DCT 152

DESIGN SPEED
SELECTION RECOMMENDATIONS

by

Ardeshir Faghri, Ph.D.
David Capparuccini
Tatiana Cvetek

Department of Civil and Environmental Engineering
University of Delaware

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DELAWARE CENTER FOR TRANSPORTATION

University of Delaware
355 DuPont Hall
Newark, Delaware 19716
(302) 831-1446

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1 EXECUTIVE SUMMARY

Current procedure for design speed selection and application has been a concern for many design engineers, researchers, etc. for a long period of time. "There has been growing suspicion that the concept may have deficiencies if applied literally" [15]. "Growing numbers of geometric design researchers and practitioners recognize that the design speed concept as applied in the United States is unable to guarantee consistent alignments"[9]. There are two major concerns that must be considered when selecting the design speed: first, the fact that the design speed is being exceeded by the majority of drivers, and, secondly, there is a distinct difference between driver's behavior and the road's speed selection. Current approaches neglect the importance that design speed has on current users, society, environment, and neighborhood. Due to the limitations of the current design speed selection approach based on AASHTO guidelines, DelDOT design engineers desire alternatives to ensure a better design speed selection process. The scope of this paper is to provide DelDOT design engineers with research that includes the best available information on design speed selection. The research is compiled from the following sources: other state's DOTs, other agencies, foreign countries, and current articles on the topic. The ultimate goal of this research is to create an advanced guide for the context sensitive design-speed selection in Delaware. The design speed issue is not purely engineering in nature. It is affected by the local public and deals also with economical and environmental aspects. "Context-sensitive highway design considers the environmental, scenic, aesthetic, historic, community, and preservation impacts of a road project, as well as access for other modes of transportation, such as bicycling and walking" [4].

2 INTRODUCTION

In order to make roads safe (the primary objective of highway design and operations), it is necessary to build its various features to the operating speed. Therefore, vehicle speed is a crucial control element in the road design process. In the United States, the speed to which road alignment should be designed is called design speed. Road plans and construction that are based on the design speed concept are supposed to result in consistent alignment. However, over time there has been growing concern about the design speed selection procedure. The main concern is that the design speed is being exceeded by a large number of drivers on roads with lower design speeds (below 90 km/h). In 1991, a study of 28 horizontal curves in Maryland, Virginia, and West Virginia revealed a disparity between the design speed and operating speeds [9]. One curve had a design speed of 100 km/h and the other 27 curves had design speeds ranging from 30 km/h to 80 km/h. All curves with design speeds less than or equal to 80 km/h had 85th percentile speeds that exceeded the design speed. The curve of 100 km/h (design speed), was the only one that had an 85th percentile speed lower than the design speed. This implies that driver's desired speeds are being underestimated even though AASHTO guidelines advise that "the speed selected for design should fit the travel desires and habits of nearly all drivers"[1].

Another issue related to design speed is the assumption that the consistency of the road can be achieved by building individual alignment features upon the same design speed. However, research has shown that the design speed concept fails to provide alignment consistency. One of the reasons for this is that AASHTO guidelines advise that "above minimum design values should be used where feasible" while design speed concept controls just the minimum values. This approach results in a situation where drivers would speed up on a few successive, relatively flat curves not knowing that the next curve is a sharp one. On the other hand, the presence of a curve with a smaller radius than the minimum radius may not be a cause of inconsistency if that curve follows and precedes curves with slightly larger radii. In addition, AASHTO policy also assumes that drivers operate uniformly on a roadway that has all of its alignment features built based on the same design speed. This assumption is highly unrealistic. Australia's McLean states that "design speed is no longer the speed adopted by the faster driving group but has become a design procedural value"[15], or "a speed which is `safe` from the designer`s point of view" [9]. As a result, it seems that a more flexible approach should be used to select the design speed for a given roadway.

2.1 Speed terms

Different types of speed terms have been defined and are used in the design process. They are listed below:

2.1.1 Design speed

The current AASHTO definition is:

"the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern"

Design speed is applied to individual geometric elements rather than to sections of a road. The main factors by which design speed can be determined are:

- sight distance
- radius
- superelevation
- friction of the road element

In order to provide a logical procedure for selecting a design speed it is necessary to define additional speed terms. Another definition to design speed was adjusted by AASHTO in 1928 while discussing the "policy on highway classification": "the maximum approximately uniform speed which probably would be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones." In AASHTO`s "Policy on Geometric Design of Rural Highways", design speed concept has been changed from the behavioral measure to the minimum standard for all design elements being related to the chosen design speed: "A speed used for the design and correlation of the physical features of a highway that influence vehicle operation" [1].

2.1.2 Operating speed

Operating speed is the speed at which drivers operate their vehicles. The 85th percentile speed of a sample of observed speeds is usually regarded as the operating speed on a particular section [12].

2.1.3 Posted speed

Posted speed refers to the maximum speed limit posted on a section of highway using the regulatory sign [12]. Speed limits are typically set based on a roadway's design. For example, whether it is a narrow two lane road or a modern controlled access freeway and whether it is in an urban, suburban or rural setting. The posted speed limits, if perceived as reasonable by the majority of drivers should result in uniform traffic flow. Advisory speed plates are often used in cases where design and operating speeds are different [9]. The speed limits should also give the motorist an idea of what is a reasonable speed to drive in an unfamiliar location. Advised speeds generally seem low to the majority of drivers because AASHTO's maximum side-friction factors by design speed are based on 1940's measurements. These values may not reflect the performance and tolerance of today's vehicles and drivers.

It has been pointed out that measuring the speed distribution of a roadway and setting the speed limit to the 85th percentile speed, may reduce the need for enforcement and also reduce crash risk by narrowing vehicle speed variation. However, numerous studies of travel speeds on rural interstate highways have shown that 85th percentile speeds increased when speed limits were raised to 65 mph. Therefore, the 85th percentile speed is not stationary; rather it is a moving target that increases when speed limits increase.

"In states where speed limits were raised to 65 mph in 1987, there was a 15-20 percent increase of fatal accidents on rural interstates each year" [10]. Two assumptions that follow from basing a design speed on the 85th percentile speed are: Motorists are able to decide on an acceptable travel speed, and the speed limit is set at the 85th percentile speed. TxDOT suggests using the design speed as the initial speed limit when a new facility is designed [22]. After a reasonable operation period, an 85th percentile speed can be used to set the new speed limit.

2.1.4 Legal Speed

The legal speed is the minimum or maximum speed limit that can be posted on a particular road class. Under normal roadway conditions it is illegal to go below the minimum speed limit or to exceed the maximum speed limit posted on a particular road class.

2.2 Context Sensitive Design

The Intermodal Surface Transportation Efficiency Act (ISTEA) and the National Highway System legislation of 1995 are the first steps toward context-sensitive design.

During the design process, engineers have to cope with different aspects of design (environmental, etc.) that will sometimes be in conflict with the engineering design concept. Context sensitive design could be described as design in harmony with the community and the environment. A design engineer's traditional training and education have been challenged with the need to approach this problem from various perspectives.

2.2.1 Land Use:

Lack of coordination between land use and transportation plans often results in roadway facilities that are not designed to be of optimum service to the community. Closer coordination between land use and transportation planners would result in an appropriate road design speed selection and be of maximum benefit to the community. Selection of design speed should take into account the expected change in a facility over time, for instance, from a rural environment to a suburban one [22]. The phenomena of growing pollution and other environmental issues must be recognized and incorporated in the road design process.

2.2.2 Environmental Issues:

Environmentally sensitive areas such as wetlands, animal habitats, nature conservation areas, etc. impose certain limitations when choosing locations for transportation facilities. Aesthetic issues must be considered. When designing a road through a scenic area, the general view of the area should not be obstructed. Preserving the natural environment and ensuring community livability is an essential consideration when designing/ building a new roadway.

2.2.3 Community Livability:

Roads are no longer being designed solely for automobile use. There is a variety of other users that include the following: pedestrians, bicyclists, buses, farm equipment, and heavy trucks. This requires creative and flexible approaches along with solutions to road design, and therefore, to the design speed selection process. An equally important goal in designing a transportation facility is to preserve the attributes and characteristics of the community because it is a major "client".

2.2.4 Public Involvement:

Citizen participation should be a significant part of the road design process. The needs and desires of the local and public community should be incorporated in the design process. Public workshops and other events that bring the public together with engineers to discuss the road design process should be encouraged.

2.2.5 Summary of the Context-Sensitive Design:

Designing roads in a sensitive context entails a compromise between engineering judgement (safety, geometric design) and environmental aspects. Therefore, using context sensitive design aspects in the design process is necessary to ensure successful design i.e. roadways that provide the best mobility while ensuring the highest safety standards, and address the natural and human environmental aspects.

2.3 Current research at the University of Delaware

Formal research was employed in order to obtain the results displayed in this paper. The method of research employed included the following information-gathering procedures:

- A study of Federal Guidelines (AASHTO)
- Studying Delaware's road design manual
- Contacting the Departments of Transportation in all fifty states, and obtaining the responses from almost one-half of them. Some design manuals are available on the Internet.
- Contacting the Departments of Transportation from foreign countries and obtaining responses from Australia (Rural Roads Design Manual), Denmark (email), and Yugoslavia (Design Guidelines). Information from other countries such as Germany, Great Britain, France, and Switzerland was obtained through published articles.

3 PURPOSE OF THE PROJECT

The purpose of this project is to provide DelDOT with a brief methodology for selecting context sensitive design speeds. In addition to researching selection practices of other DOTs, and those of other countries, a complete literature search is planned to investigate any additional research that has been performed on this topic. These findings would help formulate a methodology of the design speed selection process that: covers a variety of situations, encompasses the most up-to-date-research, prevents inappropriate design speed placement, and is a concise and user-friendly guideline. These guidelines should help DelDOT engineers easily and efficiently select the appropriate design speed for a roadway; basing this on existing or proposed roadway, traffic, and environmental conditions.

4 AASHTO AND FEDERAL GUIDELINES

The federal guidelines and codes which are the most important and most commonly used resources for designing highways and street are found in the Policy on Geometric Design of Highways and Streets, (AASHTO 1994).

The guidelines for design speed are:

- Design speed is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern. The assumed design speed is directly related to topography, adjacent land use and type of highway.
- The selected design speed should be the highest that a desired degree of safety, mobility, and efficiency under constraints of environmental quality, economics, aesthetics, and social and political impacts allow.
- The selected design speed should be similar to the operating speed. The selection of design speed on a secondary road has to consider topography conditions before enabling driving at relatively higher speeds. Drivers adjust their speeds to the physical road limitations and traffic. The influence of road hierarchy is negligible.
- The speed selected for design should fit the travel desires and habits of the majority of drivers. A cumulative distribution of vehicle speeds has the typical S pattern when plotted as percent of vehicles versus observed speeds. The design speed should be a high-percentile value in this speed distribution curve, i.e. almost all typically desired speeds should be considered.

