road network.

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[1] 1. The S.A.N.T.O.S Project was sponsored by the Federal Ministry of Research and Technology under the Registration Number 19 S 9826 A/B. Project Leader Dr.-Ing. W. König, Robert Bosch GmbH, FV/SLN, research and pre- development and C. Mayser, BMW Group, EV-22, research, preliminary development and planning. The responsibility of the contents of this publication lies with the authors.

2 Fundamental Principles of the SC-System

Flaws in the alignment of roads are often the cause of increasing numbers of accidents. This can be traced back, on the one hand, to mistakes in driving behaviour (ie. behaviour behind the wheel), and on the other hand to the physiological and psychological capabilities of the vehicle driver. The vehicle driver must continuously adapt his behaviour in relation to speed, and this can, in turn,lead to an inhomogenous speed profile. (see Fig.3)

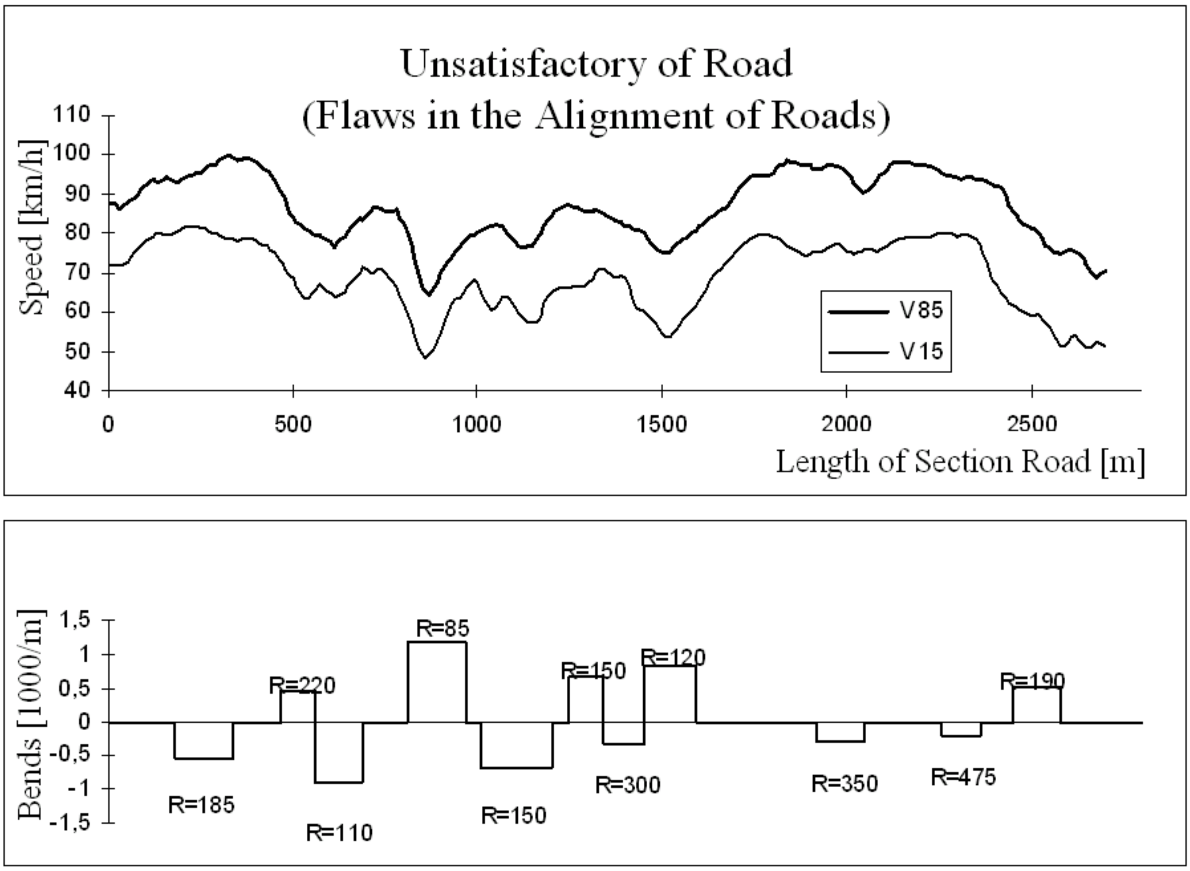

Fig.3: Speed Profile for an out of town road with flaws.

The consequences of an incorrect estimation of the stretch of road ahead can result in an inappropriate speed for the road geometry. If the driver is informed in time about an excessive speed he has chosen, then accidents could be avoided. The SC System is characterized by an individual, adaptive and integrated form of assistance. Different user types have varying requirements regarding the design of such an assistance system. The driver can select from the following driving styles:

- Sporty driving style
  The vehicle driver drives at high speed, which results in increased radial acceleration in curves. This style of driving is depicted, to a greater degree, in accordance with the regulations, by the V_{85}[2] speed, as used in road design.

