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Three-dimensional GIS-based approach for highway design consistency evaluation

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THREE-DIMENSIONAL GIS-BASED APPROACH FOR HIGHWAY DESIGN CONSISTENCY EVALUATION

by

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B.Eng.,
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Three-Dimensional GIS-Based Approach for Highway Design Consistency Evaluation

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ABSTRACT

The mission of transportation is to transport people and goods safely and efficiently. Therefore, traffic safety has been one of the most important topics since the birth of the subject of transportation. Improving highway design consistency is considered as an important strategy for improving traffic safety. Geographic information systems (GIS) has been popular for decades due to its great ability to deal with spatial or spatially-related data. Contributions from GIS to transportation have become well known in some aspects. However, GIS, especially its 3D visualization function, has not, in previous studies, been integrated into the core of the highway design consistency evaluation procedure. In contrast, the major objective of this thesis research is to integrate the latest advanced GIS techniques including its 3D visualization function and the state-of-the-art knowledge from previous studies into the highway design consistency evaluation procedure. By adding new functions specifically developed for highway design consistency evaluation, a 3D GIS-based highway design consistency evaluation methodology is developed. This newly developed methodology and associated software tools, as a combination of GIS, including its 3D visualization function, and highway consistency modules, will make significant contributions in the following aspects: highly automated consistency evaluation procedure, 3D-alignment-based consistency level analysis, impressive evaluation result presentation, and spatially based consistency improvement suggestion. Verification of this methodology on a typical 3D-highway segment in Ontario shows very promising results. This study, to a great extent, is convincing that, in the near future, designers could be able to design highways in a regular GIS environment.

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INTRODUCTION

It is well recognized by transportation engineers that highway design consistency is a very important issue related to traffic safety. How to improve the consistency levels of highways, especially two-lane rural highways, has been a focus of studies on highway safety and geometric design for decades. Evaluating the design consistency of existing two-lane rural highways has been believed to be an efficient way to identify consistency problems in the design stage of new highways and, therefore, to avoid or eliminate potential inconsistent designs. Having noticed that most data of highways are spatially related and frequently under the impacts of three-dimensional (3D) nature of the alignments, it is reasonable to try to merge geographic information systems (GIS), including its 3D GIS visualization function, into the design consistency process to produce an efficient and persuasive methodology for consistency evaluation.

This study embodies the attempt to apply GIS into highway consistency evaluation. In addition to exploring the potential two-dimensional (2D) and 3D GIS visualization applications to highway design consistency, a 3D GIS-based highway design consistency evaluation methodology is developed, in which GIS will take part as not only a single data manager but also a data analyst. With contributions of 3D GIS visualization, well known for its 3D graphing and spatial data analysis, the procedure of operating speed consistency evaluation becomes simpler and more persuasive.

The methodology for a GIS-based design consistency evaluation is a good example of developing GIS integrated tools, which will also benefit the whole field of highway geometric design. There is no question that this project, as a combination of transportation and geomatics, may bridge the fields of GIS and highway geometric design and significantly benefit the latter, in particular, highway design consistency evaluation.

The primary software programs used in the thesis work include ArcGIS (including 3D Analyst) and Visual Basic 6.0 (the registered trademarks including the names of some software products quoted in this thesis are listed in Appendix A). ArcGIS is the most updated GIS software package released by Environmental Systems Research Institute (ESRI). It contains three components, ArcView, ArcInfo and ArcEditor. In addition to the original functions of ArcView 3.x, the new version of ArcView has been equipped with many other useful functions, such as geodatabase creation, which were only found originally in ArcInfo. With the help of 3D Analyst, ArcGIS can visualize 2D geographic data and analyze 3D spatial data easily. In the study, the function of customization in ArcGIS and ArcGIS 3D Analyst is used frequently. It is this function that makes the integration of GIS and highway design consistency evaluation modules possible.

The major objective of this thesis research is to integrate the latest advanced GIS techniques and the state-of-the-art knowledge from previous studies into the highway design consistency evaluation procedure. The most significant contribution from this thesis research has been a newly developed 3D GIS-based highway design consistency evaluation methodology. This newly developed methodology and associated software tools, as a combination of GIS, including 3D GIS visualization, and highway consistency modules, will make significant contributions in the following aspects: highly automated consistency evaluation procedure, 3D alignment based consistency level analysis, impressive presentational evaluation results, and spatially based consistency improvement strategies. Verification of this methodology on a typical highway segment in Ontario shows very promising results. This study, to a great extent, is convincing that, in the near future, designers could be able to do highway designs and design consistency analysis together in a GIS platform.

This thesis is structured in seven chapters (Figure 0.1) as follows:

Chapter 1: This chapter is an in-depth literature review on both highway design consistency evaluation and associated GIS topics. It covers the current status and future perspectives in such fields as GIS, GIS in transportation (GIS-T), 3D GIS, geometric design, and highway design consistency. This thorough literature review revealed what has been done and what's not, where the motivation for this thesis project stands. This resulted in the major objective for this study: integrating the latest 3D GIS techniques with the state-of-the-art knowledge into the consistency evaluation procedure to enhance the automation of this procedure.