If there is a continuity of tangent or flat curves in rugged terrain, drivers will naturally use higher speeds, and such road sections should be designed for higher speeds. A pertinent consideration in selecting design speed is the average trip length; it follows that the longer the trip, the greater the desire for expeditious movement. Changes in terrain and other physical features may dictate a change in design speed on certain sections. In such conditions a low design speed should be implemented gradually in order to guarantee safety. Generally, design speed does not change significantly with respect to elevation. In northern climates, elevated structures are subject to rapid freezing. Thus, superelevation rates may have a greater impact on design speed. All new highway features should be based on selected design speed in order to ensure a balanced design. If the above stated guidelines are followed this should result in a more consistent design speed selection. However, due to the fact that AASHTO does not provide quantitative guidance for these guidelines, this will eventually result in inconsistent design.

5 DESIGN SPEED SELECTION PROCESS BY DELDOT

DelDOT currently selects design speed as described in: The State of Delaware Road Design Manual (Chapter 3, section 3.1.2)

Applications of standards in Delaware are based on AASHTO design criteria: "most of the AASHTO design criteria are expressed as minimum values or as ranges of values for particular conditions. There is some degree of flexibility in the specific practices that might be adopted by an individual agency. The standards adopted by the Delaware DOT, generally adhere to the basic framework of AASHTO design polices."

Section 3.1.3 (DelDOT manual) discusses departure from standards:

"Normally, it is required that at least the minimum design standards be provided, but occasionally there may be conditions that warrant consideration of a lower standard. In such cases departure from design standards must be thoroughly documented for review and approval by the Chief Engineer, and when applicable involved FHWA review and approval is also required."

5.1 Standards Based On Design Speed

The following standards are based on design speed:

- Curvature and super elevation
- Required sight distances

Both these road design parameters are directly related to the design speed. Since they are also closely related to traffic safety at least minimum values for these standards must be achieved. Basically, current DelDOT design speed selection procedure is performed by extracting design speed values from four tables: (1)two lane rural roads, (2)rural multi- lane highways, (3)urban multi-lane highways, (4)two lane urban arterial and collector highways.

6 A SUMMARY OF DESIGN SPEED SELECTION PROCESS BY STATE DEPARTMENTS OF TRANSPORTATION

6.1 Arizona

Arizona DOT (ADOT) uses design speed to establish specific minimum geometric design elements for a highway segment. According to ADOT, approach design speed does not necessarily define the maximum safe speed that can be maintained on a highway. Rather, design speed is considered as a minimum and thus highway geometric design elements can meet or exceed the design standards for that particular design speed for new alignment projects. The design standards are based upon unfavorable or near-worst case conditions (conservative approach). Therefore, the maximum safe speed under normal conditions will be much greater than the design speed. They emphasize that posted speed limit should reflect the 85^{th} percentile speed value. The speeds which drivers find comfortable to travel are independent on design speed as well as are posted speed which reflects 85^{th} percentile speeds. It implies that design speeds are independent on the posted speed limit.

As far as design speed selection is concerned high design speed should be used in order to save public money through lower vehicle operation costs and reduced time of travel in spite of greater initial cost for construction investment and right of way. The selection of a design speed does not impose an upper limit on geometric design.

Table 1 shows appropriate values of design speeds for various conditions. Design speed values in parentheses are minimum values to be used in irregular circumstances.

Table 1: Relation of highway type to design speed (Arizona DOT)

Highway type	Design speed (km/h) (min); desirable
Controlled access highways	
• level terrain	(110) 120
• rolling terrain	(110) 120
• mountainous terrain	(80) 110
• urban/fringe urban areas	(90) 110
Rural divided highways	
• level terrain	(100) 110
• rolling terrain	(90) 110
• mountainous terrain	(80) 100
Rural Non divided highway	
• level terrain	(100) 110
• rolling terrain	(90) 100
• mountainous terrain	(70) 90
Urban/Fringe Urban Highways	
• Arterial streets	60-100
• Arterial streets with extensive development	50-80

6.2 Arkansas

The Arkansas DOT uses Green Book guidelines to select design speed.

6.3 California

The California DOT definition for design speed is: "A speed selected to establish specific minimum geometric design elements for a particular section of highway. These design elements include vertical and horizontal alignment and sight distance". During the detailed design phase of a project, special situations may arise in which engineering, economic, environmental or other considerations may make it impractical to provide the minimum elements established by the design speed. Most likely case is horizontal sight distance restriction imposed by bridge rails, bridge columns, retaining walls, sound walls, cut slopes, and median barriers. It can result in a reduction of design speed at such locations.

According to California DOT, "Where the local facility connects to a freeway or expressway the design speed of the local facility shall be a minimum of 55 km/h. The design speed should be 75 km/h when feasible."

6.4 Colorado

Colorado DOT basically refers to AASHTO guidelines in their manual.

6.5 Connecticut

Connecticut DOT provides copies of pages of their Highway Design Manual relevant to the design speed selection process for 3R (resurfacing, restoration, and rehabilitation) and 4R (resurfacing, rehabilitation, restoration and reconstruction) and new construction projects for rural and urban roads. These copies include tables for different road classification and project types. For 3R projects design speed has particular range of values based on the actual speed measured in the field. **Table 2**, placed below, contains the design speed for 3R projects based on the 85th percentile speeds obtained. The procedure for the latter is the following:

The Division of Traffic Engineering provides speed studies in the vicinity of the proposed project. If there are no recent studies available, then field measurements may be necessary. The designer then evaluates the speed data to determine the 85th percentile speed. Next, based on a table of various 85th percentile speed ranges the appropriate design speed is chosen. Connecticut DOT's criteria for new construction also apply to 4R freeway projects. The designer can make certain decisions and is allowed some flexibility. For choosing the design speed, the manual provides tables based on functional classification (rural freeways, multi lane rural arterials, two-lane rural arterials, rural collector roads, rural local roads; urban freeways, multi-lane principal urban arterials, two lane principal urban arterials, minor urban arterials, urban collector streets, local urban streets).

Table 2: Design speeds for 3R projects (Based on 85th percentile speeds) – Connecticut DOT

85th Percentile "V" (km/h)	Design Speed (km/h)
0≤V≤30	30
30≤V≤40	30/40
40≤V≤50	40/50
50≤V≤60	50/60
60≤V≤70	60/70
70≤V≤80	70/80
80≤V≤90	80/90
90≤V≤100	90/100
V≤100	100/110

6.6 Georgia

The Georgia DOT has no formal method of determining design speed. Design speed is one criterion for the project and it is based on the roadway functional classification as defined in the AASHTO guidelines. Moreover, the designer may occasionally base design speed on a local speed ordinance for off system routes or state law. For example, it is specified that unpaved roads should have a speed limit of 35 mph and paved roads have a speed limit of 55 mph if there are no speed limit signs posted.

6.7 Idaho

The Idaho DOT uses the AASHTO Green Book criteria for selection of design speed on National Highway System (NHS) routes. For non-NHS routes Idaho DOT uses separate state standards that correspond to the same criteria (functional classification, terrain type and traffic volumes) for the design speed selection.

6.8 Illinois

Illinois DOT uses the following general guidelines when selecting design speed: "Minimum 60 km/h design speed is used in relatively undeveloped areas where economics, environmental conditions, and signal spacing permits. The statutory speed limit in urbanized areas is 30 mph (50 km/h). A design speed of 80 km/hr should be used in open-suburban areas."

6.9 Indiana

Indiana DOT selects design speeds for new and reconstruction projects based on their own manual, which is almost identical to the AASHTO green book. For 3R projects they use present posted speed as the design speed.

6.10 Kentucky

Kentucky DOT selects design speed primarily in accordance with posted speed, or expected speeds to be posted on a highway.

6.11 Minnesota

Minnesota DOT chooses design speed based on functional classification, major section forecast, AADT, terrain, adjacent land use, and the functional use of the highway. The desired degree of safety, access, mobility, and efficiency are weighted against environmental, right of way and cost impacts. Design speeds usually fall between 50 and 120 km/h at 10 km increments. Facilities with design speed greater than 70 km/h are considered as high-speed facilities, and low speed facility design speeds are 70 km/h or less. Design speeds must equal or exceed the posted speed.

6.12 New Mexico State

New Mexico State highway & Transportation Dept. uses the AASHTO guidelines for design speed selection. After construction, they conduct a survey and adjust the posted speed to the 85th percentile speed.

6.13 New York State

New York State DOT provided the definition of design speed from their Design Criteria chapter.

6.14 North Carolina

North Carolina DOT sets the design speed at 5 mph above the anticipated posted speed.

6.15 Rhode Island

Rhode Island Department of Transportation does the following: roadway classification and the horizontal/vertical curve data from the AASHTO Green Book is utilized to establish speed limits on new roadways, and the 85^{th} percentile speed is used to establish speed zones if they get a request to modify a speed limit on an existing roadway.

6.16 Tennessee

Tennessee DOT uses The Green Book for design speed selection. They use topography, land use, traffic volumes, cross-section and actual operating speeds in order to establish project criteria.

6.17 Utah

Utah DOT selects design speed so as to meet AASHTO standards. Before a final decision is made, the operating speed characteristics on adjacent road sections should be examined.

6.18 Vermont

Vermont DOT states that the minimum design speed used should be 40 km/h since it is the minimum posted speed allowed under Vermont State Law. The design speed should be as high as the legally posted speed limit. If there is a change in legally posted speeds within the project limits, different design speeds may be used for those different sections. On new road projects, where there are no posted speeds, the design speed should be no less than the anticipated legally posted speed. On most state and town highways, Vermont State Standards limit the selection of design speed to the actually legally posted speed, so selection of a higher speed is not allowed. For Interstate projects design speed may be higher than the legally posted speed. Their manual contains a table that shows how the metric design speed correlates with the posted speed.

6.19 Virginia

Virginia DOT defines design speed as the speed used in design corresponding to the physical features of a highway that influence vehicle operation. For each road class, design speed is provided in an appropriate table.

6.20 Washington

Design speed selection procedure is not a rigorous one for Washington State. It is selected during the planning stage. Washington DOT found that categorizing a highway by terrain often results in arbitrary reductions of the design speed. In fact, the terrain enables a higher design speed without materially affecting the cost of construction.

6.21 Wisconsin

Wisconsin DOT uses AASHTO design speed definition. It also emphasizes that the chosen design speed should be a high-percentile value in the speed distribution range, to satisfy the desired travel speeds of the majority of drivers. The DOT suggests using design speeds approximately 8 km/h greater than the posted speed.

7 REFERENCES FROM FOREIGN COUNTRIES

7.1 Australia

The following is a definition of design speed from Australia's Rural Road Design manual, "Design speed applies to individual geometric elements and is the speed that is used to co-ordinate sight distance, radius, superelevation and friction demand for elements of the road so that a driver negotiating each element at its design speed will not be exposed to unexpected hazards. It must be a speed that is unlikely to be exceeded by most drivers." [21] In Australia, design speed should not be less than the estimated 85th percentile of the speed distribution that will result from the construction of a particular geometric element within a given speed environment. Design speed of successive geometric elements should vary when driver's speeds are expected to vary. The limiting curve speed must never be below the design speed.

Speed environment

"Since the environment of the road principally governs the desired speed of drivers, the term speed environment has been used to describe a characteristic of a section of a road. It is regarded as being uniform over a section of a road that is reasonably consistent in both terrain and general geometric standards". [21] **Table 3**, placed below, contains speed environment guidelines for Australia, based on the terrain type and the approximate range of the horizontal curve.

