# INNOVATIVE APPROACHES TO HIGHWAY GEOMETRIC DESIGN IN POLAND

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A series of new requirements was introduced into Policies on Geometric Highways Design elaborated recently in Poland. Positive influence of these changes on traffic safety as well as on operational quality of highways was proved by tests and traffic surveys on Polish roads. New elements of Design Policies in Poland, which are expected to help in improving the quality of Polish roads, are:

- determinant speed and its determining on basis of such design elements, that has to be adjusted to the speed of passenger cars in free flow, with regard to traffic safety,
- procedures of evaluation of road alignment design correctness,
- strict determination of visibility requirements on the roads,
- principles of planning for reconstruction of two-lane rural highways with paved shoulders.

Thus, the requirements focus on roadway design control and sight distance.

## DESIGN SPEED AND DETERMINANT SPEED IN ROAD DESIGNS

The basic control in road designs is the design speed; however, a determinant speed was also introduced into the designing process, as it is strictly connected with forecasted traffic speed on the road.

Design speed, Vp, is chosen on basis of road function within a road network and type of terrain, while taking economical factors into consideration. The designed speed is to be used for determining limiting (the greatest or the smallest) values of road geometric elements and the scope of additional facilities necessary. Design speed represents road functions within a network and is constant on the long road sections.

Determinant speed, Vm, is used for road alignment determining. This speed provides a possibility for determining such design elements as intersections and interchanges, which, regarding to traffic safety, should be adjusted to the speed of passenger cars in free flow.

Functions of design speed and determinant speed in the designing process as well as design elements, intersections and interchanges, which are influenced by these two speeds, are shown in the Figure 1.

The manner of determining the determinant speeds is adjusted to the range of data available at the designing stage and results from limited usefulness of models of speed estimations in the process of determining the speeds. Value of 85th percentile of distribution of speed of passenger cars in free flow on pavement in wet condition was assumed as a determinant speed.

The way of determining the speed is dependent on type of roadside development, and the type of cross-section (Figure 1):

1. On a two-lane highway in a rural area, determinant speed is determined for every homogeneous (regarding degree of curvature) road section. The speed is a weighted average of calculational speeds along the road, determined from the Chart (Figure 2) or calculated using a computer program. Calculational speed depends on type of road cross-section, grade, horizontal curve radius and center angle. The model of speed estimation described above defines the dependence which was elaborated on the basis of results of tests carried out on Polish roads.

2. On a dual-carriageway road in a rural area

   $Vm = Vp + 10$ km/h      at $Vp = 100$ km/h;

   $Vm = Vp + 20$ km/h      at $Vp < 100$ km/h;

   where:

   $Vm$ = determinant speed (km/h),

   $Vp$ = design speed (km/h).

3. For a road in urban area, determinant speed $Vm$ should be assumed as the highest speed limit for passenger car on the road, determined by a speed limit, and increased by:
   - 20 km/h if it is a road of a rural cross-section, or
   - 10 km/h if it is a road of street or semi-street cross-section.

A simplified way of determining the determinant speed was applied for roads specified in sections 2 and 3 above, due to the lack of model of speed estimation for these roads. The way of ascertaining the determinant speed, included in Policies on Geometric Highways Design, will be modified and will become more detailed as new experiences are encountered.

## EVALUATION OF ROAD ALIGNMENT DESIGN CORRECTNESS

Determinant speed is in practice variable along the road. The scope of the speed changes along the road and conformity with the design speed is the basis for evaluation of road alignment design correctness and the traffic safety level.

Road alignment design may be deemed correct provided that:
- the difference between determinant speeds on adjoining road sections does not exceed 10 km/h

(while designing road reconstruction, the difference is acceptable if it does not exceed 15 km/h),

- the determinant speed on the road section does not exceed design speed by more than 20 km/h.

Should above specified requirements not be met, geometric alignment of the design road must be changed. An example of determining the determinant speed on a two-lane road and selecting design elements in horizontal alignment is shown in Figure 3.