Chapter 2: This chapter offers a thorough overview on current operating speed consistency research. Both 2D and 3D operating speed prediction models are reviewed and summarized in detail. In particular, one of the most important operating speed consistency model types, speed-profile model, is extensively investigated and an advanced 3D operating speed-profile model is introduced. This model is later integrated into the newly 3D GIS-based developed highway consistency evaluation methodology.

Chapter 3: Some software basics used by the consistency evaluation methodology are described in this chapter. General knowledge is provided on GIS, such as ArcGIS System, ArcGIS desktop, and ArcGIS extensions as well as their interrelationships. It is concluded that the motivation on this thesis project is completely feasible based on the

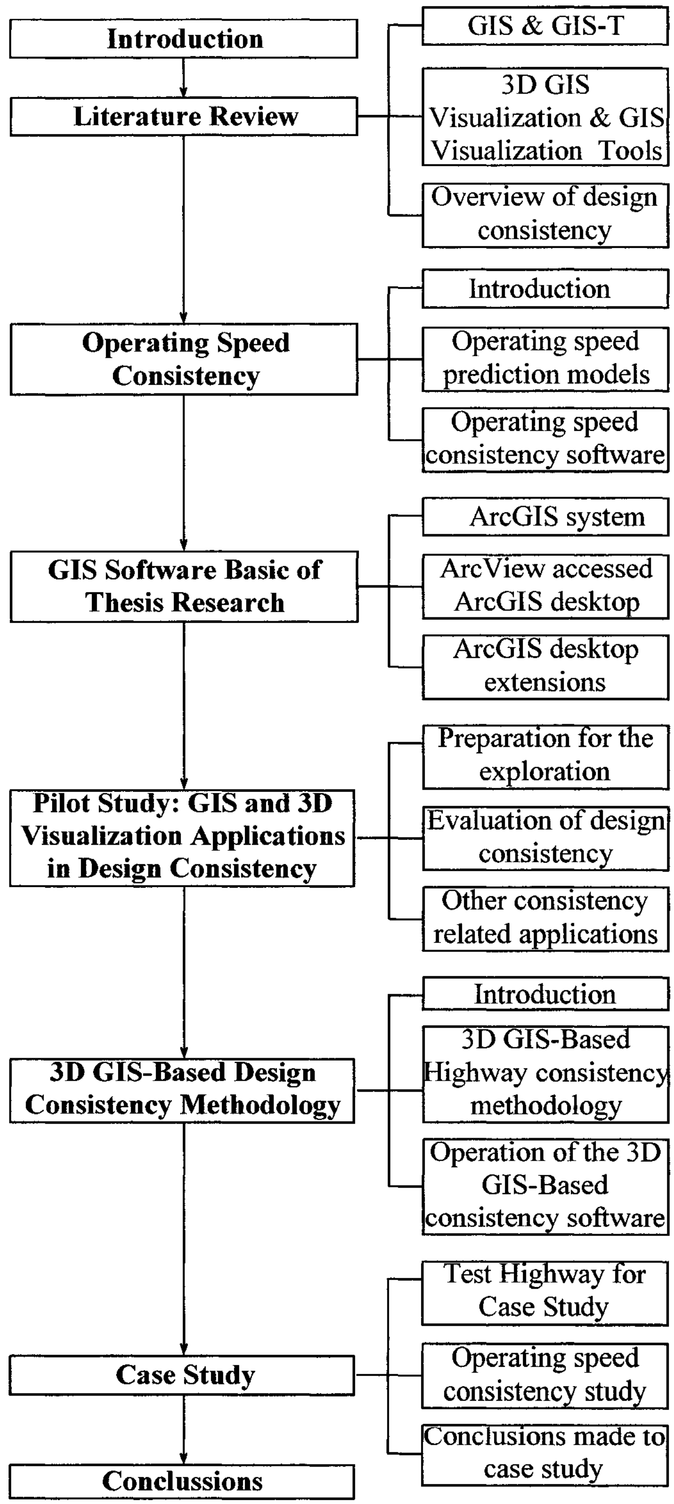


Figure 0.1: Thesis Structure and Research Activities

findings on the state-of-the-art knowledge (Chapters 1 and 2) and the latest GIS technology (this chapter).

Chapter 4: This chapter explores possible GIS and GIS visualization applications to highway design consistency evaluation. A fictitious 3D highway segment is designed for demonstration purpose. To examine the feasibility of different methodologies, many potential GIS and GIS visualization applications that may be helpful for highway design consistency evaluation are tested.

Chapter 5: In this chapter, based on the findings from previous chapters, a 3D GIS-based design consistency evaluation methodology is developed. The conceptual design for the developed methodology is presented first. Then, the main features of the newly developed consistency methodology are introduced. Finally, the operation of the core of the methodology – 3D GIS-based operating speed consistency software, is described in order to give a thorough understanding of this newly developed highway consistency methodology.

Chapter 6: As a validation of the developed methodology, this chapter presents a case study in Ontario. Through this case study, the practicality of the newly developed design consistency evaluation methodology is thoroughly testified. The results of this case study are very promising, especially in such aspects as problem identification and solution.

Chapter 7: This concluding chapter contains detailed summary of the major conclusions from this thesis research. Also pointed out at the end of this chapter are some potential future improvements to the newly developed highway design consistency evaluation methodology and software.