Table 3: Australian speed environment guidelines [21]

Approximate Range of Horizontal Curve Radii (m)	Terrain Type			
	Flat	Undulating	Hilly	Mountainous
Less than 75			75 km/h	70 km/hr
75-300		90 km/h	85 km/h	
150-500		100 km/h	95 km/h	
Over 300-500	115 km/h	110 km/h		
Over 600-700	120 km/h			

High-Speed Environments

On roads of consistently high geometric standards, speeds on curves and straights are not significantly different. Therefore by definition, the speed environment and design speeds typically do not exceed 120 km/h. However, design speeds up to 130 km/h are still used. They are regarded as national vehicle travel speeds. Roads designed to these standards provide increased factors of safety in operation, and a higher quality of service to all drivers. Normally, selection of design speeds over 100 km/h will be made only for one of two reasons: Where the high standard geometrics are compatible with the terrain, or where the importance of the road is considered to justify the additional costs of achieving the added quality of service. [21]

Intermediate-Speed and Low-Speed Environments

"In low-speed and intermediate-speed environments, the design speed will vary over the length of the road in accordance with the predicted value of the 85th percentile speed. For safe operation, incremental changes in design speed must be limited". "Normally, design speed should not differ by more than about 10 km/h on successive geometric elements ...Where some local constraints necessitates a change in design speed in excess of 10 km/ h and the extent of the change is insufficient to define a new section speed environment, a change may be accomplished by using a sequence of horizontal curves whose predicted 85th percentile speeds do not reduce by more than 10 km/h at each step. The predicted speed of each element is used as the speed environment value to derive the design speed for the succeeding element...On one way roads, the 10 km/h restriction on change of design speed does not apply in the direction of increasing design speed." [21]

7.2 Canada

Ontario's highway geometric design standards state that the traditional approach of selecting an arbitrary design speed does not guarantee design consistency [7]. In most respects, the Canadian policy on rural alignment design is similar to U.S. Policy [9]. The desirable practice for Ontario Highways is to select a design speed 20 km/h greater than the speed limit [7].

7.3 Denmark

For interurban areas the design speed is the desired speed plus 20 km/h. The desired speed is normally 80 km/h on two lane roads and 110 km/h on motorways. If there are no slow moving vehicles on the two-lane road a design speed of 90 km/h can be chosen, but is not recommended due to the likelihood of fatal accidents. When the speed is 50 km/h or more separate cycle tracks are recommended. Currently, there is discussion of reducing the speed in all intersections to 50 km/h to reduce the risk of fatalities.

7.4 Germany

German standards use the "Entwurfgeschwindikeit Ve", which is close to the design speed concept. The speed selection is based on environmental and economic conditions, as well as the function of the road. It is used to determine the minimum values of the horizontal and vertical alignment radii and the maximum gradient. The 85^{th} percentile speed is calculated on the basis of the curvature change rate and the width of the road and it is used to determine superelevation and control sight distance. The curvature change rate is computed for roadway sections as the sum of the angular change in direction divided by the length of the segment. For a simple circular curve without spiral transitions, the curvature change rate is equivalent to the degree of curvature except for different units [9]. The 85^{th} percentile speed (V85) should not be much different from the design speed Ve. If the difference between them is larger than 20 km /h, design speed should be raised or characteristics of alignment should be modified to reduce V85. To ensure consistency, the difference between the values of 85^{th} percentile speed (V85) on any two successive sections should not exceed 10 km/h.

7.5 Great Britain

In Britain, design speed is defined as a speed that is consistent with the actual speeds expected on the alignment. The functional classification concept is not included. They emphasize the effects of alignment and layout (cross section and access control) constraints on operating speeds in selecting a design speed. Design speed is determined through an iterative procedure: an alignment is based on trial design speed and the actual speeds are determined from the model and compared with design speed. If necessary, adjustment of the alignment or design speed will be carried out. British standards ensure consistency between design speed and journey speed on a road section at least 2 km long based on a solid model. The actual speed used is an 85th percentile speed calculated on these sections. "The model used to predict this speed is based on different variables related to the average curve characteristics of the section, the average visibility, the number of access points per kilometer, and shoulder width." Also, British standards allow the choice of a characteristic smaller than the minimal values [9]. British standards focus on passing (overtaking) behaviors as the principal safety concern on two lane highways.

7.6 France

The new French guidelines depart from the design speed concept and emphasize that driver-roadway interaction influences speed behavior. The old French guidelines had five road categories and each had a design speed range of 40 km/h to 120 km/h. The new guidelines specify only a 20 km/h range of design speed for each of the three new road categories [9]. In France, design speed determines only the minimum radii of curvature for horizontal and vertical alignment and the maximum gradient. However, the design speed concept is not explicitly mentioned in the manual. The 85th percentile speed is also used and it is determined at each point of the alignment. A service agency of the French Ministry of Transport (SETRA) is developing microcomputer software for the estimation of 85th percentile operating speeds. The software would be used early in the design process, and input data would include: the general cross section (number of lanes, lane widths), horizontal alignment, and longitudinal profile. The output is an 85th percentile speed profile along the proposed alignment [9]. Consistency is very important in the new French guidelines.

7.7 Sweden

For the country of Sweden the respective design speeds selected are those which the survey results indicate 85 percent of people drive below. This consideration is reflected in the design guidelines through two sets of standards: regular minimum and exceptional minimum. The regular minimum is based on the 85th percentile speed associated with the design speed, while the exceptional minimum is based upon driving at the speed limit [9].

7.8 Switzerland

In Switzerland, design speed is defined as the maximum safe speed for travel on a certain road element. It is used to determine geometrical alignment of the elements of the road and is consistent with the 85th percentile speed. To check consistency, design speed profile diagrams are used. The original procedure estimates the speed profile along an alignment and identifies excessive speed differentials between successive elements. It was applied to rural highways only [9]. Research revealed that grades up to 6 to 7 percent have no influence on passenger car operating speeds, therefore speeds are estimated only from the horizontal alignment. **Table 4** presents Swiss standardized speeds for various curve radii, including urban roads.

Table 4: Swiss standardized speeds for various curve radii [9]

Road Type	Speed (km/h)	Radius (m)
Urban Roads	40	45
	45	60
	50	75
Rural Roads	55	95
	60	120
	65	145
	70	175
	75	205
	80	240
Freeways	85	280
	90	320
	95	370
	100	420
	105	470
	110	525
	115	580
	120	≤ 600

The speed profile for a road should satisfy three conditions:

1) If the preceding element is tangent or a large radius curve, i.e., ≥ 420 m (1,378 ft), then the speed differential to the succeeding curve should not exceed 5 km/h (3.1 mi/h)
2) In a sequence of curves, the speed differential should be ≤ 10 km/h (6.2 mi/h). Differentials ≥ 20 km/h (12.4 mi/h) must be avoided.
3) The existing sight distance should equal or exceed the length of transition required to change speed at a rate of 0.8 m/s^2 (2.6 ft/s^2) between successive curves.

7.9 Netherlands

National law establishes general speed limits for various roadway types. The speed limit on motorways for light traffic flow is 120 km/h. Motorways with lower design standards (lower level of service), or with heavy traffic flow, have a limit of 100 km/h. On rural roads, the general limit is 80 km/h. Urban roads have a general limit of 50 km/h, and the limit in residential areas is 30 km/h.

8 ADDITIONAL LITERATURE REVIEW

The next sections (8.1-8.13) present 13 recent papers that correspond to the design speed subject. Most of the articles discuss problems resulting from design speed being exceeded by operating speeds, inconsistency of roads, etc. Some of the articles address problems with the design speed selection process itself.

8.1 Design Speed, Operating Speed And Posted Speed Relationships

Authors: Kay Fitzpatrick, Raymond A. Krammes and Daniel B. Fambro
Source: ITE Journal, February
Year, or time of Publication: 1997

This paper discusses the relationships among several different kinds of speeds. Differences in design and operations criteria can frequently result in higher values of posted speed limit (based on the 85th percentile speed) that exceed the roadway's design speed. This is directly related to the criteria used in highway design that incorporate a significant factor of safety. TxDOT sponsored a study (surveys, personal interviews and field studies) to document concerns and difficulties regarding the relationships between design, operating, and posted speeds.

Anticipated operating speeds and/or posted speeds are frequently considered when selecting design speed. However, functional class (urban vs. rural), and the department's design criteria, are more important in consideration than anticipated operating speed. When selecting speed limits on existing roadways it is important to examine the 85th percentile speed (V85). When the facility is new, half of the survey respondents considered design speed as the initial speed. The speed is modified after the facility is in operation, using the 85th percentile operating speed determined from speed measurements. This can result in 85th percentile speed being greater than the design speed.

Nearly all FHWA interviewed engineers and AASHTO members agreed that the current AASHTO definition for design speed "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern" is incomplete. The term "maximum safe speed" was considered improper because speeds greater than design speed can be safely negotiated on many sections of highway when "conditions are favorable". Engineers explained that roadways are designed with factors of safety that typically allow drivers to exceed the design speed without creating hazardous conditions (roadways are designed for near worst-case conditions).

Factors considered when selecting a design speed are as follows:

- anticipated operating speed
- anticipated posted speed limit
- commercial development
- construction costs
- cross section
- curb and gutter
- DOT design criteria
- design vehicle
- environmental implications
- functional class
- legal speed limit
- site topography
- urban vs. rural design

8.2 AASHTO Speed Guides Questioned

Author: Olivarez, David

Source: Better Roads

Year or time of publication: June 1998

This paper suggests review of the green book in order to properly determine how the AASHTO design speed relates to the establishment of speed limits.

"When designing roads the engineer makes every effort to meet the AASHTO criteria based on the established design speed. In many instances, it is not practical or feasible to satisfy the established criteria."

"As an example, if one chooses a design speed of 40 mph for a two lane, two way highway in mountainous terrain, then one would need a minimum passing sight distance of 1500 ft. This would mean that virtually every hill would have to be flattened."

"The minimum passing sight distance from the MUTCD is about half of the established design criteria. This is an example of AASHTO establishing one set of criteria for design and another for operations." "If we were to set the speed limits based on AASHTO design criteria, our rural interstate would need a night speed limit of 30 mph. "Realistically one cannot use the design speed directly to establish speed limits. Virtually all unexpected stops by drivers are panic stops, which require far less stopping distances than those established by AASHTO."

8.3 Survey Investigates the Relationships Among Design Speeds, Operating Speeds, and Posted Speeds

Source: TranSafety reporter
Year, or time of publication: 1997

This paper presents TxDOT research on the relationships among design speeds, operating speeds, and posted speeds. More than half of all respondents reported that they consider the anticipated operating and posted speed limit in their design selection process. One of the responses also underscored belief that "design speed should always exceed or equal expected operating speed."

About half of all respondents mentioned that there were road sections (under the agency's responsibility) where the operating speed or the posted speed of a section exceeded the design speed. However, they indicated that no actions were taken unless there was an increase in crashes or another safety problem as identified. The common actions undertaken were to install advance warning signs, in order to warn the drivers and decrease the operating and posted speed.