Criteria of road alignment design correctness assumed in Polish Policies on Geometric Highways Design are in accordance with settlements of traffic safety specified by Lamm (1). Lamm has elaborated his criteria on basis of survey of traffic conditions and analysis of road accidents in Germany and USA.

Usefulness of criteria of road alignment design correctness evaluation, introduced in Policies on Geometric Highways Design, with respect to traffic safety will be verified on basis of observations of traffic conditions and road accidents analysis in Poland.

## STOPPING SIGHT DISTANCE

The basic aim, regarding traffic safety, that has to be achieved during road designing is providing visibility of an obstacle, of particular height, lying on the pavement, from the certain distance that allows a car to be stopped before the obstacle. It is assumed that the distance consists of a road section that the car transverses during driver's braking reaction time plus the braking distance of a vehicle.

Analysis of models of speed estimations applied for determining the braking distance indicates that:

- a flat, stiff car model, with one degree of freedom, is usually used for describing braking process,
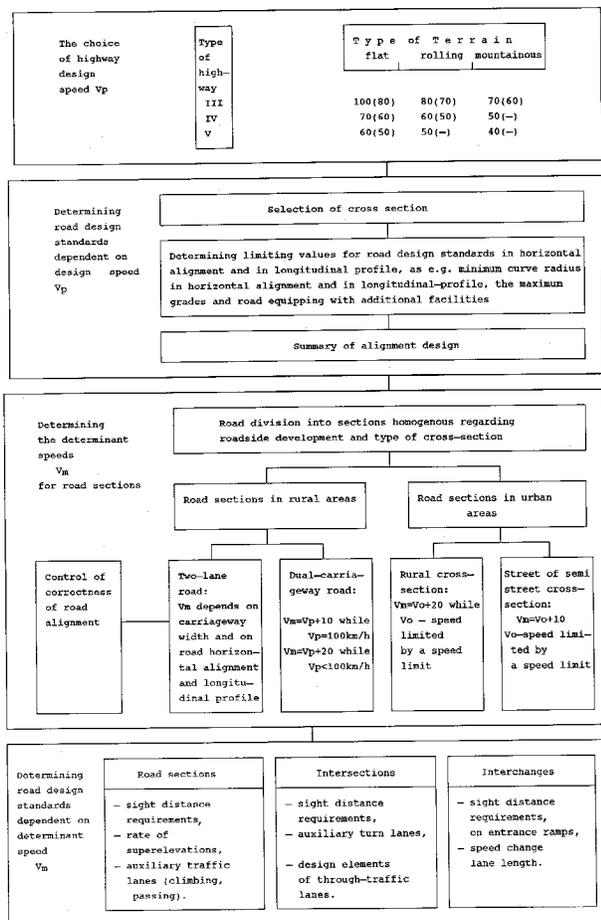