Chapter 1

LITERATURE REVIEW

Highway design consistency is an important indicator of highway safety; a consistent design of a highway will significantly increase its safety level. Therefore, the introduction and evaluation of highway design consistency in highway geometric design have been attracting more and more attention from the transportation engineering community. To reduce or even eliminate highway collisions caused by the lack of driver expectancy of highway geometry, a great amount of research work has been done on seeking good highway consistency rating models. The models tend to be more and more accurate; meanwhile, the evaluation procedure is becoming more and more practical and automated. For example, designers of operating speed prediction models have been trying to consider the 3D nature of highway alignments. Recently, they tried to incorporate techniques from various areas such as expert system (Faghri and Harbeson 1999) and GIS (Lamm et al. 1995, Faghri and Harbeson 1999).

Currently, the 3D GIS visualization techniques are getting boomed in many fields such as environmental studies and urban planning. One powerful aspect of GIS is its ability to model many kinds of spatial objects to meet particular user needs and requirements. It is quite natural to ask that, "Will this technology benefit the evaluation of the highway design consistency of the 3D alignments?" This section will offer a detailed summary of the research status and outcomes in the associated fields. These fields include general GIS, 3D GIS visualization, and highway design consistency evaluation.

Based on this thorough literature review, the perspective of GIS and 3D GIS visualization in highway design consistency evaluation is explored.

1.1 GIS and GIS-T

1.1.1 Geographic Information Systems (GIS)

GIS have existed since the 1960's, although the techniques used by GIS predate this. The popularity of GIS and GIS tools was initially inhibited by the expense and expertise required to set up a system. In recent years, the use of GIS has grown dramatically (Julie 1999). It was developed when the demands for data on topography and other specific themes of the earth surface, such as natural resources, have accelerated greatly in many disciplines.

GIS is popularly used for collecting, storing, retrieving, manipulating, transforming and displaying spatial data from the real world for a particular set of purposes. It can be defined as a computer-based system that provides four sets of capabilities to handle geo-referenced data (Aronoff 1989):

1 Data input,

2 Data management (data storage and retrieval),

3 Manipulation and analysis,

4 Data output.

So far, GIS has been widely applied to many disciplines including forestry, agriculture, environment, information highways, transportation, utilities, land information, and large-scale civil engineering projects (Easa et al. 2000). The major areas that may benefit from GIS are listed as following (GISdevelopment.net 2000):

1. Different Planning Streams: Urban planning, transportation planning and architectural conservation planning.
2. Street Network Based Applications: Vehicle routing and scheduling, location and site selection and disaster planning.
3. Natural Resource Based Applications: Management and environmental impact analysis of wild and scenic recreational resources, flood plain, wetlands, ground water and forests, wild life habitat study and migration route planning.
4. ViewShed Analysis: Hazardous or toxic factories sitting and ground water modeling.
5. Land Parcel Based Zoning: Sub-division plans review, land acquisition, nature quality management and maintenance etc.
6. Facilities Management: Water supply management, sewer lines management and planning and tracking energy use.

1.1.2 Transportation GIS (GIS-T)

Introduction

As mentioned before, GIS has shown its indispensable helps in many fields. In recent years, the use of GIS in transportation has become increasingly popular because GIS can provide engineers with much useful geographic information and the ability to deal with this information. By applying GIS to transportation, a new branch of knowledge appeared and is known as transportation GIS or GIS-T for short. With the help of GIS, transportation engineers can cut the costs of transportation design and management. They can even analyze the road safety and manage the highway network more efficiently without going outdoors to the sites.

Many applications of GIS have been implemented in transportation industry. Some good examples are the management of urban transport infrastructure and the assessment of road and traffic impact on the environment. Generally, GIS applications in transportation fall into two categories: infrastructure management and fleet/logistics management (Easa et al. 2000). GIS-T covers many areas. For instance, GIS has been used to generate inputs to transportation models (Prastacos 1991), to evaluate transportation planning options using analysis and overlay functions, and to generate diverse outputs in transportation planning (Easa et al. 2000).

GIS-T is a valuable tool in integrating transportation system based cartographic data with other forms of tabular data. Such integration in a visual format facilitates understanding of the interrelationships between different transportation system variables and provides a better indication of potential implications of changes or policy initiatives in any given mode of transportation (Melchiorre et al. 1998). In Melchiorre et al. (1998), a computer-based approach was developed for assessing highway layouts by using GIS and a geographically-referenced database. The results demonstrated the potential of the developed approach in incorporating new evaluation criteria at the route layout design stage and in automating the route layout assessment procedure.

Although previous GIS-T is mainly aiding transportation planning processes and road safety management and analysis, the trend of future GIS-T may be reflected by the following forecasts, as predicted by Waters (1999).

1. *Use of expert systems (ES)*

   ES has been deployed, more or less, in current GIS-T, and an example is that it is used together with GIS to help evaluate the highway consistency of horizontal alignment (Faghri and Harbeson 1999). In the near future, GIS-T is more likely to benefit from an infusion of techniques related to ES. For instance, ES may be used to determine which infrastructure improvements are appropriate in light of changes (such as demographic changes) within the GIS-T. Therefore, the GIS-T can be used to evaluate the effects of infrastructure changes and the results can then be entered into the ES.