Participants were asked which factors they considered for determining the posted speed limit on an existing facility. Nearly all respondents stated that 85 percentile speed, recent crashes and state mandated maximum speed limits were more important than design speed. More than 75% of the respondents agreed that anticipated operating speed should be considered when selecting the design speed of a roadway.

8.4 Designed For Speed: How Roads Are Engineered

Source: AASHTO Quarterly magazine (1996)

This paper discusses speed limits. Approximately two thirds of Americans think that the speed limit on Interstate freeways should be 65 mph or higher. According to the U.S. Department of Transportation, 94 percent of speed related fatalities occur on roadways with speed limits of 55 mph or less.

American Automobile Association's (AAA) supports the concept of 85^{th} percentile speed that represents the user determined speed limit. They consider that such a limit would best serve the public interest and provide the appropriate balance between speed and safety. However, increased speed limit does not only increase the chance for road accidents, but has also environmental consequences (air pollution, noise, etc.). According to NHTSA, an exploration of the relationship between fuel consumption and speed showed that passenger cars and light trucks use approximately 50 % more fuel efficient traveling at 75 mph than at 55 mph. A chance for serious injury doubles for every 10 mph, above 50 mph, which a vehicle travels at.

TxDOT studies have shown that motorists select their speeds based on the driving environment-roadway geometry, traffic conditions, weather, pedestrians, comfort, and safety. "If the objective is to maximize driver compliance and optimize a blend of safety, efficiency and motorist satisfaction, the proven technique is setting speed limits that reflect 85^{th} percentile speeds."

8.5 Geometric Design Guidelines To Achieve Desired Operating Speed On Urban Streets

Authors: Poe, Mason

Source: 65th ITE annual meeting compendium of technical papers

Year , or time of Publication: 1995

The paper investigates the guidelines for the design of low-speed urban streets. It investigates "geometric guidelines that would assist in attaining operating speeds consistent with the intent of the low speed environment." Low operating speeds are desirable in providing safety to pedestrians and bicyclists. Low speed is defined as vehicle operating speed that is lower than 64 km/hr. Selection of geometric elements and their design values would be based on the "expected" vehicle operating speed.

Design speed is a fundamental criterion upon which the design of roadways is based. A designer will select a design speed based on the land use, topography, and function of the roadway. The geometric elements of the roadway are then selected based on this design speed. The design speed concept is limited in the low-speed environment because only a few geometric elements are controlled by the selection of a design speed value.

Several sources present the planning and design of local streets. AASHTO Green Book discusses the geometric design of low-speed streets. Design speeds are suggested to be between 30 and 48 km/h for local roads and above 48 km/h for urban collectors.

Results of the analysis showed that "for design speeds below 60 km/h, the majority of sites had 85th percentile speeds above the critical design speed. However, in this range there was strong correlation between the 85th percentile speed and the critical design speed, which was determined by the geometric conditions." Sites with more restrictive geometry had lower mean operating speeds than sites with less restrictive geometry. The findings provide design values for geometric elements that can be useful in achieving desired operating speeds. The values are presented in **table 5** below.

Table 5: Design values for geometric elements

Design Element	Vehicle Operating Speed Range			
	20-40 km/h		40-60 km/h	
	Min	Max	Min	Max
Curve Radii (m)	10	25	60	230
Sight Distance (m)	50	125	65	285
Absolute Value Grade	0.0	16	0.0	5.0
Lane Width (m)	2.9	3.6	3.2	5.45
Parking Availability	None	None	None	None
Lateral Clearance	0	0	0	3

Lateral clearance: 0-no obstructions, 3 - some flexible and fixed objects within 1.5 meters of roadway, 4-continuous objects within 1.5 meters of roadway.

8.6 An Alternative to the Design Speed Concept for Low Speed Alignment Design

Author: McLEAN
Source: Transportation Research Record 702
Year , or time of Publication:1979

A design speed concept that originates from driver behavior considerations is now treated as an arbitrary means of designing and matching geometric elements. Research from Australia on the relationships between driver speed behavior and alignment design shows that for alignments based on design speeds of 110 km/h or more, driver behavior appears to be in accordance with the design speed concept. For alignments with design speed of 90 km/h or less, driver speeds vary along the route and are consistently in excess of the design speed.

Australian road authorities face the problem of designing roads for long distances, and often high-speed travel, while only modest geometric standards can be afforded. This forced designers to look closely at the principles underlying geometric design practices. It has led to a growing suspicion that the traditional design speed approach may not be appropriate for the design of lower speed range alignments. The paper emphasizes that horizontal curves and other alignment properties have a great influence on driver speed behavior and safety of traffic operations. The authors provide three criticisms of design speed:

1) Designing according to the design values permitted by a specified design speed does not necessarily ensure consistent alignment standards.

2) Designing according to the design values permitted by a specified design speed does not necessarily ensure compatibility between the standards for combinations of design elements (e.g. vertical elements and horizontal curves).

3) Free vehicle operating speeds and design speed are not necessarily synonymous.

Speed standard and perception of hazard presented by the alignment may vary along a road designed with a constant design speed. The speed adopted by a driver tends to vary accordingly and may often be in excess of the design speed. In addition, increasing curve radius in order to improve sight distances may merely serve to increase operating speeds.

For roads with design speeds greater than 110 km/h in rolling terrain, or 120 km/h in flat terrain, 85^{th} percentile desired speeds are less than the design speeds. In rolling terrain, for roads with design speeds of 100 or 110 km /h, speeds will vary according to the speed standards of individual features.

As far as sight distance is concerned, ARRB research suggests that modern vehicle/tire/pavement combinations are capable of achieving much higher deceleration rates than are assumed for the derivation of current stopping distance standards. Traditional standards based on the design speed concept have “attempted to build safety into design through the employment of very conservative design criteria.” However, for the lower range of speed standards, drivers compensate for the conservative criteria by traveling at speeds greater then the nominated design speed. Introducing additional safety through additional conservatism in design criteria will only increase the discrepancy between actual speeds and the assumed design speed.

8.7 Highway Alignment and Superelevation: Some Design Speed Misconceptions

Author: Hayward John

Source: Transportation Research Record, No. 757

Year, or time of Publication: 1980

A potential cause for traffic accidents is increasing degrees of curvature. Sharp curves in segments that otherwise have good alignment tend to surprise drivers and create hazardous situations. Consistency in design speed along significant sections of highways has been advocated by some as a means of controlling the incidence of surprise curves in otherwise "gentle" alignments. The design speed on horizontal curves is a function of the maximum superelevation, adopted by the design agency. Moreover, different design speeds can be determined by agencies that have different maximum superelevation policies. Hence, such use of design speed criterion (superelevation) for identifying potentially hazardous horizontal alignments might not be appropriate.

FHWA (1978) gives additional information on design speed: "The purpose of the design speed is to correlate those physical features of a highway that influence vehicle operation." The selection of design speed depends on the type of highway and the terrain.

One way to identify problem alignments within a highway system would be to display the design speed of each component graphically and look for discontinuities in the design speed curve. If a difference of less then 24 km/h (15 mph) exists between the calculated design speed for a curve and the designated design speed of adjacent sections, the curve ought to be signed and marked accordingly. If a difference of more than 24 km/h exists for horizontal curves, corrective work should be undertaken.

8.8 Speed Study Examines Design And Posted Speed

Author: Fitzpatrick, Kay

Source: Texas Transportation Researcher

Year of Publication: 1996

This paper discusses speed limits after congress has eliminated the national speed limit, since that task has become more complicated for traffic engineers. A conclusion of a TxDOT study is that speed limits based on 85^{th} percentile speed are considered safe and appropriate, even when they exceed the design speed. Another objective of the study is to address the relationships between design speed and posted speed (speed limit for a given section of road). Drivers as a group tend to travel at speeds appropriate for the roadway conditions. 85^{th} percentile operating speeds enhances speed uniformity, which is a safety benefit.

8.9 The Computer –Based Road Alignment Consistency Evaluation

Author: Vojo Andjus

Source: International Road Federation-Regional Conference for Europe, Belgrade, Yu

Year, or date of Publication: 1991

The paper describes the personal computer-based road alignment consistency evaluation program, from the user's perspective. The interactive PC-based system "VIA SOFT" is specially made for the road design engineer. It is developed to cover geometrical and dynamical analyses of road routes as an efficient and valuable tool for preliminary and final road designing. The software can optimize horizontal and vertical roadway elements. There are six subprograms: curvature profile, design speed profile, sight-distances profile and surface drainage gradients profile. Basic parameters for road alignment consistency evaluation are coefficients of geometric (Gh) and dynamic (Dh) homogeneity, which are also used as indicators for alternative evaluation.

Determining consistency and homogeneity of applied road design geometry elements is a key step in the process of achieving safe and comfortable driving on future roads. Homogeneity of horizontal and vertical road design elements may be considered from two points of view: geometrical and dynamical and they are related with analysis and application of harmonious and functional spatial forms.

Parameters of geometrical homogeneity of the road route include curvature (horizontal) and geometrical homogeneity coefficients. Dynamical parameters of consistency and homogeneity are considered on the basis of the resultant design speed profile. Design speed represents a theoretical value that is used for dimensioning a certain road element to provide for safe and comfortable driving in free flow conditions. Parameters of dynamical homogeneity are: mean design speed value (Vp) and coefficient of dynamic homogeneity. The coefficient of dynamical homogeneity allows for the comparison of road alignments with the same and/or different design speed values.

"VIA SOFT-VD" Program system is used in the following way: Depending on the road rank and the terrain conditions, as well as the applied elements of horizontal and vertical alignment, the calculation of driving –dynamic parameters are formed for the basis for the calculation of curvature, design speed profile, superelevation, acceleration and jerk profile, sight distance profile, and surface drainage profile.

8.10 Speed Variance and Its Influence On Accidents

Authors: Nicholas J. Garber, Ravi Gadiraju

Source: Department of Civil Engineering – University of Virginia

The level of safety on any highway is related to the geometry of the roadway. The geometric characteristics of a section of highway, e.g., maximum grade, minimum curvature, etc. are based mainly on the design speed. An important traffic characteristic which has been found to influence safety is speed variance. The objective of the study is to investigate the traffic engineering factors that affect variance of vehicle speeds in a traffic stream. The major factor identified is the difference between the design speed of the highway and the posted speed limit. It is determined that the speed variance will be minimum if the posted speed limit is between 6 and 12 mph lower than the design speed, and outside this range, speed variance increases with increasing difference between the design speed and the posted speed limit. Results show that minimum speed variance will occur when the difference between design speed and the posted speed limit is 10 mph.

According to this article some studies have indicated that:

- Speed is not necessarily an important cause of accidents, but is an important determinant of severity.
- Nearly 75 percent of all accidents involve some violation other than speed.

A study conducted by Elmberg [6] revealed that drivers pay little attention to posted speed limits and also choose a speed which they themselves consider appropriate for prevailing conditions.

Recommendations:

In order to reduce speed related accidents, speed limits should be posted for different design speeds as presented in **table 6**.

Table 6: Relationship between design speed and posted speed limit.