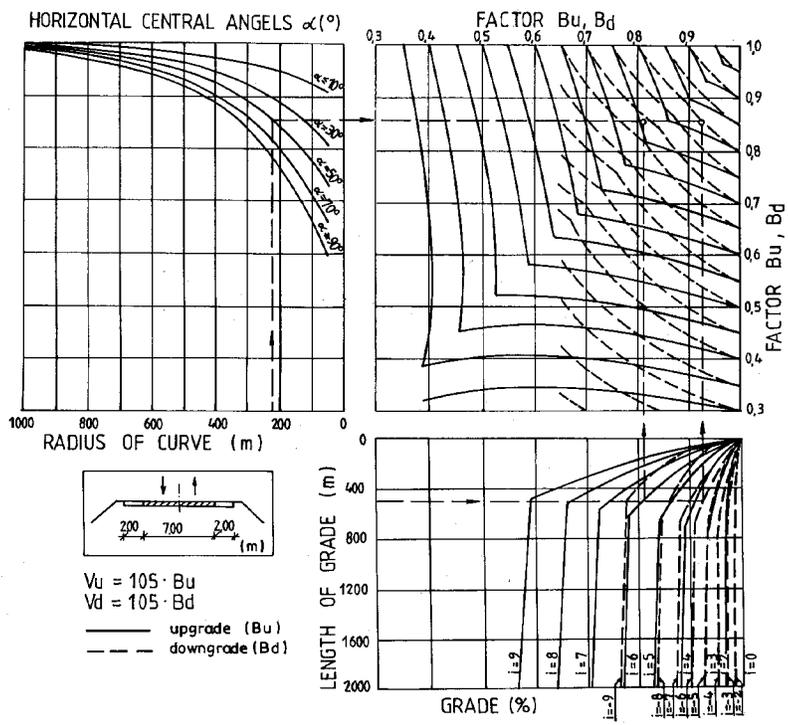FIGURE 1  Design Speed and Determinant Speed in Road Designs
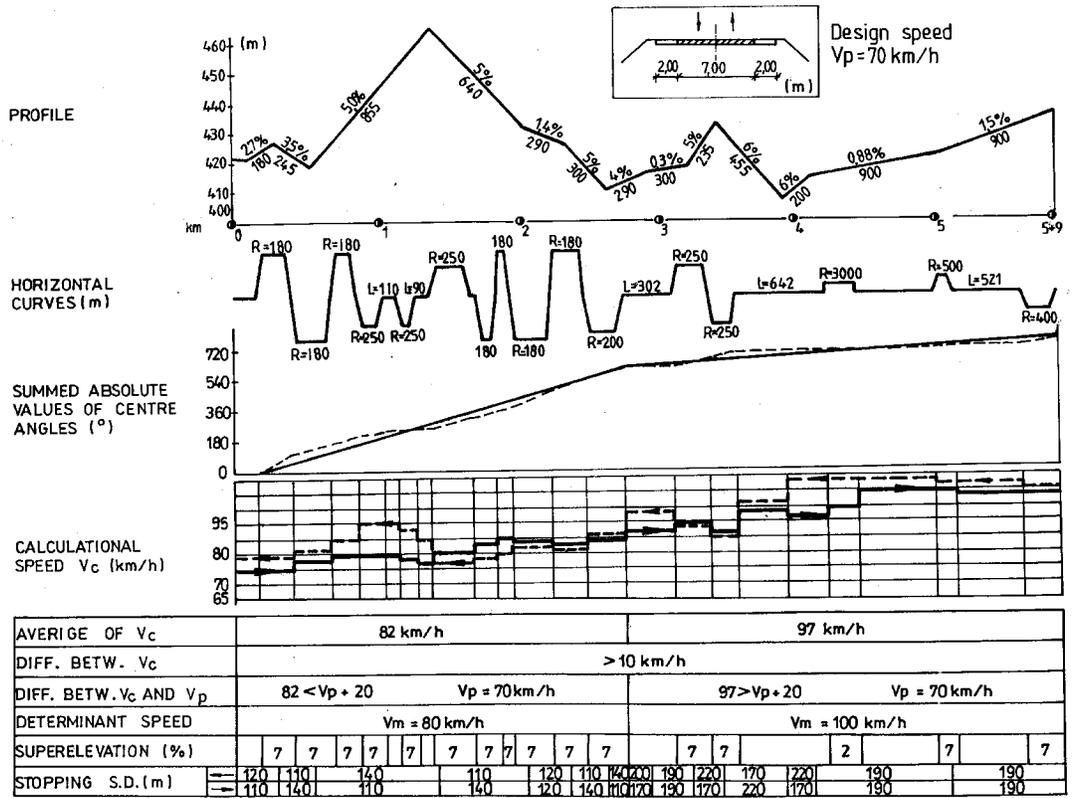
**FIGURE 2 Chart for Determining Calculational Speed**

HORIZONTAL CENTRAL ANGELS α(°)

FACTOR Bu, Bd

FACTOR Bu, Bd

RADIUS OF CURVE (m)

1000  800  600  400  200  0

Vu = 105 · Bu
Vd = 105 · Bd

——— upgrade (Bu)
— — — downgrade (Bd)

LENGTH OF GRADE (m)