2. *Integration with other surveillance technologies*

   A major development in the future for GIS-T will be its close integration with other surveillance technologies. GIS-T has been used for analysis work within urban centers. This has been proved by the case that incorporating traffic collision data into a GIS-T. Engineers can show that speeding increases the likelihood of collisions, especially at intersections. The work supports the use of photo radar devices which are used by the police to reduce speeding at such locations, despite of concerns over these surveillance technologies.

3. *The Internet and embeddable technology*

   In future, data, maps and software will be mostly available on the Internet for downloading or simply viewing. GIS will be redesigned into object-oriented applets or other components which will handle highly specific computation tasks and can be used to carry out more complex operations.

4. *Temporal GIS-T*

The construction of temporal GIS databases is one of the ongoing challenges for the GIS community. Such formulations are particularly useful in the transportation sector. Since many transportation data, such as pavement data, traffic flow data, traffic accident data and land use data, are not only spatially referenced but also temporally referenced. The importance of handling spatiotemporal data in transportation applications of GIS should certainly never be ignored.

To provide a general background of GIS-T in highway design and planning, especially highway geometric designs, a summary of the activities of pioneers in this field and some related fields will be presented. The design process of a proposed highway involves preliminary location study, environmental impact evaluation, and final design. This process normally relies on a team of professionals, including engineers, planners, economists, sociologists, ecologists, and even lawyers (Easa 2002). Since GIS is a set of tools for creating, maintaining, analyzing and displaying maps and data in digital format, many designers have been using it to make their highway design process simpler and more efficient. To the civil engineers, GIS technology offers the ability to overlay map graphics, merge them with non-graphic data, and perform spatial analyses on various layers of information at any given geographic point. GIS allows engineers to obtain quick answers to questions such as: What exists at a given location? Where is the location of a certain feature, or associated attribute? What are the identifiable patterns in the features and/or attributes in a geographic area? What happens if something is added or changed in the existing conditions? (Sadek et al. 2001).

GIS-T in Highway Network Planning

GIS has played an important role in transportation planning. In fact, the objective of transportation planning is to guide development of a land-use / transportation system to achieve economic, social and environmental benefits. GIS can greatly contribute to the transportation planning process through such powerful features as spatial database management, geographic visualizations of possible scenarios, and tools for processing geographic data into geographic information. GIS can also significantly enhance both the quantity and quality of information flows among components of transportation planning process. Consequently, It can influence decision making within these processes (Miller 2000).

GIS provides efficient tools for data organization. It is widely used in highway planning to plan roads for the future or improve the existing networks. Mukherjee and Landman (2000) published a paper on identifying a procedure for preparing Traffic Analysis Zones (TAZs) and building transportation networks for small cities using available information on a desktop GIS platform. Meanwhile, Urbitran Associates recently conducted a study for the New York State Department of Transportation to investigate problems and deficiencies at the interchange of the Sheridan and Bruckner expressways in Bronx (Jobes and Papayannoulis 1998). Dixon et al. (2000) described a GIS-based tool for rural multi-model transportation planning. The main strength of this tool is that, by combining the existing data with GIS maps, field verified default factors, widely accepted planning and analysis methods, and regionally calibrated planning algorithms, system-level planning can be performed at the city, county, multi-county, or state levels.

In addition to all mentioned above, Bjurstrom and Tornberg (2000) used GIS with other 3D software to create a 3D model of the virtual reality to design a new transportation system in existing urban environments. Guggisberg (2000) integrated GIS into an automatic passenger counting systems for transit service performance measurement. Krishnat and Hancock (1998) presented a research of which the primary objective is to develop a GIS-based approach for distributing and assigning freight flows in Massachusetts. Alam and Fekpe (1998) studied a case of I-90/I94 corridor analyses to show an application of GIS-T in freight data analysis. Jia and Ford (2000) explained the planning of Fairfax County Department of Transportation for a fixed route bus system (Fairfax Connector) which encompasses 58 routes.

GIS-T in Highway Network Optimization

At the planning stage of a highway project, various location alternatives must be explored subject to a set of design constraints. A computerized tool to compare different alignment alternatives would significantly reduce the time and resources spent as well as help find a minimum cost (or maximum net benefit) solution (Wade and James 1998). For example, highway design optimization (HDO) is a computerized process that minimizes an objective function composed of significant highway costs, subject to a set of design constraints including curvature, gradient, and sight distance. Several costs of alignments such as right-of-way, earthwork, and environment costs are sensitive to geography. In a highway cost model, since a GIS can spatially represent the locations of properties, floodplains, streams, and other geographical characteristics of significance, it may be exploited to compute such costs for use in highway design optimization models (HDOMs) (Jha and Schonfeld 2000).

Based on the analysis of an example in Talbot County, Maryland, Jha and Schonfeld (2000) developed an integrated model by linking a GIS model with an optimization model employing genetic algorithms (GAs). The GIS model provides accurate geographical features, computes location-dependent costs, and transmits these costs to an external program. That program computes length-dependent costs and user costs and, then using GA's, optimizes the highway alignment to minimize the sum of all costs. A comprehensive formulation is also provided for right-of-way cost computation. Jha (2000) also studied the use of GIS as a dynamic decision making tool in performing highway optimization.