Design speed (mph)	Posted speed limit (mph)
70	60 or 65
60	50 or 55
50	40 or 45

8.11 Speed Zoning For Highways, Roads And Streets In Florida

Prepared by:
Florida Department of Transportation
Traffic Engineering Office, Tallahassee, Florida
Year, or date of Publication: 9/97

On subdivision streets where adjacent development is anticipated within a reasonable time, design decisions should be based on traffic speed expected to occur from such development (residential home construction). Such design decisions would include cross section, degree of curvature, superelevation (if any), treatment of fixed objects, and/or tree removal.

An engineer cannot assume residential land use with a well designed road, particularly a main road fed by a network of other streets and/or carrying traffic through the subdivision, will operate at 30 mph. It is not uncommon for such streets to become semi-arterial and posted speed with 25 or 30 mph signs plus one of the many versions of non-authorized CHILDREN PLAYING OR PLAYGROUND (W15-1) signs that have no measurable benefits on traffic. This may even have a negative safety effect by appeasing resident's concern about safety for children.

Traffic safety would be improved if residential lots on such roads had substantial building setbacks to lessen the likelihood of; (1) children playing in the streets, and (2) resident's vehicles being parked on or parallel to the street.

8.12 Managing Speed

Special Report 254

Source: Transportation Research Record

Year of Publication – 1998

The main focus of this article was with designing roads to manage speed. Highway geometric design procedures in Europe and Australia currently incorporate predicted vehicle operating speeds as an important determinant of highway design. The key to the approach is the accurate prediction of target operating speeds. Thus, research in the United States is currently focused on the development of models for predicting expected speeds as a function of roadway geometry, land use, and other traffic elements. Model development efforts are focused on higher-speed, two-lane rural highways where inadequate consistency and continuity of design contribute to a wide dispersions in driving speeds and increased crash risk.

8.13 Design Consistency and Driver Error

Author: Mark D. Wooldridge

Source: Transportation Research Record 1445

Geometric design consistency is considered a major factor in accident rates on rural highways. However, there is little assistance to engineers who need to design roads consistent with driver's expectations. AASHTO focuses on individual elements, basing guidelines on functional classification, volume and design speed. The current methods for quantitatively assessing design consistency are focused on speed consistency and driver workload.

Speed consistency consists of analyzing predicted speeds on a highway and striving to keep these speeds within a narrow range. Workload consistency for geometric design has been the focus of only one major study by Messer et al. [17] in 1981. They developed procedures that assign subjective workload ratings for features along the roadway, depending on the severity of the features, the sequence of features and the proximity to other features. It was concluded that roadway sections with either high workload magnitudes or large positive changes in workload were associated with high accident rates when compared with accident rates on other sections of roadways.

Driver expectancy in general can be defined as a set of possible probabilities regarding a given situation. Expectancy is a known function of reaction time, signal detection, and vigilance. A driver expectancy of a specific situation is formed by his or her experience.

Some researchers have examined design consistency in order to provide a consistent roadway design. One of the methods employed in examining consistency of a roadway design is to check various measures such as speed differential. The fact that drivers do not always recognize the risk potential of roadway features [18] make it appear reasonable to question procedures that rely strictly on the results of driver controlled speed tests.

9 A COMPREHENSIVE, COMPLETE, AND LOGICAL PROCEDURE TO SELECT DESIGN SPEED

Design Speed is defined as:
"The maximum safe speed that can be maintained over specified section of highway when conditions are so favorable that the design features of the highway govern" [1] Also, it has been defined as "The theoretical value of speed governing the design of a road elements in conditions of safe and comfortable travel in a free traffic flow" [18]

"Although clearly identified as design criteria policies or guidelines, the AASHTO publications entitled A Policy on Geometric Design of Rural Highways (Blue Book) and A Policy on Design of Urban Highways and Arterial Streets (Red Book) have been consistently accepted by the courts as the nationally organized standards for highway and Street Design" [2]. The general opinion of DelDOT design engineers is that design speed selection procedure, based on AASHTO guidelines, does not provide enough flexibility. Several sources show that design speed does not provide consistency in road design. It is often exceeded by a large amount of drivers, thus, increases the likelihood for accidents. "A tendency exists for some drivers to travel faster than the design speed on which the original design of the road section was based by substantial amounts especially at the lower design speed levels" [20]. Basic design goals include: safety, efficiency, economy, comfort, ease of maintenance, environmental quality, social issues, usage of the facility, etc. Frequently, most of the goals mentioned above should be attained with limited resources. In order to start the process of selecting design speed, design engineers need information of a certain type.

9.1. Necessary Information For Selecting the Design Speed

Selecting a suitable road and its appropriate design speed requires some information:

- Location, in order to classify the road (arterial, collector, local, etc)
- Area characteristics
- Topography

Based on such information an initial road alignment can be performed. It can be accompanied with an estimate of the project cost in order to have its approval by the initiator (government, state agency, private). Toward the beginning of the design speed selection process, further information is needed.

In the case of reconstruction or the maintenance of an existing facility, current problems and desired objectives should specify necessary resources. If the information on design speed is not available, it should be estimated from geometric features like sight distance and horizontal curvature along highway sections. Once funding for the project is available, a detailed design of the road can begin. The designer has to be familiar with the project in order to maintain an accurate cost-benefit analysis and make a good selection of the design speed. During that process the designer needs to decide which part of the project is going to be reconstructed (or rehabilitated) and which part requires a new design and rebuilding, in order to establish a reasonable level of safety and service.

Subsections 9.1.1-9.1.9 presents essential information that an engineer has to understand. The subsections include the whole methodology for selecting an appropriate design speed, and, at the same time, place the design speed suitably within the design process.

9.1.1. Terrain characteristics

- level
- rolling

- mountainous

Level terrain is defined as any combination of vertical and horizontal alignment that allows heavy vehicles to maintain approximately the same speed as passenger cars [16]. It generally includes short grades of no more than 2%. A second definition for level terrain is an area on which the grade ranges between 0 to 8 percent [19].

Rolling terrain is defined as any combination of vertical and horizontal alignment that causes heavy vehicles to reduce their speeds substantially below those of passenger cars, but does not cause heavy vehicles to operate at crawl speeds for any significant length of time [16]. A second definition for rolling terrain is an area on which the grade ranges between 8.1 to 15 percent [19].

Mountainous terrain is defined as any combination of vertical and horizontal alignment that causes heavy vehicles to operate at crawl speeds for significant distances or at frequent intervals [16]. A second definition for mountainous terrain is an area on which the grade is above 15 percent. Once terrain characteristics have been specified, the designer should select the type of the road (urban/rural).

9.1.2. Type of the road for the projected year

- urban
- rural

Urban areas, within boundaries that are set by state or by local officials have populations of five thousand or more people. Urban areas are further classified as "urbanized areas" if the population is larger than fifty thousand. They are classified as small urban areas if the population is between five and fifty thousand [1]. Rural roads, are roads that do not fall into the classification criteria for urban roads. Urban areas should be further classified by several attributes: residential, commercial, school zones, resort areas, high density, cyclists, etc. Similar classification might be important for rural areas: wetlands, industrial zones, zones of economic interest, etc.

The next step is determining the function of the road. Roadway functions differ in their transportation role. Local streets are access roads, whereas arterials emphasize mobility. Collectors are ranked between local streets and arterials i.e. they serve as access roads and also have mobility purposes.

9.1.3 Functional classification with predominant service and access:

Urban Roads

- Interstate (mobility, restricted and fully controlled access)
- Freeway or expressway (mobility, controlled access)
- Other principal arterial (mobility with partial or no control of access)
- Minor arterial (more access, less mobility than major roads, serves local bus routes)
- Collector (land access service and traffic circulation within residential, commercial and industrial areas, serves local bus routes)
- Local (has the lowest level of mobility, permits direct access to land, usually does not serve bus routes)

Rural Roads

- Major arterial (freeway with full control of access or other major arterial)
- Minor arterial
- Major collector (approximately provides equal levels of mobility and access)
- Minor collectors
- Local (access to land adjacent to the facility)

9.1.4 Traffic volume for the projected year

Forecasting the number of vehicles that are supposed to use the designed road.

9.1.5 Acceptable traffic flow quality (level of service which reflects social costs such as travel time delay, energy consumption)

Lower limit of design speed (Vdl) should be determined after considering:

- Traffic flow quality (level of service)
- Terrain characteristics
- Functional classification of the road

Anticipated traffic volumes should also be used for determining the number of lanes required for the desired level of service. DelDOT policy when planning a new road is to provide as many lanes as necessary for the anticipated volume. The minimum acceptable level of service is C or D. However, traffic volume and level of service do not play a role in the design speed selection process.

9.1.6 Traffic composition

- Passenger car (%)
- Single unit truck (%)
- Single unit bus (%)
- Semi trailers (%)

In order to design safe roads it is important that speed differences among vehicles not exceed 15 km/h. The presence of a significant number of trucks (vehicles that have six or more wheels) can result in non-uniformity of speed. A potential solution is adding a lane for slow moving vehicles. If this is not practical, lower design speeds should be chosen.

Speed variance

Garter and Gadiraju (8.10) show that speed variance on a highway segment is a minimum if the difference between the design speed and the posted speed limit is between 8 and 16 km/h (5 and 10 mph). Today, however, truck's technology is much more advanced than in the past. Therefore, speed differences are much smaller.

Nevertheless, DelDOT designers do not see traffic composition as a vital factor during the design speed selection process.

9.1.7 Constraints that prevent achieving higher design speeds:

There are several difficulties that might limit the magnitude of the design speed:

- High construction costs
- Difficulties in acquiring right-of-way (physical objects: such as buildings, mountains, houses, etc.)
- Social (public concern, residential areas, etc.)
- Environmental (wetlands, etc.)
- Energy related (higher speeds, higher gas consumption)
- Presence of pedestrians, cyclists, school zones, residential areas

These constraints can result in posted speed limits lower than the desired design speed. In order to avoid over-design, sections that encompass some of those constraints (or part of them) should be considered primarily. Hence, a more adequate value of design speed might be maintained.

"In most design guides, the selection of design speed for a specific road section of a particular classification is primarily influenced by the nature of the terrain (level, rolling, mountainous). In addition, the selection of design speed is influenced by motorist's expectation in relation to the free speed at which it is safe to drive (in rural areas), or legal to drive (in urban areas). In urban areas many disruptions to flow (e.g. from intersections) result in free speeds that are less than those on rural roads. Drivers are also more likely to adjust their desired speeds to the imposed speed limits. Consequently, the design speed for the new road or a major road improvement in an urban area is usually selected after taking into account the likely speed limit regime for the road." [3] Speed limits are often based on the limitations of driver's sight distances or road conditions like the surrounding environment (trees, objects), poor pavement, school zones, etc.

9.1.8 The anticipated operating speed (85th percentile speed)

The 85th percentile speed is generally considered the most appropriate choice for design speed [3]. Anticipated operating speed for a new road can be determined from operating speeds on similar roads. Several analyses have shown that the degree of curve is the best predictor for determining operating speeds. "Relative to other alignment properties, road curvature had greatest influence on driver speed behavior". Lamm and Choueiri [16] developed a model that relates the 85th percentile speed to the degree of horizontal curve: V85=58.656-1.135D (D-degree of curve) "For new roads, operating speed V85 can be selected using the general range of curve radii likely to be adopted. For reconstruction of the existing facility and realignment the existing V85 can either be estimated from **table 2** or be measured directly from speed studies on existing straights" [21]. "In practice, designers obviously cannot take direct account of actual speed expectations on proposed alignment sections for new roads or major improvements and they rely instead on typical speed distribution data previously obtained on similar existing roads" [3].