- Normal driving style

  The vehicle driver drives briskely at a medium radial acceleration. The 75% quantile V_{75} depicts a suitable velocity, which can describe this style of driving.

- Relaxed driving style

[2] The V_{85} rule is adapted for the speed which 85% of unhindered driven cars do not exceed on wet roads

The vehicle driver drives at a speed whereby only minimum radial acceleration occurs in arcs.This style of driving can be approximately described by V_{50}.

Additionally, the driver can choose, depending on his current mood, more or less assistance in the form of:

- A warning signal which would be displayed if an excessively high speed is chosen
- A recommendation for a driving speed which will meet the regulations controlling speed limits.

When going on a recreational day trip, the driver has less need for assistance than, say when undertaking a long, monotonous drive. Should the surrounding conditions change, then the assistance system can influence his behaviour by adaptive strategies [König and others 2000]. One has less choice in vehicle speed on a wet road than on a dry one. The aim of the integrated assistance system is the coordination of the various systems available, and the prioritizing of their system outputs. If, for example, the driver is holding a telephone conversation, then the speed can be reduced to that recommended by the SC System. An incoming SMS would be signaled to the driver, after he has coped with a critical situation, such as braking as a result of a defect on the carriageway. An accurate knowledge of the characteristics of the road ahead is necessary, for the calculation of the suitable vehicle speed. Comprehensive digital maps are now available for navigation systems. Information about route distances, road junctions and road types can be obtained from these maps in order to determine the route distances, location of roadside rest stops and travel times. For the SC System to work, it will be necessary to have digital maps, which will contain information about, or be able to calculate the exact geometry of the route, as well as the surrounding conditions. For example precise digital prototype maps could map out defined areas. Sections of the route would be broken down into a series of digital reference points. When the points are lying at suitable distances to each other, then the intervals and angles of deviation of the individual points along the route can be calculated by geometric processes. When more points are added to the curve, then the curve radius and the clothoid parameters can be calculated. [Schulz 2002]. The elements can be clearly described by utilising a large number of reference points, which are set down in a dense format.

3 Initial Parameters for the Vehicle Speed

3.1 General

The process of driving (the human is integrated into this process as the regulator) can be described by a feedback control system [Durth 1974, Dilling 1973]. In this respect, the carriageway is the decisive guiding factor, alongside the disruptive factors (weathering and traffic). The driver percieves about 90% of the information about the stretch of road ahead visually. The distorted picture the driver gets cannot be quantified at the time (Weiss and others, 2001), so that the existing vehicle speed model is restricted to the following classifications, ground plan, longitudinal section and cross section, as the input quantities. In the document, the following influencing quantities regarding choice of speed will be mentioned:

- Ground plan
  - Radius
  - Angle of deviation
  - Clothoid parameters
- Longitudinal section
  - Vertical curvature
  - Longitudinal gradient
- Cross section
  - Width of carriageway
  - Transverse gradient
- Derived quantities
  - Bendiness of roads on the ground plan
  - Troughs and crests in the road
  - Visibility distance
  - Spatial elements

Two types of vehicle speed models can be deduced:

Type 1: The speed will be estimated taking into account each individual element or

Type 2: The speed will be calculated taking into account a coherent section.

Models of Type 1 have as their input quantity the ground plan geometry of individual elements (for example radius, angle of opening, longitudinal gradient). With models of Type 2, known quantities of road characteristics are taken (eg bendiness of the road on the ground plan, troughs and crests in the road), where changes to these quantities result in the formation of new sections and thus the speed is recalculated. Because of the heterogeneous road network one is not only restricted to one vehicle speed model for a vehicle speed prognosis. When one considers a measured vehicle speed profile (see fig. 4), it becomes obvious that there are areas where an almost constant speed is kept to (green area) and individual elements where a greater difference in vehicle speed arises (yellow area indicates singularities).