GRADE (%)

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**FIGURE 3 Example for Determining of Determinant Speed and Design Elements on Road**

PROFILE

HORIZONTAL CURVES (m)

SUMMED ABSOLUTE VALUES OF CENTRE ANGLES (°)

CALCULATIONAL SPEED Vc (km/h)

Design speed Vp = 70 km/h

| AVERIGE OF Vc | 82 km/h | | | | 97 km/h | | | |
|---|---|---|---|---|---|---|---|---|
| DIFF. BETW. Vc | > 10 km/h | | | | | | | |
| DIFF. BETW. Vc AND Vp | 82 < Vp + 20 | | Vp = 70 km/h | | 97 > Vp + 20 | | Vp = 70 km/h | |
| DETERMINANT SPEED | Vm = 80 km/h | | | | Vm = 100 km/h | | | |
| SUPERELEVATION (%) | 7  7  7 7  7 | 7  7 7 7  7  7 | | | 7  7 | | 2 | 7 | 7 |
| STOPPING S.D.(m) | 120 110 140 | 110 120 110 140 | 200 190 220 170 220 | 190 | 190 | | | |

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- the interaction between rubber tire and the road pavement is usually described in the stable stage of braking as the sliding friction coefficient *(2, 3)*,
- a variation of sliding friction coefficient in connection with speed increase was implemented in RAS-L-1-84 *(4)*,
- in the model *(5)*, braking intensity is limited by constant value of average delay (0.375 g), regardless the initial speed.

It is assumed in all the models that the driver is forced to brake by an unexpected appearance of an obstacle on the traffic lane. In reality the following phases may be indicated during such braking:

- the phase of wheel slowing, when the deformation slip of a wheel is increasing, until the peak value of rolling friction coefficient is achieved,
- the phase of wheel locking, when a sharp decrease of wheel speed takes place, and the rolling friction coefficient decreases until reaching total slip, and
- slip phase of variable force of tire friction on the pavement, when the slip takes a longer time, and the value of sliding friction coefficient is variable, as the result of some reactions taking place on the friction surface. The value of sliding friction coefficient varies around a certain constant value.

As it is indicated (Figure 4), the complicated process of the changes in the rolling friction coefficient was, in applied models, reduced to the phase of slipping.
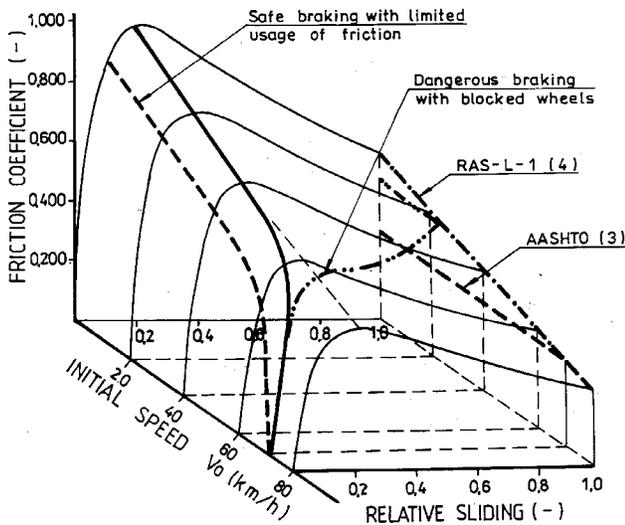
The analysis function

$$u = 0.14\left(\frac{V}{100}\right)^2 - 0.640\frac{V}{100} + 0.615$$

where
u = sliding friction coefficient;
V = speed (km/h)

assumed in RAS-L-1-84 *(4)* does not describe the changes of the friction coefficient during a certain braking in total slip, until the car stops, but it is only a substitute concept. The function does not appear in reality independently regardless of the type of braking system the car is equipped with, as well as regardless of the braking strategy chosen by a driver.

The conclusion is that the models that have been applied up to the present have not provided a satisfactory basis for constructing geometrical road elements, while they allowed uncontrolled run of vehicles already in their assumptions.