9.1.9 The anticipated posted speed limit for the road

For each road section, the anticipated posted speed should be considered in terms of the constraints discussed in section 9.1.7.

Initial design speed value (approximately Vdl+20km/h) should be chosen in a way that reflects the anticipated operating speed or anticipated posted speed limit that are generally larger. The upper limit of the design speed range (Vdu) should be used as the speed limit for the appropriate road class plus 20 km/h for additional safety.

9.2 Process of Selecting Design Speed

The expected 85th percentile speed should be obtained before starting the design speed selection process.

9.2.1 Expected 85th percentile speed for each road section

Radius (or degree of curve) computation is based on initial design speed value. Each curve and each tangent (DC=0) has its expected 85th percentile speed: V85=58.656-1.135D (D-degree of curve). Once the initial design speed has been selected (85th percentile speed), it is necessary to perform consistency evaluation to ensure uniformity of operating speed on the given road section.

9.2.2 Consistency evaluation

Potential design inconsistencies can result from exceeding the design speed on a specific curved section or from a significant difference in operating speed on two successive sections, as a result of a large rate of change of curvature. Krammes et al. [12] showed that there are weaknesses in the design speed concept as applied in the US. "The weaknesses make it ineffective at identifying and addressing operating-speed inconsistencies that horizontal curve whose design speed is less than the driver's desired operating speed. This inconsistency increases accident potential."

The process of checking for consistency includes:

- Calculating the change in degree of curve (ΔDC) between successive elements.
- Calculating the change in 85th percentile speed between successive design elements.
- Calculate the difference between the 85th percentile speed and the existing or selected design speed Vd for the investigated curve or tangent.

Definition of Good design:

A design is considered 'well' (consistency in horizontal elements exists), if $\Delta DC \leq 5$ and $\Delta V85 \leq 6$mph (10km/h) between successive design elements and $|V85-Vd| \leq 6$mph (10km/h) for the investigated curve or tangent.

A design is considered 'fair' if, $5 \leq \Delta DC \leq 10$, 6mph$\leq \Delta V85 \leq$12mph (20 km/h), and 6mph$\leq |V85-Vd| \leq$12mph. These road sections exhibit some minor inconsistencies in geometric design. Traffic warning devices may be used to correct these defects. However, despite traffic warning devices, road sections with $5 \leq \Delta DC \leq 10$ have a double rate of accidents in average, compared with well designed roads.

A design is considered 'poor' (strong inconsistencies in horizontal elements), if V85>12 mph between successive elements and $|(V85>Vd)|>12$ mph (or 20km/h) for the investigated curve or tangent. Average accident rates are more than four times higher than on the 'well' designed roads. The next step is to memorize the initial value of the selected design speed and make corrections that minimize differences between successive road features. The discussed procedure for consistency evaluation is most suitable for two lane rural roads. General application of the procedure is described in Reference 23.

9.3 Design Speed Selection Process for Various Road Classes

Introduction and definitions

The first step in the design process is to define the function that the facility has to serve [1]. Sections 8.3.1 and 8.3.2 present a list of road classes, which are found in reference 1 and State DOT manuals. Design speed selection criteria will be discussed for the most common road types. The following is a short explanation of some terms:

The Interstate System is part of the principal arterial system. It is a network of routes selected by the state. The highest class of arterial highway is the freeway, which is defined as an express with full control of access, meaning that access to and egress from these facilities are permitted only at controlled locations such as entrance and exit ramps [1] . On the other hand, expressways have partial control of access, i.e. access or egress may be permitted directly from or to abutting property or via a limited number of at-grade intersections [1]. The level of service, which is the quality of traffic flow, provides a rational and cost effective basis for the selection of design speed [1].

Control of access is the degree of through traffic interference by conflicting vehicle and/or pedestrian movements such as vehicles/pedestrians, entering leaving or crossing the highway. A facility is ranked in higher hierarchy (higher classification), if its control of access is superior.

Table 7 presents the level of service that corresponds to the highway type and location [1].

Table 7: Type of Area and Appropriate Level of Service [1]

Highway Type	Rural Level	Rural Rolling	Rural Mountainous	Urban and Suburban
Freeway	B	B	C	C
Arterial	B	B	C	C
Collector	C	C	D	D
Local	D	D	D	D

9.3.1 Urban

9.3.1.1 Principal arterial - Definition:

The urban principal arterial system serves the major CBDs (Central Business Districts) of urbanized areas, the largest traffic volume corridors and the longest trip desires and carries a high proportion of the total urban area travel even though it constitutes a relatively small percentage of the total roadway network. The system should be integrated both internally and between major rural connections [1]. The designer must be familiar with the characteristics of both systems to provide adequate transition as the arterial traffic flows between the rural and urban settings [1].

The principal arterial system carries most of the trips entering and leaving the urban area, as well as most of the through movements bypassing the central city. This system is not restricted to controlled-access functional routes. The main characteristic of the urban arterial is mobility with limited or restricted service to local development. Urban principal arterials provide travel service to major traffic movements. Before designing an urban arterial, it is important to establish its extent and need. If the need is established, steps must be taken to protect the design from such things as strip development or the unplanned locations for major traffic generators

Generally, the design speed of urban freeways should reflect the desired safe operating speed during off-peak hours, but should not be so high that it exceeds the limits of prudent construction, right of way, and socioeconomic costs. Design speed for urban arterials generally ranges from 60 to 100 km/h, and occasionally may be 50 km/h. The lower speeds (less than 60 km/hr) apply in the central CBDs and intermediate areas. Higher speeds are more applicable to the outlying business and developing areas. On urban arterial freeways, a design speed of 100 km/h is normally used. The corridor of the main line may also be relatively straight, and the location of interchanges may permit high-speed design. Under these conditions a design speed of 110 km/h is desirable because higher design speed means better overall quality and higher safety of the facility.

Where terrain is mountainous a design speed of 80 km/h or 100 km/h, which is consistent with driver expectancy, may be used. Although, it should be pointed out that there that 20 km/h is a large range. Generally, urban multilane freeways have 10 km/h lower design speed than corresponding rural multilane freeways. For acceptable degrees of congestion, rural and suburban principal arterials should be designed for level of service C. Heavily developed sections of metropolitan areas may necessitate the use of level of service D [1].

9.3.1.1.1 Principal arterial - Design Speed Selection-Other States

- **Arizona**

Arizona Department of Transportation: For urban arterials with low density development, suggest a design speed range of 60-100 km/h. For arterials with extensive development, they suggest a design speed range of 50-80 km/h.

- **Connecticut**

Connecticut DOT suggest determining the design speed values for multilane urban freeways from the 85th percentile speed. For example, for a 85th percentile speed that ranges between 90 and 100 km/h, they use a design speed value of 90 or 100 km/h.

9.3.1.1.2 Principal arterial - Design Speed Selection-Other References:

For urban principal multilane freeways in low density developed areas and for posted speed limits of 80 or 90 km/h, the design speed should not be less then 100 km/h (90 km/h) in mountainous terrain. For urban principal multilane arterials in high density areas and for posted speed limits of 70 or 50 km/h, the lower range of design speed should not be less than 80 km/h and 60 km/h. The upper range should be between 70 and 90 km/h [13].

The recommendations for urban (and rural) multi-lane freeway systems are summarized below in **table 8**.

Table 8: Urban/Rural principal arterial system: Multilane freeways (Interstate and other freeways)

Terrain characteristics	Flat/rolling	Mountainous
Extent of access control	Full	Full
One way DHV 1950-2999	+	+
Recommended LOS	**B**	**C**
Posted speed limit	90 (105) km/h	70 (100) km/h
Design speed	100-140 km/h	80-120 km/h

9.3.1.1.3 Principal arterial - Other Important Points

Hiersche and Lamm [8] studied the effect of design speed on accident rates and accident costs. Their results as presented in **table 9** (below) shows that accident rate decreases significantly as design speed increases from 60 to 80 km/h. For higher design speeds, higher operating speeds lead to more severe accidents [13].

Table 9: Accident Rate and Accident Cost Rate versus Design Speed [13]

Design Speed, km/h	60	70	80	100
Vehicle kilometers (absolute), 10^6 vehicle kilometers	52.3	18.0	234.5	52.0
Vehicle kilometers traveled, %	14.6	5.2	65.7	14.5
Accident rate, accident/10^6 vehicle kilometers	2.12	1.78	1.15	1.11
Accident cost rate, dm/100 vehicle kilometers	3.62	3.85	4.21	5.21

9.3.1.1.4 Other Principal Arterials – Multilane Highways

The characteristics of Multi-lane highways (including their design speed selection procedure) are those of freeways. Multi-lane arterials carry heavier traffic volumes, have more frequent intersections, and more development of adjacent land. The frequency of at-grade crossings has a significant effect on accident and road capacity.

A divided arterial is an arterial that has separate lanes for traffic in opposite directions. It is recommended that all new arterials requiring four or more lanes be divided. It is not recommended an arterial be divided, unless it has two full lanes in each direction of travel and the median width is 1.2 m or more. It also has to be constructed or marked in a manner to preclude its use by moving vehicles except in emergencies or left turns. The major advantages of dividing the multilane arterial are: increased safety, comfort, and ease of operation.

A divided arterial is generally designed for high-volume and high-speed operation for which a flowing type of alignment should be provided [1].

A multilane undivided arterial is the narrowest arterial on which each traffic lane is intended to be used (going one direction). Overtaking is accomplished on lanes that are not in use by opposing traffic. The ability to pass without traveling in the lane of opposing traffic results in smoother operation and a larger capacity compared with two lane arterials. Undivided arterials with four or more lanes are most applicable in urban and suburban areas where there is considerable development of adjacent land [1].

Other Important Issues

The minimum required sight distance at all points is the stopping sight distance, because overtaking does not require the use of a lane with opposing traffic.

9.3.1.2 Urban Minor Arterial - Definition

The minor arterial street system includes all arterials that are not classified as principal. The system emphasizes more land access and its traffic mobility is more restricted compared with the principal arterial system. It distributes travel to smaller geographic areas and enables urban connection to rural collector roads.

9.3.1.2.1 Urban Minor Arterial - Characteristics

The minor arterial street system interconnects and augments the urban principal arterial system. It accommodates trips of moderate length at a limited level of travel mobility, but is useful for carrying local bus routes.

9.3.1.3 Urban Collector - Definition

The collector street system provides both land access service and traffic circulation within residential neighborhoods and commercial and industrial areas.

9.3.1.3.1 Urban Collector - Characteristics

Urban collector streets provide higher levels of mobility than local streets. The collector street system can penetrate residential neighborhoods. It distributes trips from the arterial to the local system and vice versa, i.e from the local streets in residential neighborhoods to the arterial system. In the Central Business District (CBD) and in other areas of similar development and traffic density, the collector system can include the entire street grid. It can also carry local bus routes as well as pedestrian traffic. It often accommodates public utility facilities within the right of way.