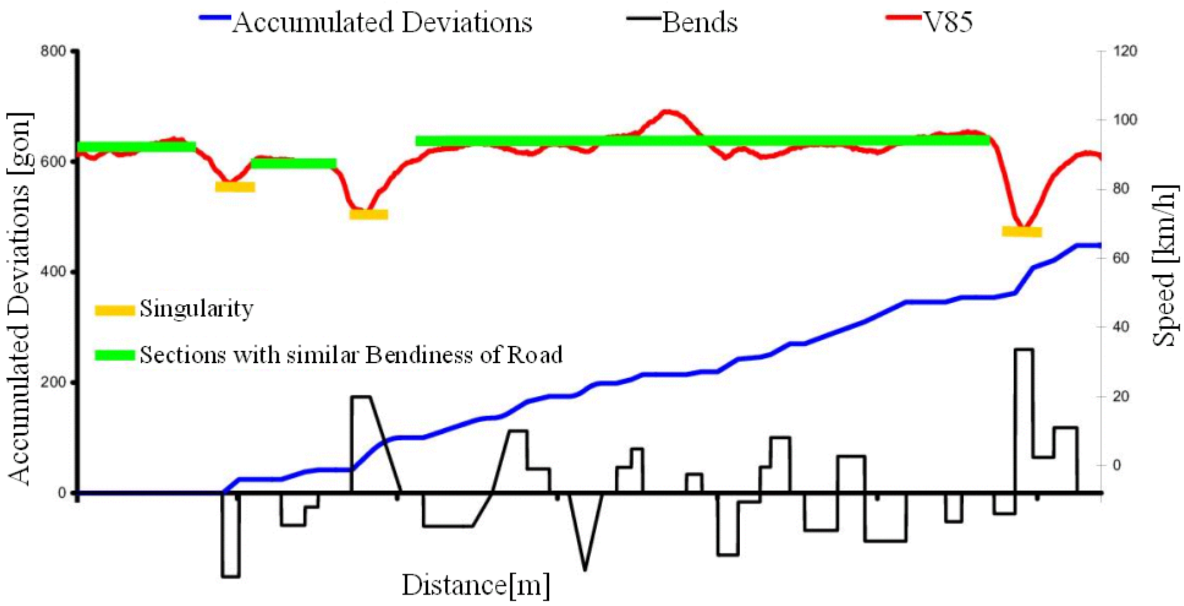

Fig. 4: Vehicle Seed Profile and Acccumulated Deviations

Sections in which an almost constant speed is driven are generally indicated by a similar route characteristic. Singularities are geometrically inconsistent along the road route (eg small radii). With the subdivision of the route into:

- Sections with similar route charateristics
- Singularities

actual vehicle behaviour can be quite well illustrated. Criterion can be defined for the separation of the individual sections from each other and can also be defined for the singularities. The rise in the number of accumulated deviations can be used following the current guidelines [RAS – L 1995]. The criteria for an approximation to the same bendiness is similar to the increase of the accumulated deviations. It will be calculated from the sum of the individual deviations between neighbouring points. In the areas of designated singularities the accumulative deviations increase dramatically, and on the other hand one can establish with reasonable accuracy in the remaining areas a similar rise in deviations. (see fig.5)

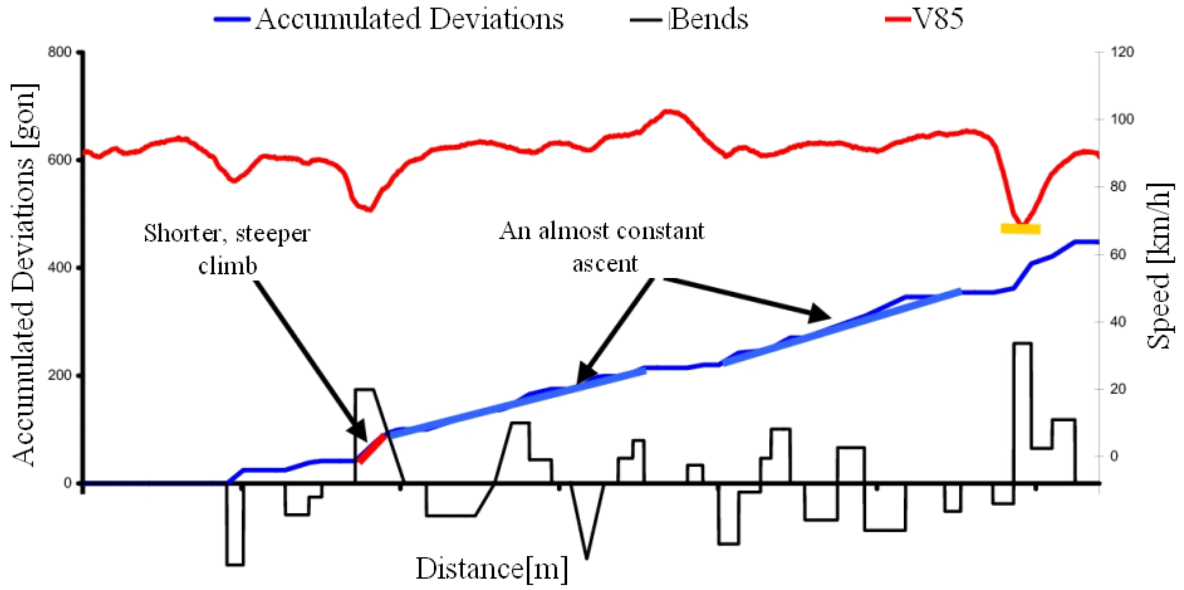

Fig. 5: Route Geometry and Accumulated Deviations

In order to utilise the section divisions, the accumulated deviations must be determined from the known ground plan geometry. If the same angle increase is shown over a longer section, then a section with approximately similar bendiness is defined. When it suddenly changes over a short stretch, then a singularity occurs, when likewise the ground plan radius R > 200m. No new vehicle speed models should be developed for the first application of the SC-System. The following elements from the precise digital map of the ground plan are available as input quantities:

- Radius and length of curves
- Width of carriageway
- Bendiness of road.