GIS-T in Other Related Areas

GIS-T has been applied in many other areas, such as highway drainage design, cost-benefit analysis, and highway safety. A significant part of the most highway design projects is the design of drainage facilities such as storm drains, highway culverts, bridges, and water quality and quantity control structures. Through case studies, a detailed description of the application of GIS for design of highway drainage facilities was published by Olivera and Maidment (1998). In their report, using a raster-based model, GIS was used to analyze the watershed and calculate some of the necessary hydrologic data for designing highway drainage facilities, considering the spatial variability of the terrain.

Highway planning involves selection of a cost-effective corridor in an environmentally responsible manner. James et al. (2000) showed, by a case study, the implementation of GIS in cost/benefit planning in the Illinois Department of Transportation. They made two benefit estimates: Efficiency Benefits and Effectiveness Benefits resulted from the traditionally intangible areas such as increased integration and accessibility of information for improved decision making. The former would result from the automation of previous manual efforts, such as special purpose cartographic production, with GIS outputs. The user areas reasonably identified and quantified benefits for their GIS projects. The latter was conservatively estimated for two high priority areas: accident analysis and program development. They found the determination of Effectiveness Benefits for accident analysis and program development portrayed the large benefits of GIS implementation and the justification for future development.

Safety is always a very important evaluation factor of highways. It is ranked as the first goal to be achieved in the highway design and planning. It is found that GIS has been playing an important role in this regard. With assistance from GIS, planners can identify locations where traffic collisions occur or may occur in future. Consequently, highways can be planned or redesigned accordingly (Miller 2000).

In summary, although GIS has been widely applied in highway design and planning, there have been few applications of GIS employed exactly in the field of geometric design of highways. Therefore, the field of GIS applications in highway geometric design is relatively new and may have a promising future. This thesis research was intended to provide a significant contribution to this new field.

1.2 3D GIS Visualization and 3D GIS Visualization Software

1.2.1 3D GIS Visualization

The true power of a 3D GIS is its ability to communicate complex geographic phenomena. The increased dimensionality of a 3D GIS allows geographers to produce fence diagrams, isometric surfaces, multiple surfaces, stereo block diagrams, and geo-object cut-aways (Swanson 1996). However, currently, there is no "real" 3D GIS available. Hence, 3D GIS is typically reduced to a 3D visualization of geo-data (Jasnoch et al. 2000).

With the birth of the geography, the term of map became familiar to every person. It is well known that the goal of maps is to simulate the real world or to provide the geographical information to human sense. Unfortunately, former maps are most flat, or in other words, they are two-dimensional. Some of them are so complicated that only those specialists can understand. Although some kinds of 3D maps, or it is more proper to call them models, are used for military purposes or water conservancy projects, they are so primitive that it is very hard to be modified or be transferred.

This situation had not changed until the implementing of 3D visualization. The advantage of 3D lies in the way the information is shown. It is estimated that 50 percent of the brain's neurons are involved in vision. Furthermore, it is believed that 3D displays stimulate more neurons: involving a larger portion of the brain in problem solving processes. With 2D contour maps, for example, the mind must first build a conceptual model of the relief before any analysis can be made (Swanson 1996). Considering the cartographic complexity of some terrain, this can be an arduous task for even the most dexterous mind. A 3D display, however, simulates spatial reality, thus allowing the viewer to more quickly recognize and understand changes in elevation.

Visualization can be defined as the use of computer technology for exploring data in visual form and for experiencing virtual worlds using all the human sensory channels to make the spatial data more understandable. It is a series of transformations that convert raw simulation data into a displayable image. The purpose of the transformation is to convert the information into a format amenable to understanding by the human perceptual system (Visvalingam 1994). When visualization is combined with GIS, it turns into a powerful tool for manipulating spatial or spatially related data for various purposes. 3D GIS visualization puts viewers directly "into the picture" to help identify and recognize real places rather than just view abstract maps. It visualizes 2D GIS data into 3D form for different streams of applications.

Currently, there is a trend to introduce GIS visualization to any area which is already benefiting from 2D GIS. Computer graphics have been around us for decades, but the current race to push the limits of visualization may carry profound implications for GIS users (Sheppard 1999). The introduction of 3D graphics into architecture, engineering, and molecular biology has fostered new expectations in these fields. For example, it could provide a very persuasive tool in hands of city planners, urban designers, and traffic engineers. It is also very likely that they could use it to bring abstract project variables, like visual impact analysis, into the cost-benefit equation (Swanson 1996). It is easy to imagine that GIS visualization may shine in such areas as follows:

1. Presentation

3D GIS visualization gives people deeper impression than 2D graphic packages. It sometimes may be much more pervasive than words and gestures. It attracts the audience's focuses directly to what is emphasized. Furthermore, the combination of 3D GIS visualization and Internet may make points much more easier to be understood by people all over the world.

2. *Guiding*

GIS 3D maps provide clear guidance to travellers. It could be used in many kinds of traffic guiding and military guiding. For example, a 3D terrain picture shows a pilot not only the x, y coordinates (or longitude and longitude) on the earth surface but also the absolute flying height and the relative height to the rolling earth surface. In such a picture, mountains are high as they really are; canyons are deep as they really are. It is very helpful to a pilot for making proper decisions when they know the 3D relationships to the berries.

3. *Reconstruction*

The application of GIS visualization would also benefit reconstruction. GIS visualization helps analysts to recreate what was in the past in order to understand what happened and why that happened. For instance, Hoogenboom (2001) presented a case to show how GIS visualization can help in disaster analyses.