Taking into account previous analysis the following conclusion may be made:

Required stopping sight distance is the distance necessary for the driver to safely stop the car after an obstacle appears unexpectedly on the road.

The distance consists of the road section distance that the car traverses during brake reaction time plus the safety braking distance. The safety braking distance should be met by braking using friction of rubber-tired wheel to the road pavement, while driving stability is not disturbed and the car driving route is controllable at all times during braking.

In order to achieve more detailed representation of a car during braking and to calculate the safety braking distance as the basis for the required sight stopping distance, the analytical model of a car drive of three degrees of freedom was elaborated. The following were taken into account as external factors:

- the force of front aerodynamic drag,
- the moments of braking of front and rear wheels as non-linear functions of time, elaborated on basis of road tests, and
- the tangent forces, resulting from the effect of wheel friction on pavement.

A mathematical description of the interaction between the rubber-tired wheel and a road pavement was elaborated on basis of results of tests of the rolling friction coefficient and the sliding friction coefficient on wet



**FIGURE 4**
**Use of Friction Coefficient During Braking**

bituminous pavements in Poland. Graphical form of this description is shown in the Figure 4.

In order to represent the variety of driver's behavior in the model, the following braking strategies were implemented:

- continuous braking, when the press on brake pedal increases until the car stops. The strategy is suitable both for braking not caused by any danger, and for so-called 'panic' braking. In both cases the pace of increase of a press on brake pedal is different, thus so is the process of braking itself.
- cautious braking, when the press on brake pedal increases until the moment when one axle's wheels are blocked,
- pulsatory braking, characteristic for experienced drivers or for cars equipped with ABS system.

The analytical description of a model of vehicle movement may be expressed as set of ordinary differential equations, which may be solved by applying numeric methods only. A program solving the problem was written in Turbo-Pascal 5. The fourth degree method by Runge - Kutty was applied in the program for the integration of equations. Model verification involves ascertaining statistical accordance of the characteristics of the braking process acquired from the model, with the results of road tests.

An example of calculation results of characteristics of braking process of a standard passenger car while having initial speed of Vo = 100 km/h and assuming continuous braking of different intensity of press on brake pedal in different tests (from very little press to "panic" braking) are shown in Figure 5.
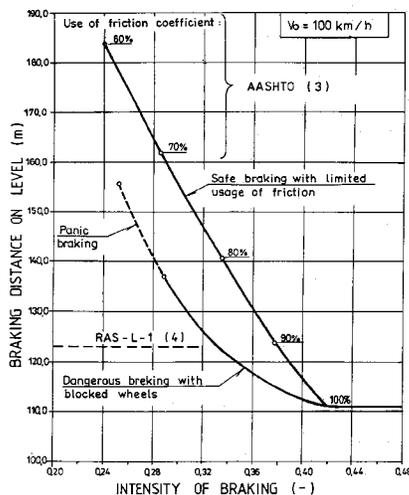
Comparison of characteristics of braking process of a standard passenger car in Poland, acquired from the elaborated model with braking distances assumed in design guidelines, allows following conclusions to be made:

1. Braking distance calculated according to AASHTO (3) model corresponds with the strategy of safe braking in the case of using a friction coefficient in longitudinal direction between 50% and 70% (Figure 5). Detailed analysis (6) indicates that a car is safe if the use of friction coefficient in longitudinal direction does not exceed 70%. The rest, which should be understood as a vector difference, which is approximately 70%, should be reserved for transmitting side forces and turning moments.
2. Braking distances calculated according to the RAS-L-1 (4) method correspond with braking distances with almost total usage of the friction coefficient in longitudinal direction (Figure 5), which means braking effectiveness is achieved by experienced drivers or those in cars equipped with an ABS system.
3. Safe braking takes place while having different intensities of braking ( from 0.445 while having Vo = 40 km/h to 0.285 while having Vo=100 km/h), and the different expressions of this intensity result from different risk rates accepted by drivers, different pavement surface characteristics and different states of tires assumed as 'standard' (Figure 6).
4. Results acquired from elaborated model of vehicle drive were used for verifying visibility requirements in new road designing guidelines in Poland.