The models described in the document for the prognosis of vehicle speed were analysed. It was necessary to find initial parameters which, from the few available variables from the precision digital maps, could make possible a plausible, reliable and generally valid vehicle speed prognosis.

3.2 Vehicle Speed Initial Parameters for Single Curves

Initial parameters taken from the bibliography for the calculation of speeds in ground plan curves, were examined for their suitability for the S.A.N.T.O.S.-Project, and some chosen parameters are shown in Table 1 or Fig.6.

DURTH/BIEDERMANN/VIETH	$V_{85} = 108{,}23 - \frac{6508{,}06}{R} + \frac{287439{,}55}{R^2}$
BIEDERMANN	$V_{85} = 18{,}37 + \frac{10{,}11 \cdot B}{R_m} - 593 \cdot \left(\frac{B}{R_m}\right)^2$
LENNON	$V_{85} = 104 - \frac{4527{,}643}{R}$
LAMM/CHOUEIRI	$V_{85} = 94{,}436 - \frac{3192{,}021}{R}$
KANELLAIDES	$V_{85} = 129{,}8789 - 344{,}231 \cdot \left(\frac{1}{0{,}305 \cdot R}\right)^{\frac{1}{2}}$
GAMBARD/LOUAH	$V_{85} = \frac{102}{1 + \frac{346}{R^{1{,}5}}}$
LINDEMANN/RANFT	$V_{85} = \frac{105}{1 + \frac{69{,}62}{R^{1{,}11}}}$
MORALL	$V_{85} = e^{4{,}561 - \frac{37{,}3282}{R}}$
KRAMMES	$V_{85} = 103{,}6 - \frac{3405}{R}$ $V_{85} = 102{,}44 - \frac{2742}{R} + 0{,}012 \cdot L - 0{,}09 \cdot \gamma$
SPACEK	$V_{85} = \frac{100{,}5}{1 + 17{,}346 \cdot R^{-0{,}792}}$
LIPPOLD	$V_{85} = 82{,}461 + 2{,}817 \cdot B - 0{,}084 \cdot R + 0{,}0005 \cdot R^2 - 5092 \cdot 10^{-10} \cdot R^3$

Table 1. : Velocity Initial Parameters for Single Curves

From Table 1 it follows that the initial parameters for the calculation of curve speeds and their function types and the included parameters vary. In principle, the speed given is dependent on the ground plan radius *R.* Varying initial parameters broaden the equation for the width of the carriageway ([Biedermann 1984], [Lippold 1997]). For the initial stage, according to [KRAMMES 1993], besides the radius *R* , the length *L* and also the deviation of the arc span are considered. In Fig.6 the speeds in accordance with the various initial parameters have been marked in. It becomes apparent that there are marked differences, especially in the lower area of arc
(R<100m). Several investigations using suitable databases establish an increasing mean variation of the individual values. The investigations carried out by Lippold [1997] and the investigations for RAS-L (1995) [RAS-L 1995] lie in the upper area, because, due to reasons of safety and being the most decisive values, they lay the foundation for the highest speeds at the beginning of curves. The width of the carriageway B

should be considered as the greatest influencing input. Taking into account this point of view, the initial parameters described by Biedermann, (1984) and Lippold (1997) are worth considering.