4. *Simulation*

A key function of GIS visualization is to simulate the scenes that do not explicitly exist. Such a function is very important to planners and some historians. It would also become a magic stick in hands of architects or other kinds of designers.

Although GIS visualization has been significantly progressed recently, it still could be improved in both hardware and software. So far, some meaningful extensions had already been explored by GIS technology pioneers. Here are some reasonable improvements of GIS visualization.

1. *Introduction of 3D GIS visualization into more fields*

   Although GIS visualization already got extensively utilized in many areas, to a great extent, it seems still limited to geology, geophysics, meteorology, climatology, and hydrology. Volumetric analysis has proven to be well suited to hydrogeological applications such as petroleum reservoir characterization or groundwater contamination modeling.

2. *Improvement of display quality*

   Some improvement of 3D GIS visualization could be achieved from hardware. Nobody can deny the contribution of computers to the GIS visualization, but with the increasing demand of analyses of more and more complex spatial data, it is obvious that the computer monitor limits the displaying of detailed information. The new display media should be invented to display the complicated spatial data both microscopically and macroscopically. Florence et al. (1997) tried using a GIS wall device, called Wallboard. This device allows multiple users to view and interact with a large-scale, touch-sensitive media, and to display complex spatial information. This may be a nice step towards a potential revolution of 3D display of GIS.

3. *Integrate high-intelligence and high-reality techniques to 3D GIS Visualization*

   Current GIS visualization tools are classified into two groups. The first group emphasizes analysis function and can visualize and analyze 3D data intelligently. In contrast, the other group focuses on how to make the visualization model most close to the real world. Although they both have their own advantages, they only can partly meet the users' needs. How to build a tool which can both analyze 3D data intelligently and visualize 3D world accurately would be a challenge for GIS specialists. Feasible ways can be combining the two kinds of programs together by, for example, enabling the import of other high-reality data formats into those programs being good at analyzing.

4. *Combination of animation with GIS visualization*

   Animation is one of the most advanced forms of visualization. Instead of showing a static scene, animation presents people a dynamic process of changing. Animation could be considered as the four-dimensional form of data display because it takes time factor into account. However, current animation of GIS is still limited to navigating or flying in a certain 3D scene. With helps of animation technology, it is possible to display or simulate changing processes of any GIS data.

1.2.2 3D GIS Visualization Software

The success of GIS and advanced 3D GIS visualization highly depends on the support of 3D visualization software. To meet the requirements from GIS users with different skill levels, many visualization programs are developed. Sheppard (1999) summarized the four core functions of visualization software. They include:

1. Data visualization (scientific visualization), which allows the visualization of numerical, chart or 2D mapping data in an enhanced but conceptual form (e.g. 3D charts and diagrams or animations of changing map data through time);

2. Landscape visualization, which displays the third dimension of terrain and other geographic features draped over a land-base surface, using many of the same data structures as in conventional 2D GIS mapping;
3. High-reality landscape visualization, which generates 3D imagery of an almost photographic or ultra-realistic nature, using techniques such as texture mapping and growth models for vegetation that sits above the terrain surface; and
4. 3D visualization of solid objects, with continuous attributes at all depths in the model (e.g. subsurface geology or groundwater modelling).

Generally, software programs used for GIS visualization are divided into two groups. The first group includes those developed for all kinds of visualization and, some of them are also good at animation. This type of software is named as general visualization software (e.g. Auto CAD, 3D Studio MAX and Softimage). The second group is the software developed specifically for GIS visualization purpose, which is called dedicated 3D GIS visualization software. There are various dedicated 3D GIS visualization software programs contributing to GIS visualization. All of these software packages claim their unique specialties. Some examples of relatively popular dedicated 3D GIS Visualization tools are listed as following.

- *3D Analyst (ESRI 2002)*

  This is an ArcView or ArcGIS extension that helps users integrate 3D data into their analysis (see Figure 1.1). It enables generic surface modelling, supports triangulated irregular networks (TINs), simple 3D vector geometry, as well as interactive perspective viewing.

- *SiteBuilder 3D (MultiGen-Paradigm 2002)*

SiteBuilder 3D (Figure 1.2) allows users to transform ArcView GIS 2D map data into a 3D visual form. It helps you better visualize spatial relationships for sound decision-making. SiteBuilder 3D can be also an extension of ArcView GIS software, and all 3D scene generation is done from inside ArcView GIS.

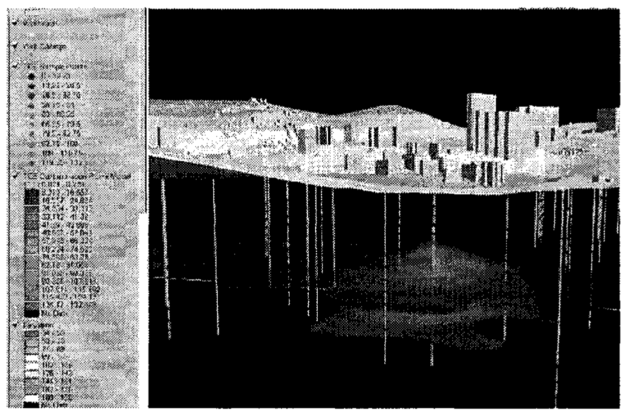


Figure 1.1: ArcView GIS 3D Analyst
(Source: http://www.esri.com/software/arcview/graphics/3d_big.jpg)