## PLANNING RECONSTRUCTION OF TWO-LANE HIGHWAYS

Increase in traffic density on the Polish road network forces both network modernization and creation of new road routes. Due to many reasons, modernization of road routes will be a main way of adjusting the road networks to increasing traffic needs. Road traffic in Poland concentrates on 4800 km of roads marked as international roads. Half of these roads are two-lane highways with paved shoulders of 1.5-2.0 m width. These roads, regardless of their basic function of providing national and international connections, are usually also used by equipage vehicles and local traffic. Lack of cooperation arises with town and country planning, and as the result these roads usually cross urban areas. As a result, pedestrians and bicycle traffic appear on the roads. The increase in traffic density that has taken place in recent years has caused common use of paved shoulders by slower vehicle traffic. This fact often results in the situation when three or four vehicles appear on a road



**FIGURE 5**
**Characteristics of Braking Process while having Initial Speed Vo = 100 km/h**

cross section. As a consequence of this fact the threat to traffic safety on these roads is the biggest in Poland. The problem of elaborating the program of modernization of these roads has become an urgent matter.

Considering the estimated increase in traffic density, and the results of simplified costs and profits analysis, the author of the article has proposed the following principles for reconstruction of roads with paved shoulders (Figure 7):

1. Paved shoulders should be used by pedestrian traffic, bicycle traffic and local traffic as well as by vehicles, if the traffic density (average daily traffic - ADT) does not exceed 5000 veh/24 h.

2. While having ADT over 5000 veh/24 h and pedestrians and bicycle traffic on shoulder, the shoulder shall be separated from the road with the continuous line and appropriated for pedestrians and bicycle traffic only. While having ADT of 8000-10000 veh/24 h pedestrians and bicycle riders are forced by cars using the shoulder for traffic to use an edge of road crown only. No organizational means may effectively prevent such actions. Accidents are so costly that in such a case it is economically reasonable for drivers, pedestrians, and local traffic to stay out of the road crown. The biggest effectiveness may be obtained by reconstructing the road to 2+1 lane cross-section.
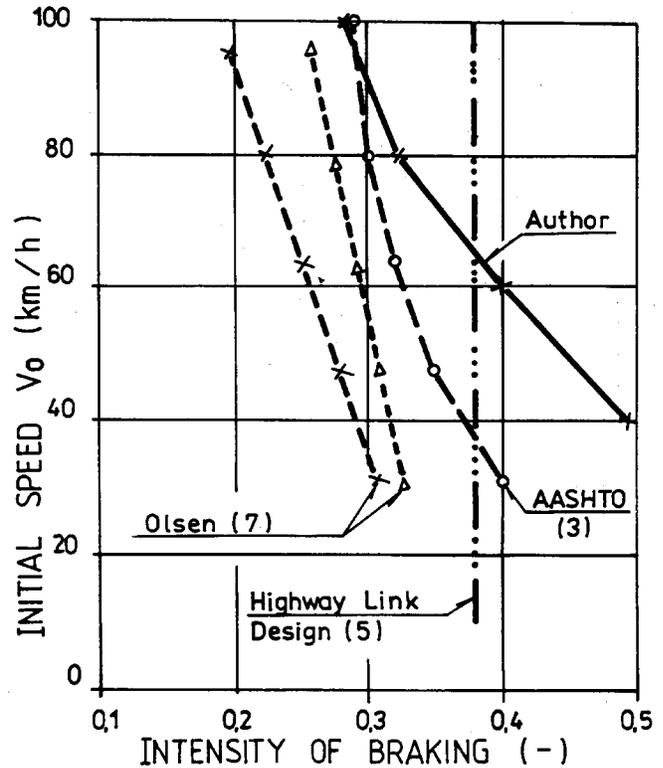