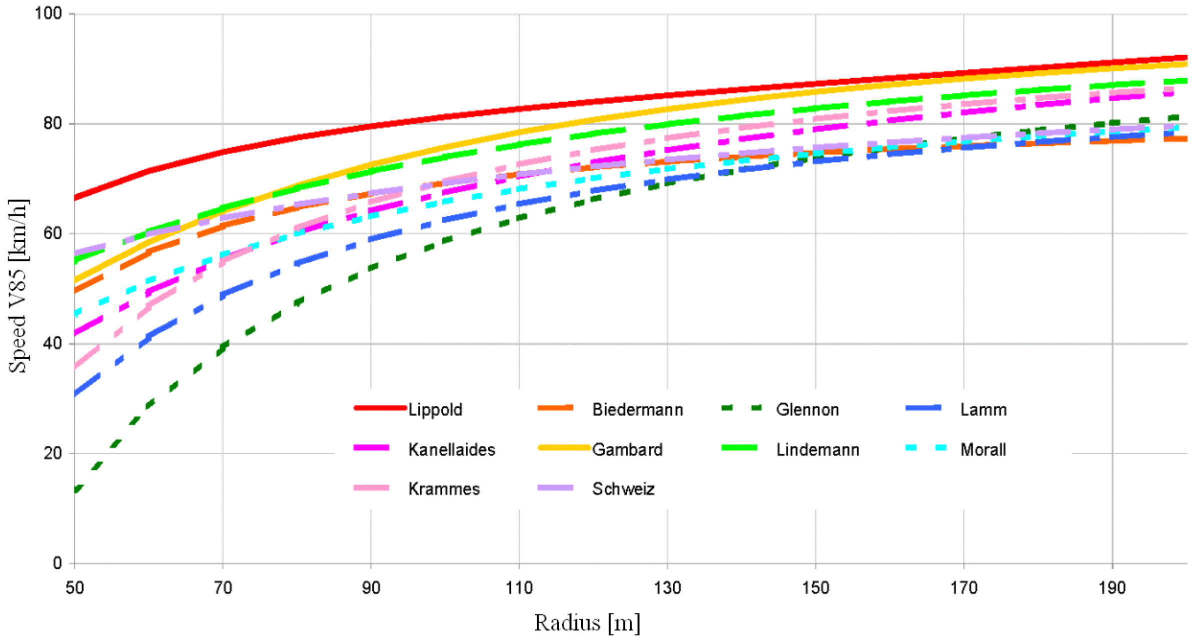

Fig.6 : Vehicle speed initial parameters for single curves.

3.3 Vehicle Speed Initial Parameters for Sections approximating to Similar Bendiness of Road.

For the S.A.N.T.O.S. – Project, the displayed initial parameters, taken from the bibliography, were more closely investigated. For all the displayed initial parameters, there will be included, besides the bendiness *KU* of a section of the route, additionally the carriageway width *B.* In Fig. 7 a comparison of the functional route course of the calculated initial parameters is shown. The initial parameter used by Biedermann (1984) reveals almost constant speeds, while from the initial parameters used by Köppel Bock (1979), a clear dependence on the bendiness of the road is discerned.

LIPPOLD	Fahrbahnbreite 5,0 m bis 6,0 m $V_{85}=132{,}69+0{,}0007\cdot KU^2-0{,}399\cdot KU$ Fahrbahnbreite 6,1 m bis 7,0 m $V_{85}=123{,}0350-0{,}1612\cdot KU$ Fahrbahnbreite 7,1 m bis 8,0 m $V_{85}=121{,}6211-0{,}1486\cdot KU$
BIEDERMANN	$V_{85}18{,}37+10{,}11\cdot B-0{,}000297\cdot B\cdot KU-0{,}00000015\cdot(B\cdot KU)^2$
KÖPPEL/BOCK	$V_{LEv}=55{,}65-0{,}532\cdot KU+5{,}314\cdot B$ $V_{LEv}=61{,}03-0{,}0819\cdot KU+0{,}0000496\cdot KU^2+4{,}85\cdot B$

Table 2 : Vehicle speed initial parameters for sections approximating to similar curves.

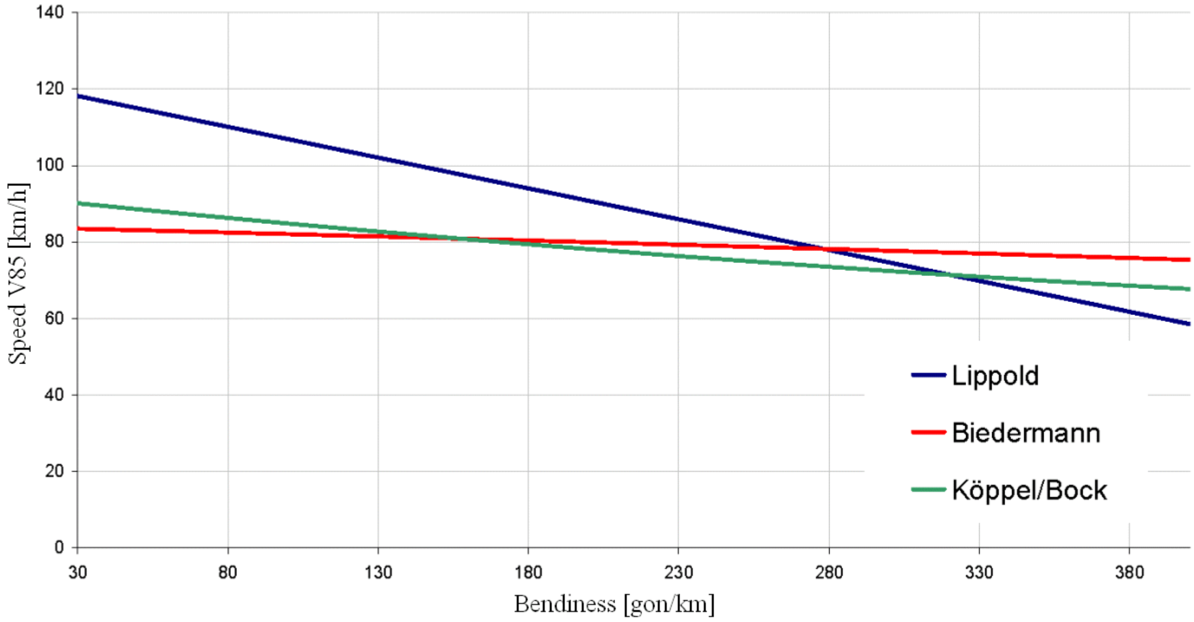

Fig. 7 : Comparison of vehicle speed initial parameters for sections with similar bendiness in the road.