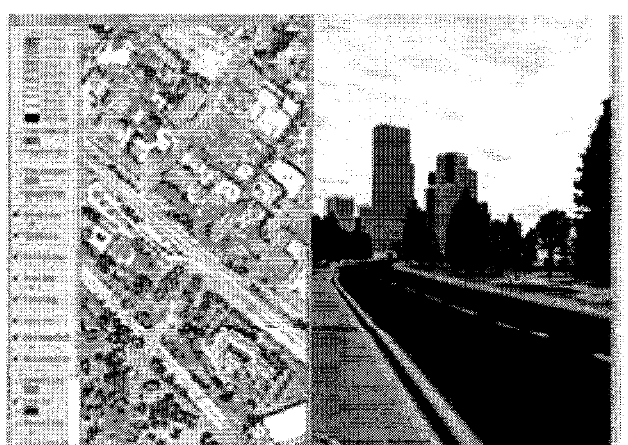


Figure 1.2: SiteBuilder 3D
(Source: http://64.49.223.163/products/3d_gis/sitebuilder/index.shtml)

- *LandSerf (City University 2002)*

  LandSurf (Figure 1.3) is good software for visualisation and analysis of continuous terrain surfaces. It allows TIN generation and interpolation and fractal surface generation. It is also compliant with Virtual Field Course Hub (VFCH) servers (sharing spatial data over the Internet) and improved 3D viewing

- *Kashmir 3D (SUGIMOTO 2002)*

  Kashmir 3D (Figure 1.4) can generate photo-realistic images and movies of landscapes using digital elevation model files from the United States Geological Survey (USGS) and the Swiss Federal Office of Topography (SFOT).

- *GeoView 3D (Doug Johnston 2002)*

  GeoView 3D (Figure 1.5) is an interactive real-time multi-dimensional visualization and spatial analysis system. It enables multi-dimensional spatial analysis (query and manipulation of 3D object attribute information), 3D modeling (static, dynamic, or process), 3D simulation (with time-step editor) and 3D animation (with fly-throughs, walk-throughs, and drive-bys).

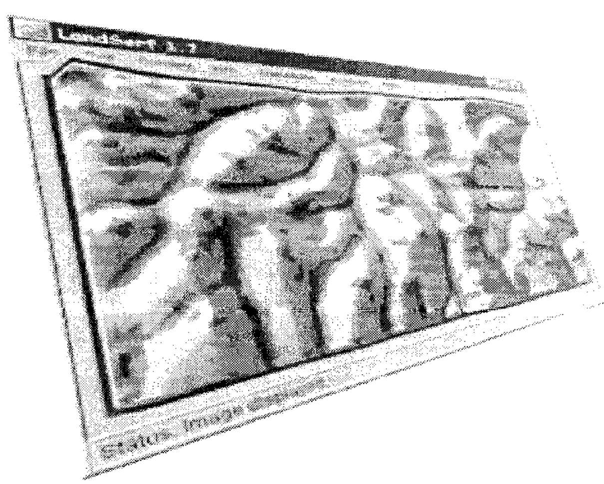


Figure 1.3: LandSurf
(Source: http://www.soi.city.ac.uk/~jwo/landserf/)

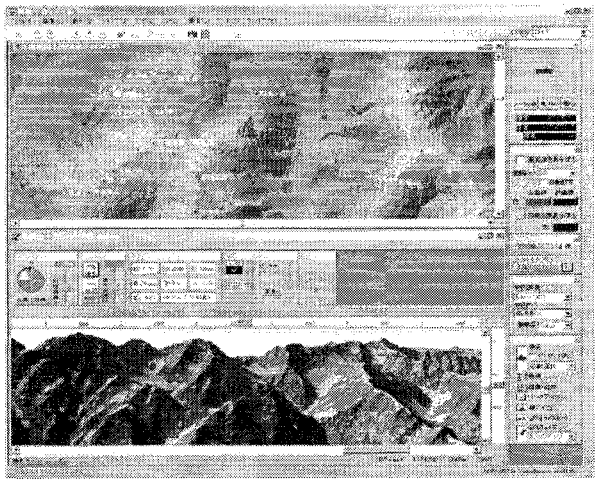


Figure 1.4: Kashmir 3D
(Source: http://www.kashmir3d.com/kash/intro/intro.html)

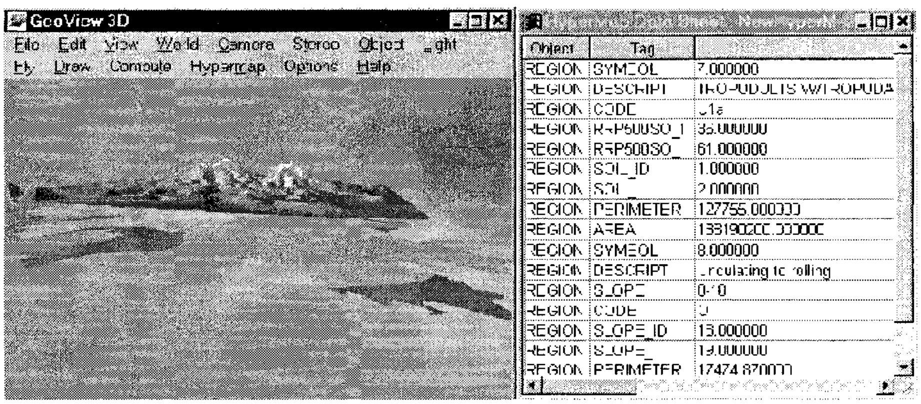


Figure 1.5: GeoView
(Source: http://www.geoanalytika.com/geoview3d_fr.htm)