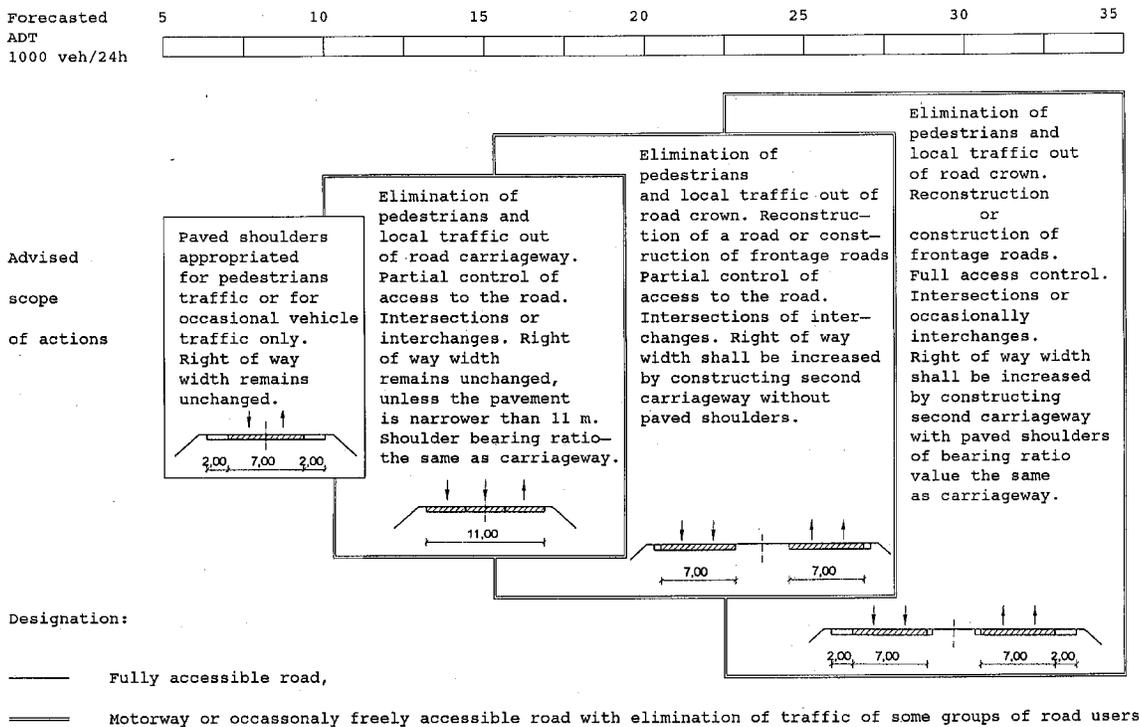FIGURE 6 Average Braking Intensities



FIGURE 7 Principles for Planning Roads Reconstruction in Poland

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3. While forecasted ADT exceeds 17000 veh/24 h, construction of a second carriageway should be planned as well as construction of frontage roads for pedestrians and local traffic. The road should be appropriated for car traffic only.
4. If the forecasted ADT exceeds 27000 veh/24 h, the reconstruction program (3) should be supplied with construction of paved shoulders.

For estimation of limiting values for ADT I have used the simplified cost benefits analysis described by the Transprojekt-Warszawa Ltd. Consulting Engineers. The first year rate of return (FYRR) includes:

- average investment and maintenances costs for reconstruction of roads with paved shoulders,
- accident costs, and
- traffic costs for four types of vehicles.

A method of journey speed estimation has been developed lately in Poland (8). The journey speed is expressed as a function of a set of variables describing road alignment and signing, road environment and vehicle flow parameters. A two-step procedure has been used for the development of speed models. In the first step, factor analysis has been applied to get mutually independent principal components. In the second step, multiple regression analysis has been used to construct speed equations with principal components as independent variables and speed distribution parameters as dependent ones.

For determining the limit of the speed-volume relationships and accident ratio on 2+1 road, the Germany study (9) has been used.

Pedestrian-bicycle traffic is taken into account in this method as a non-numerical variable (this traffic exists or not).

## ACKNOWLEDGMENTS

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