3.4 The Choice for S.A.N.T.O.S

With regard to the investigated vehicle speed initial parameters for singularities and for sections approximating to similar bendiness, the following points can be summarised:

1. The influences on speed behaviour patterns are complex and can be described by further variables. For practical reasons (availability of data) we will restrict the calculated initial parameters to fewer variables.
2. For the determination of speed in sections of the route, independent of whether it has to do with singularities or sections with similar bends, the width of the carriageway *B* and also the radius and bend of the curve should be used for improving the approximation to the actual driving behaviour.
3. The vehicle speed initial parameters shown, vary greatly in their functional path and embrace therewith a high area of variation. This is justified on the one hand by the area of validity and on the other hand by the state of motor vehicle technology at the time of development. It makes sense to choose a current initial parameter, while in the last few years motor vehicle technology has developed further, and ever greater speeds are nowadays driven. For further analysis, the large data bank of Lippold (1997), for vehicle speed initial parameters for single radii and sections of similar bendiness, will be chosen.
4. The initial parameters described by Lippold have been determined for road safety surveys, as they provide an "upper envelope" curve in vehicle speed zones. This results in a functional reduction of the values for further quantile calculations.

4 Application and Test Drives

The SC – System has been built into a vehicle made available by the BMW Group.
The S.A.N.T.O.S vehicle has its own SC computer. The speed, which is calculated from the algorithm speed, will be sent via an Ethernet connection to the S.A.N.T.O.S computer, which will further process this information. During the test drives it was of special significance, whether the geometry of the route could reliably be determined, and in accordance with the characteristics of the section of the route ahead, a plausible speed could be assigned online to it. For the further validation of the algorithm, further test drives were carried out, where the existing speed clssification was determined. The comparison can be seen in Fig.8. It seems clear that the algorithm provides a close approximation to the actual driver behaviour.

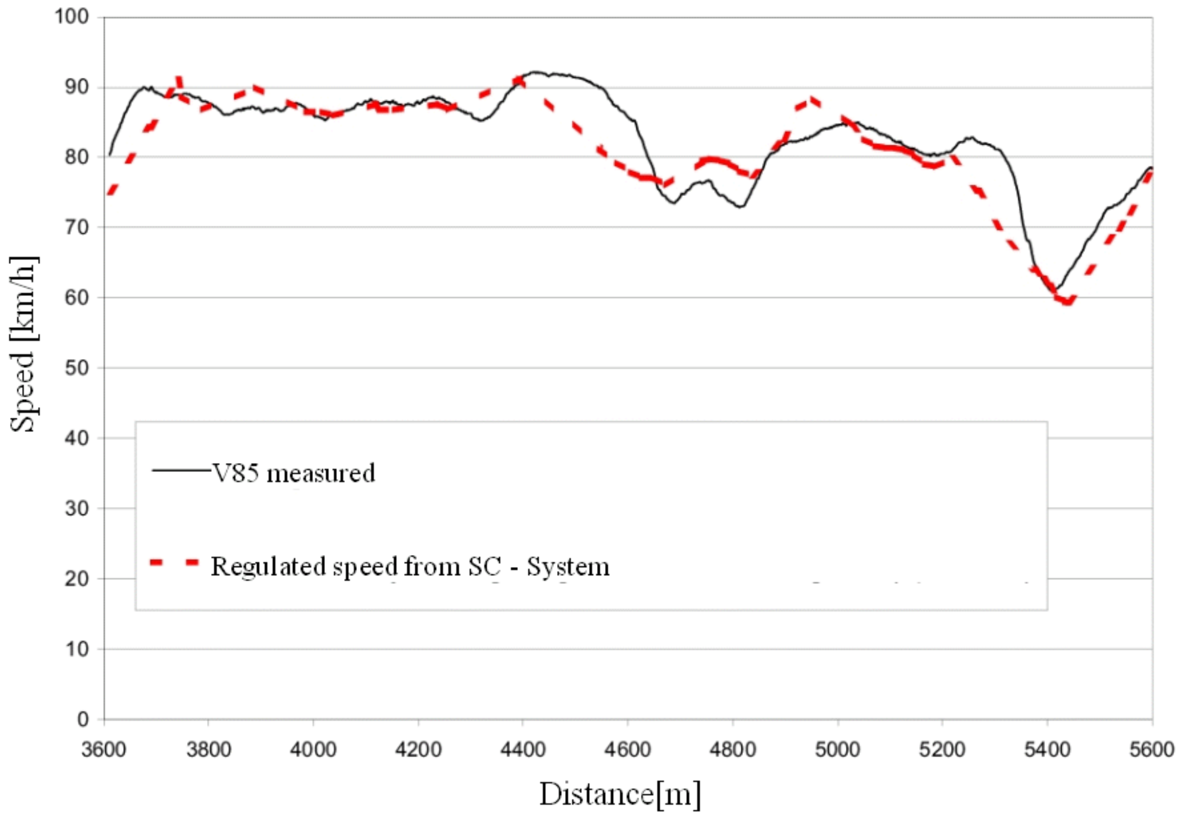

Fig. 8 : Comparison of the measured speed and the speed provided by the S.A.N.T.O.S Demonstrator.