In a typical street grid, the closely spaced intersections usually limit vehicular speeds. Therefore, design speed in local streets is trivial and the selection process does not require are complicated analysis. Nevertheless, the longer sight distances and curve radii are commensurate with design speeds that are higher than the conventional values that guarantee safety, but sometimes it might be more practical and feasible.

9.3.1.3 Urban Collector - Design Speed Selection-AASHTO

Posted speeds for urban collector should generally be less than or equal to 50 km/h, although higher design speeds of 60 and 70 km/h are being considered by some states (Illinois for example). For consistency in design elements a minimum design speed of 50 mph should be used for urban collector streets, depending on the available right-of-way, terrain, adjacent development, and other area controls. In order to ensure desired operating speeds, road features should be selected appropriately, as presented in **table 10** below.

Table 10: Urban collector design characteristics

Terrain characteristics	Flat/rolling	Mountainous
Extent of access control	none	none
One way DHV <1300	+	+
One way DHV 1300-1850	+	+
One way DHV >1850	+	
Recommended LOS	**D**	**D**
Posted speed limit	50 (60)km/h	30 (40) km/h
Design speed	60-80 km/h	40-50 km/h

9.3.1.4 Urban Local - Definition

The local street is identified with the most inferior control access. It primarily permits direct access to abutting lands and connections to higher classified systems. Local urban roads serve vehicular travel, pedestrian and bicycle traffic. It offers the lowest level of mobility and usually contains no bus routes. Service to through-traffic movement is deliberately discouraged.

9.3.1.4.1 Urban Local - Characteristics

Local distribute local traffic between neighborhoods. Design speed is not a major factor for local streets. The use of design speed concept is limited in low-speed environment. In order to insure low speeds on local streets, the designer has to foster a safer and pleasant environment. It can be implemented by using a more restrictive geometry.

9.3.1.4.2 Urban Local - Design Speed Selection- AASHTO

A design speed ranging between 30 and 50 km/h may be used in design elements, in order to enable reasonable consistency among different design elements. It depends on available right of way, terrain, adjacent development, and other area controls. Low operating speeds are desirable for a safe accommodation of pedestrians, bicyclists, and access along these streets [14].

Design speed exceeding 50 mph in residential areas may require longer sight distances and increased curve radii. However, such procedures contrast with the basic concept of local street. Moreover, the limited vehicular speed makes the process of design speed selection simpler and less meaningful [1].

9.3.1.4.3 Urban Local - Design Speed Selection –Other References

Urban areas usually involve many disruptions to flow. Drivers are more likely to adjust their desired speeds to the imposed speed limits. Consequently, the design speed selection process for a new redesigned road in an urban area has to consider the likely speed limit regime for the road [3].

Poe and Mason [14] reached several conclusions: "If planners and designers desire operating speeds below 40 km/h, then this data indicates that sections should have a maximum radius of 60 meters with respect to horizontal curvature. Similarly, sites with higher mean speeds were associated with longer sight distances, flatter grades, and wider and more open cross sections." They concluded that specific design speed ranges should encompass maximum curve radii, maximum widths for cross section, and guidance on the effects of sight distance provided.

9.3.1.5 Other important points

Posted speeds on urban local roads should be equal to or less than 30 km/h (20mph) Designers should consider traffic volume as well as the characteristic of the neighborhood. For example, in a school zone, where the posted speed limit is 20 mph, design speed should not be higher than 25 mph. An effective balance between non-motorized and motorized users of residential areas is essential.

A good transportation system design directs the passing movements through major roads. Local roads have to be fed by local traffic (especially residential) in order to preserve their nature of lower speed (**table 11**) and pedestrian involvement. It is very complicated to reorganize an existing plan of a residential roadway system due to the unexpected modification of the traffic pattern. Thus, a big emphasize should be directed on the preliminary design steps. Fast movement can be discouraged through the use of curvilinear alignment and discontinuities in the street system. This can encourage the balance between vehicle bicycle and pedestrians.

The design of local transportation systems must recognize the following factors:

- Safety for both vehicular and pedestrian traffic
- Efficiency of service for all users
- Livability of amenities
- Economy of land use, construction and maintenance

Table 11: Recommended posted speed limit and design speed for urban local streets

Posted speed limit	20 (30)km/h
Design speed	30-50 km/h

9.3.2 Rural

9.3.2.1 Principal Arterial - Definition

Principal rural arterials include the Interstate system and most rural freeways [1]. Multi-lane freeways are the largest (in terms of capacity) of arterial highways. It is defined in AASHTO [1] as an expressway with full control access. Freeways serve to provide high levels of safety and efficiency in the movement of high volumes of traffic at high speeds. They should have a minimum of two through-traffic lanes for each direction [1].

9.3.2.1.1 Principal Arterial - Characteristics

A rural principal arterial system consists of a network of routes. It is characterized by the following:

- Corridor movement with trip lengths and densities suitable for substantial statewide or interstate travel
- Movements between all or virtually all urban areas with populations over 50,000 and a large majority of those with populations over 25,000 [1]

9.3.2.1.2 Principal Arterial - Design Speed Selection-AASHTO

A freeway is the most difficult class of roadway in design because of the need to provide a high standard of operation in spite of unusual, sometimes unfavorable prevailing conditions. These roads are based on traffic volume needs and should be constructed to the highest possible standards [1]. Rural freeways generally have four through-traffic lanes except for approaches to metropolitan areas where six or more lanes may be provided [1]. In some cases, fewer lanes may be sufficient in accommodating a given volume of traffic at the desired level of service, which is usually LOS B for rural freeways [1]. Design speeds of 100 km/h to 110 km/h are normally used in level terrain, and according to **table 8** it is the lower bound. Design speed should not be less than the posted speed limit. An upper bound design speed of 140 km/hr is generally acceptable. ASSHTO suggests a design speed of 110 km/h for rural freeways. In rolling and mountainous terrain, a design speed may drop to 100 km/h or even 80 km/h to meet the driver's expectancy. The selection of design speed has to consider the recommended ranges (**table 8** – subsection 9.3.1.1.2) and also should be based on terrain characteristics, traffic volume, and available financial resources.

Freeways are designed for a future 20 years traffic forecast, but remain in service for a much longer time. The designer has to seriously consider any initial construction cost savings for lower design speeds, otherwise such a design can result in higher expenses in the future due to environmental damage, and inconvenience to traffic that accompany the reconstruction of major facilities.

9.3.2.1.3 Principal Arterial - Design Speed Selection Process- Other DOT's

- ***Connecticut***

Design speed selection for multi-lane rural arterials is based on the 85th percentile speed. If the 85th percentile speed exceeds 100 km/hr, an appropriate value for design speed is 100 or 110 km/hr.

- ***Minnesota***

The process of selecting the design speed should take into account the driver's expectancy. The driver expects to be able to drive at a certain maximum speed based on the functional (rural or urban) character of the highway. Therefore, the design speed should fit the travel desires and habits of the majority of drivers. Design speed must equal or exceed the posted speed.

- ***Mississippi***

The Mississippi DOT selects design speed values based on running speed (average speed of a vehicle over a specified section of highway). For example, for an average running speed of 58 mph the design speed chosen would be 70 mph. The 85th percentile speed is utilized as one of the factors in determining the posted, legal speed limit along a highway section. The selected design speed should equal or exceed the anticipated posted or regulatory speed limit of the completed facility. Mississippi DOT's recommendations for design speed in level/rolling terrain are 70 mph for rural freeways and a range of 60-70 mph for multi-lane highways.

9.3.2.1.4 Principal Arterial - Design Speed Selection –International References

- ***Australian Rural Road Design*** [13]

A design speed of over 100 km/h is made only when the accompanying high standard geometrics are compatible with the terrain or when the road is considered to be important enough to justify the additional costs of achieving the added quality service. Design speeds up to 130 km/h could be used. For these types of roads, high uniform speeds are expected. On roads of consistently high geometric standards, speeds on curves and straights are not significantly different [21].

9.3.2.1.5 Principal Arterial - Design Consistency Issues

Once a design speed value has been chosen for different sections of the road it is necessary to perform consistency evaluation to ensure a safe design that meets the expectancy of drivers. The drop in operating speed from section to section should not be greater than 10 km/h.

9.3.2.2 Two Lane Highways - Definition

Two lane arterials constitute the bulk of the arterial system. These roadways are adequate where traffic volumes are light and long sight distances are generally available [1]. Two lane rural highways account for over 85 percent of all arterial and collector mileage in the United States [11].

9.3.2.2.1 Two Lane Highways - Characteristics

Rural Principal Arterials excluding Interstate freeways include a rural network of continuous routes that serve and interconnect various regions that are not served by the Interstate roadway system. They have partial or free access (Illinois DOT manual). An important role of major two lane highways is linking large traffic generators. In order to maintain smooth traffic flow, it is essential to certify consistent high speeds and infrequent overtaking delays on these rural principal arterials. High volume two-lane highways are sometimes used as connectors between two major dual carriage-way roads. They expect to reduce their travel time and also improve the travel quality. Two-lane roads in rural areas should provide all weather accessibility, often for fairly low traffic volumes [3].

9.3.2.2.2 Two-Lane Highways - Design Speed Selection –AASHTO

A design speed of 110 km/h is suggested for this type of road. The recommended design level of service is B for moderate traffic volumes and C for heavier traffic [1].

9.3.2.2.3 Two Lane Highways - Design Speed Selection-DelDOT

DelDOT manual refers to the minimum value for arterial highways in order to select the design speed for two lane highways. It recommends using100 km/hr for new construction and 80 km/hr for 4-R improvements. There are also recommended design speed values for collectors and local roads, depending on the average daily traffic – ADT (in figure 3.4 of reference [5]).

9.3.2.2.4 Two Lane Highways - Design Speed Selection –Other States

- ***Arizona***

Arizona DOT uses the following design speeds for Rural Non-divided Highways: In level terrain a minimum value of 100 km/h and a desirable value of 110 km/h are recommended. In rolling terrain the minimum recommended design speed value is 90 km/hr and the desirable value is 100 km/hr. Correspondingly, the recommended values on mountainous terrain are 70 km/hr and 90 km/hr.

- ***Connecticut***

Connecticut DOT uses the 85th percentile speed for selecting the appropriate design speed for 3R projects. (**table 2** subsection 6.5). "The designer should carefully evaluate the speed data to determine the 85th percentile speed which represents the operating characteristics of a lengthy segment of the road, not just a short segment near the proposed project" (Connecticut DOT Manual).

- ***Washington***

The desirable design speed should be selected in such a way that it cannot be less than the posted speed, the proposed posted speed or the operating speed (whichever is higher). Washington DOT recommends a design speed range of 50-70 mph for rural two-lane principal arterial roads if the DHV is between 201 and 700 [23].

9.3.2.2.5 Two Lane Highways -Design Consistency Issues

Many experts believe that abrupt changes in operating speeds lead to accidents on two-lane rural roads and that these speed inconsistencies are mostly derived from abrupt changes in road geometry. Therefore, providing longer roadway sections with relatively consistent alignment is an important step toward reducing critical driving maneuvers and enhancing traffic safety. Even though design speed has been used for several decades to determine sound horizontal alignments, it is still possible to have certain inconsistencies into the highway alignment. At low and intermediate design speeds, on portions of relatively flat alignment, interspersed between the controlling curvilinear portions, operating speed profiles may exceed the design speed in the controlling sections by substantial amounts, especially on two-lane rural roads.