By test drives carried out by test drivers, and with the assistance of the test drive data related to a questionnaire completed by the test drivers, information about the suitability of use can be acquired. With that in mind, the test drivers drove over the test track twice, once without the SC and a second time with the SC. It could then be established that the driver behaviour of the test driver without the SC only partly fullfills the requirements that were met by the test driver using SC. And so, sporty drivers experienced one of the SC curve speeds, which was the same as or less than the one during the comparative drive without SC, as being too fast. (see Fig. 9)

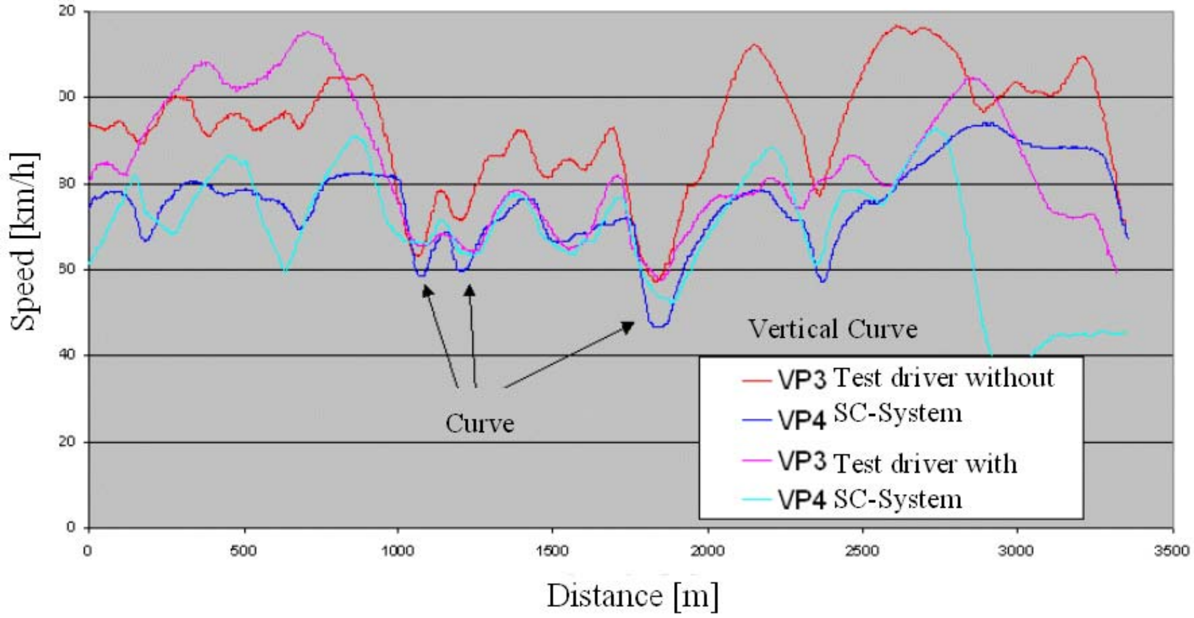

Fig.9 : Comparison of speed profiles of test drivers (TD) with and without the SC-System.

The drivers felt that, in the main, the SC – speeds were quite suitable, although these results differ markedly for those driving without the SC-System.Generally, it can be stressed that the user enjoys a more relaxed driver behaviour when an automatic speed regulator is used, than when one is not used. He has a built in safety factor, which in a critical situation, can assist him to control the car. This effect can however, be weakened with increasing habitual reliance on such a system.

5 The Current Situation and Future Trends

The designed SC-System carries out calculations of vehicle speed, which are based on geometric data from the ground plan and which the car driver can use to safely and comfortably drive through a section of the road ahead.
The calculated vehicle speed can be influenced by the driver´s choice of one of the following driving styles:

- Sporty
- Normal
- Relaxed

Regarding the selected type of assistance required, eg:

- Warning indicator
- Recommendation
- Automatic control

the driver can be either informed (warning indicator) or the vehicle automatically adjusts to the calculated speed. The test drives which were carried out show that it is practical to divide the route into singularities and sections approximating to the same road bend, and to clearly indicate the route characteristics. By this division it is possible, over longer distances, above all, in sections approximating to similar bends, to recommend constant vehicle speeds. This results in a homogenous speed classification. During the investigations it became clear that the existing vehicle speed prognosis models given in the bibliography, are suitable only in a limited way for this purpose. Because the vehicle speed initial parameters used for measuring the relevant road safety quantities were developed from highway design, they tend to produce very high speeds. Therefore, in order to adapt to the SC-System, they must be reduced by adaptive factors and functions. For a more accurate investigation of the route characteristics, digital maps would be necessary, in which the course of the route can be represented by a satisfactory density of digital points. At present, conventional navigation maps are not suitable for this purpose. Prototype digital maps with a high concentration of data were produced for the recording of the geometry. These made possible a satisfactory and accurate estimation of the ground plan geometry. For a further development of the SC-System an independent vehicle speed prognosis model should be developed, which, in the case of initial parameters, could consider not only geometric parameters of the ground plan, but also parameters of the contour plan; one example is crests on roads, which have an influence on driver behaviour. A further important aspect with regard to the calculation of vehicle speed is shown by the example of the section of road immediately ahead. This influences the driver in his choice of speed. Disruptive factors caused by weather (rain, dampness, fog) and the time of day (night driving) and structural conditions (eg bridge crossings) likewise have an influence on the choice of speed. Their influence should be integrated into the total algorithm in a suitable form at a further stage. Investigations into the acceleration behaviour of motorists should be carried out, in order to apply calculated speeds in vehicles technology. An algorithm should be developed from these investigations, which would be able to calculate a logitudinal acceleration, depending on the route characteristics and the desired driving sytle.

Bibliography

DER ELSNER
Handbuch für Straßen- und Verkehrswesen
Otto Elsner Verlagsgesellschaft
Dieburg, 2000

Biedermann, B
Straßentrassierung auf der Grundlage von Geschwindigkeiten aus Sehfelduntersuchungen
Dissertation, Technische Hochschule Darmstadt
Darmstadt 1984

Dilling, J
Fahrverhalten von Kraftfahrzeugen auf kurvigen Strecken
Straßenbau und Straßenverkehrstechnik, Heft 151
Bonn – Bad Godesberg 1973

Durth, W
Ein Beitrag zur Erweiterung des Modells für Fahrer, Fahrzeug und Straße in der Straßenplanung
Dissertation, Technische Hochschule Darmstadt
Darmstadt 1972

König,W; Weiss,K; Gehrke, H; Haller, R
Situations-angepasste und Nutzer-Typ-zentrierte Optimierung von Systemen zur Fahrerunterstützung
Vortrag zur GfA Herbsttagung
Garching 2000

Köppel, G; Bock, H
Fahrgeschwindigkeit in Abhängigkeit von der Kurvigkeit
Forschung Straßenbau und Straßenverkehrstechnik, Heft 269
Bonn – Bad Godesberg 1979

KRAMMES 1993
Practice Geometric Design Consistency
Texas AM University 1993

Lippold, C
Weiterentwicklung ausgewählter Entwurfsgrundlagen von Landstraßen
Dissertation, Technische Hochschule Darmstadt
Darmstadt 1997

RAS – L 1995
Richtlinie für die Anlage von Straßen – Teil Linienführung
FGSV Verlag
Köln 1995

Schulz, R:
Grenzen und Möglichkeiten einer teilautomatisierten Nachtrassirung im Lageplan auf der Grundlage von Punktfolgen
Studienarbeit, TU Dresden
Dresden 2002

Weise, G. Ebersbach, D; Dietze, M.
Situations-angepasste und Nutzer-Typ-zentrierte Optimierung von Systemen zur Fahrerunterstützung, 3. Meilensteinbericht
Dresden 2001

Summary
To drive the Appropriate Speed in Curves

The existing road network is characterised to a greater extent by routes which have come into being through the course of history. This network often does not meet today´s safety requirements. Defects in the road network are often the cause of increasing numbers of accidents. This can be traced back, on the one hand, to human error, and on the other hand to physiological and psychological capabilities of the vehicle driver. The results of such errors in estimation cannot ensure that the correct speed for route geometry is selected. A speed control system (SC-System), which has been developed within the framework of the S.A.N.T.O.S Project[1], assists the driver in the selection of the appropriate speed. With this system the driver can choose between varying forms of assistance for a safe and comfortable speed, for example, from warning signals for excessively high speeds to the computer assisted automatic control of the vehicle. The initial geometric input data of the ground plan for the calculation of vehicle speed

will be made available from digital road maps, in a similar form as already used for navigation systems. Navigation maps only contain information about the length of the route, road junctions and types of road, which can be used for determining route length, the location of roadside rest stops and travel times. In order to calculate the vehicle speed, a detailed knowledge of the geometry of the route ahead is of significance. For this purpose digital maps will be necessary, from which and with the help of special algorithms, the geometry of the ground plan can be calculated. Such maps will be produced for defined areas.The SC-System will establish, from the data of the route yet to be driven, which is stored in the precision digital road map, a speed which is safe and comfortable to drive. Varying driving styles (relaxed, normal and sporty) will be considered when recommending suitable driving speeds. The system has been tested in an experimental car made available by BMW, on a test track. In general, it can be shown that such a technical system can be practically applied. The first trials carried out by the test drivers have produced positive results. Within the framework of this project, a system will be developed which, based on data on roads and surrounding infrastructure, will ascertain a vehicle speed prognosis which will be suitable for the current driver behaviour and safety. The consequences of such an assistance system on the driver and vehicle driven, and also the repercussions on overall traffic safety, will have to be looked at in further research studies.

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