Design procedures for rural highway alignments for which the design speed is less than the driver's desired operating speed, cannot guarantee alignment designs that promote uniform operating speed profiles. The relationship between accident rates and design speed is not consistent. According to one approach the accident rate decreases with increasing design speed up to 80 km/hr (50 mph). However, according to [13], reducing rural speed limits from 100 km/h to 90 km/h (higher speeds) has been seen to reduce casualties by about 11 percent.

Table 12 presents recommended design speed ranges on two lane highways for several geometric and traffic conditions [1].

Table 12: Rural Principal Arterial System: Two lane highways – design characteristics

Terrain characteristics	Flat/rolling	Mountainous
Extent of access control	Partial/ Free	Partial/ Free
Recommended LOS	B (C)*	B (C)*
Posted speed limit less then:	90 (80) km/h	80 (70) km/h
Design speed	70- 100 km/h	60- 90 km/h**

* LOS C when higher traffic volumes exist.

** Add a climbing lane if there is more than 10% of heavy vehicles which speed is likely to fall below passenger vehicles on steeper grades.

9.3.2.3 Design Speed Selection Process for Rural Principal Arterial System - Summary

Rural Principal Arterial Interstate and other multi-lane freeways should provide safe traveling and smooth driving at high speed. Therefore, the roadway design process has to derive maximum values for design speed without ignoring the speed limit. In general, design speed values for principal arterial (multi-lane highways / freeways) should be between 100 and 140 km/hr.

9.3.2.4 Minor Arterial

Minor rural arterials link the urban centers to larger towns and are spaced to provide a relatively high level of service to developed areas.

9.3.2.5 Rural collector - Definition

Rural collector roads are two lane roads that form part of the rural highway system. These roads have to accommodate high practical standards that are compatible with traffic and topography. The basic information which is necessary for the design of collector roads involves safety, traffic volumes, terrain controls and alignment.

Major Collector Roads serve " (1) county seats not on arterial routes, larger towns not directly served by the higher systems and other traffic generators of equivalent intra-county importance such as consolidated schools, shipping points, county parks... ; (2) link these places with nearby large towns or cities, or with routes of higher classification and (3) serve the more important intra-county travel corridors.

Minor Collector Roads (1)... accumulate traffic from local roads and bring all developed areas within reasonable distances of collector roads; (2) provide service to the remaining smaller communities, and (3) link locally important traffic generators with their rural hinterland" [1].

9.3.2.5.1 Rural collector - Characteristics

The design speed selection procedure is not a rigorous one. In other words, it gives the engineer some flexibility giving him/her the chance to use his/her own experience. Generally, on alignments that encompass design speed of 90 km/h or less, operating speed varies along the route and is consistently greater than the design speed [1].

9.3.2.5.2 Rural collector - Design Speed Selection-AASHTO

Low design speeds (60 mph and below) should generally be applied on highways with curvilinear alignment in rolling or mountainous terrain or where environmental conditions dictate. High design speeds (80-100 mph and above) should generally be applied on highways with level terrain or where environmental conditions are favorable. Intermediate design speeds should be applied on highways "where terrain and other environmental conditions are a combination of those described for low and high design speeds" [1]. According to AASHTO [1], ADT (Average Daily Traffic) should be a basis for design. Economics (business and development) and environmental aspects affect the future traffic volume for which the specific road is supposed to take. It influences the selection of the required number of lanes and the initial and operating cost. The desired level of service is chosen according to the importance of the road in the transportation system. Such information can assist in determining the lower limit (design speed). For level terrain this should not be less than 50 km/h. For rolling terrain it should be at least 40 km/h and for mountainous terrain at least 30 km/h. The upper limit of the design speed is approximately 20 km/h higher than lower limit. The designer should strive for higher values than the minimum where conditions of safety dictate and costs can be supported.

9.3.2.5.3 Rural collector - Design Speed Selection-Other References and proposed methodology

On roads where drivers are expected to travel at speeds below 100 km/h, the operating speed is influenced by road characteristics and its surroundings. In order to select a reliable design speed range, an iterative procedure is necessary. In low-speed and intermediate-speed environments, the design speed may vary over the length of the road in accordance with the predicted value of the 85^{th} percentile speed (operating speed). If the operating speed is expected to vary over the length of the road due to relatively low posted speed limits on specific road sections, it is better to lower the design speed there. This may have saved money because of avoiding undesirable over-design situations. Another important design criterion is consistency.

For new roads it is necessary to select an initial design speed value for the iterative procedure. The higher value between the expected operating speed and the posted speed limit can be used as a starting iterate. Initial values of design speed can be based on operating speeds found on similar neighboring roads, or otherwise, it can be obtained from **table 3** [21] in accordance with the particular terrain (flat, rolling, mountainous) and the approximate range of horizontal curve radii. Based on this selection, an experimental alignment can be created. Operating speeds that encompass this alignment should be checked with those from the table.

If they differ significantly, the initial design has to be changed or refined (selection of different curve radius, etc.). Consistency evaluation should be performed to ensure that the difference between design speed and operating speed is within specific acceptable limits. By using the iterative procedure the engineer might be able to obtain unique design speed values for different road sections that best suits a particular location, environment, neighborhood, or society.

9.3.2.6 Rural Local Roads - Definition

The local rural road system constitutes all rural roads not classified as principal arterial, minor arterials or collector roads [1].

9.3.2.6.1 Rural Local Roads - Characteristics

"Rural local road system … primarily provides access to land adjacent to the collector network and serves travel over relatively short distances [1].

9.3.2.6.2 Rural Local Roads - Design Speed Selection- AASHTO

In general, design speed should be selected as appropriate for the particular environmental and terrain conditions. In the case of rural local road, low design speeds are generally applicable on winding alignments in rolling and mountainous terrain or where environmental conditions dictate. Similarly, high design speeds are generally applicable to roads in level terrain or where other environmental conditions are favorable. Intermediate design speeds would be appropriate where terrain and other environmental conditions are a combination of those described for low and high speed. The traffic influence on design speed selection for rural collector roads, as discussed in section 9.3.2.5.2, applies to rural local roads too. **Table 13** presents recommended design characteristics for rural local roads as a function of terrain condition.

Table 13:

Terrain characteristics	Flat/rolling	Mountainous
Extent of access control	Free	Free
Recommended LOS	**D**	**D**
Posted speed limit less then:	50 (80) km/h	30 (60) km/h
Design speed	60- 100 km/h	40- 70 km/h

10 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The current design speed selection procedure based on AASHTO guidelines does not provide enough flexibility in selecting design speed. Alignment consistency is not considered as well. Also, the current DelDOT road design procedure does not incorporate consistency evaluation. Many non-engineering issues have been recognized to influence the process of design speed selection; however they are still not incorporated in the road design process. There is a need for a logical, flexible and easy to use design speed selection procedure and expert systems is an example of this. Expert systems can be a potential tool for design speed selection procedure having successfully overcome some of these problems. In other words, the need for a new and novel approach to the design speed selection process can be justified and successfully realized through expert system software.

Furthermore, to continue updating and improving the road design process more attention should be given to theoretical and experimental research. Findings obtained through research should be implemented in the design process. For example, sections 8.12 and 8.13 outline current research in the area of design speed selection for consistency purposes, driver expectancy and how to design wisely keeping safety in mind. Attention and time should be given to current findings such as those just listed in order to make the road design procedure safer and more efficient. Being open to new ideas is necessary in order to advance more professional and safer solutions. On the other hand, it is necessary to stay critical and selective, since characteristics of the local environment and traffic patterns play a key role in achieving roads that operate well and are safe.

This report presents DelDOT with the methods used to select design speeds in all fifty states in addition to design speed selection practices of foreign countries. Moreover, this report presents DelDOT with an additional literature review that contains innovative ideas and the latest research on the design speed selection topic. Section 9, which is a "Comprehensive, Complete and Logical Procedure to Select Design Speed" will systematically guide DelDOT design engineers through the design speed selection process for a variety of classifications (urban or rural arterials, collectors, local roads, etc.), areas and topography. While not intending to be the end-all guide for the road design process this report should help guide DelDOT design engineers

REFERENCES

[1] AASHTO, A policy on geometric design of highways and streets, 1994

[2] Blaschke, Joseph D. John M. Mason; Impact of the AASHTO green book on highway tort liability, TRR – 100.

[3] C. A. O`Flaherty, Editor, Transportation Planning and Traffic Engineering

[4] Context-Sensitive Highway Design (http://www.scenic.org/roads.htm)

[5] DelDOT Road Design Manual, Chap 3- Design Standards 2/1998.

[6] Elmberg C.M., Effects of speed zoning in urban areas, M.S. Thesis, Purdue University, 5/1960.

[7] Hassa, Gibreel, and S.M. Easa, Evaluation of Highway Consistency and Safety: Practical Application

[8] Hierche E-U, R. Lamn, K. Dieterle and A. Nikpour, "Effects of highway mprovements designed in conformity with the RAL-L on traffic safety of two lane rural highways"; Research Road Construction and Road Traffic Technique, Vol. 431, Minister of Transportation, Bonn Germany, 1984.

[9] Horizontal Alignment Design Consistency for Two-Lane Highways, FHWA-RD-94-034, 1995

[10] Insurance Institute for Highway Safety, Highway Loss Data Institute, Speed and Speed Limits (http://www.hwysafety.org/safety_facts/qanda/speed_limits.htm)

[11] Kalivoda, Eric, The effect of Design Speed on two lane rural highway safety, Phd. Thesis, 1995

[12] Krammes R., Fitzpatrick K., Blaschke J., Fambro D., Speed: Understanding design, operating and posted speed, Report No. 1465-1

[13] Lamm R., Psarioanos B., Mailaender T., Highway design and traffic safety engineering handboook, 1999

[14] Mason, John M., Poe, Christopher M., Geometric Design Guidelines to Achieve Desired Operating Speed on Urban Streets, Institute of Transportation Engineers 65th Annual Meeting

[15] Mc Lean J., An Alternative to the design speed concept for low speed alignment design , Australian Road Research Board, Low Volume Roads: Second International Conference, Transportation Research Record 702, 1979

[16] Mcshane, Roess, Prassas; Traffic Engineering, 1997.

[17] Messer C.J., J.M. Mounce and R.Q. Braquet., Highway geometric design consistency related to driver expectancy. FHWA, USDOT 1981.

[18] Mihailo Maletim, Vajo Anjus; Standard speeds and flows in the road design process, 1985.

[19] Recommended guidelines for subdivision streets; ITE publication.

[20] Reudiger Lamn, Elias M., Choueiri, Theodor Mailaender; Comparison of operating speeds on dry and wet pavements of two lane rural highways; TRR 1280.

[21] Rural Road Design, Australia, 1999

[22] Transafety Reporter, Survey Investigates the Relationships among design speeds, operating speeds, and posted speed limits, 1997

[23] Washington DOT Manual.

Additional References are used in Section 8 – Additional Literature Review

Delaware Center for Transportation
University of Delaware
Newark, Delaware 19716