1.3 Highway Geometric Design and Design Consistency

1.3.1 Highway Geometric Design

Geometric design of highways refers to the design of visible dimensions of such features as curves, cross sections, sight distance, bicycle and pedestrian facilities, and intersections. The main objective of geometric design is to produce a highway with safe, efficient, and economic traffic operations, while maintaining aesthetic and environmental quality (Easa 2002). The design process of a proposed highway involves preliminary location study, environmental impact evaluation, and final design. This process normally relies on a team of professionals, including engineers, planners, economists, sociologists, ecologists, and, sometimes, lawyers.

According to the North American highway geometric design guides including A Policy on Geometric Design of Highways and Streets (AASHTO 2001) and the Geometric Design Guide for Canadian Roads (TAC 1999b), the primary design elements in the highway geometric design include horizontal alignment, vertical alignment, cross section, and sight distance.

Horizontal Alignment

TAC's (1999b) design guide suggests that the horizontal alignment is a relatively permanent feature of a roadway and is usually difficult and expensive to modify after its construction. Therefore, it is critical that the designers can be aware of and account for a number of key factors which can have a significant influence in defining the boundaries of the design domain for the various elements of horizontal alignment. The design of horizontal curve involves the designs of:

- Circular curve: the design of circular curve must meet the minimum curve radius control. This is related to issues such as design speed, superelevation, lateral friction, and sight distances.

- Transition: the design of transition includes the design of tangent-to-curve transition, spiral curve transition, and compound curve transition. Issues related to this design include the transition of superelevation, lane widths, and radius transition.
- Superelevation and lateral friction: this provides other design considerations with many prerequisites such as maximum/minimum superelevation.

Vertical Alignment

The topography of the land traversed has an influence on the alignment of roads and streets. While affecting horizontal alignment, topography has a much more pronounced effect on vertical alignment. Therefore, the design of vertical alignment is very important and many controls need to be considered to guarantee road safety:

- Grades: usually, the design of grades must meet the allowed maximum and critical lengths of grade, which depends on factors such as design speed and road types.
- Vertical curves: These include sag curves and crest curves. The design of vertical curves will provide reasonable and smooth transition between different grades. In this process, sight distance will be the major concern.
- Special lanes related to vertical alignment: lanes with special purpose and related to vertical alignment include climbing lane, passing lane, and emergency escape ramps.

Cross Section

Similar to the design of its horizontal and vertical alignment, the design of cross sections of a roadway must focus on driver needs. The cross section elements provide vital guidance to the driver through their presence, dimensions and coordination. The design of cross section elements includes the design of traveled way, shoulders or curb and gutter, related drainage features, side slopes and back slopes. In urban areas, it may also include provisions for pedestrians and cyclists as well as special purpose lanes and separators.

Sight Distance

Sight distance is one of the most important design considerations because it has significant influence on drivers' expectancy and, hence, on drivers' maneuvers. Usually, sight distances are only considered for the design of vertical alignments and horizontal alignments separately. Easa et al. (1996) presented their work on modelling and calculation of sight distances on complex highway vertical alignment. Hassan et al. (1996, 1997) further extended to 3D combined highway curves. There are four types of sight distances that have been generally accepted and included in the design guides: stopping sight distance, passing sight distance, decision sight distance, and intersection sight distance.

1.3.2 Highway Design Consistency

Traffic safety has been one of the most important issues studied in transportation since its birth. It was reported that, in Canada, traffic collisions in 1999 resulted more than 220,000 injuries and 2,600 deaths (Transport Canada 1999). To improve the road safety, lots of strategies have been studied. Among these studies, good geometric design of the highways is definitely one of the most important factors for the traffic safety.

In the multitudinous elements of geometric design, the design consistency concept is considered to be a very important factor due to its direct relationship to highway safety. Design consistency is defined as the degree to which highway systems are designed to avoid critical driving maneuvers and to ensure safe traffic operation (Al-Masaeid et al. 1995). In fact, the significance of the design consistency has been appreciated for decades and many researches have been done to pursue consistent designs of roadways. The following section shows a summary of previous design consistency research works.

Since design consistency is closely related to road safety, achieving design consistency should be one of the most important aims for road designers. This is explicitly presented in the design guide of Transportation Association of Canada (TAC) (1999a). It is believed that the more consistent road designs are over a wide geographic area, the more effective the designer's contribution will be to reduce collision occurrence. Evaluation has been the focus of previous studies due to the fact that evaluation of design consistency of exiting highways can give references or experiences to designers for their pursuing better highway network designs.

Two-lane rural highways are always the targets of design consistency studies. This is mainly due to the fact that two-lane rural highways are an essential element of transportation network in many developed countries. For example, about 82% of the Canadian highway network consists of two-lane rural highways (Hassan et al. 2001). Another reason is that they are more eligible for design consistency research because, while owning the typicality of many kinds of curves, they have less disturbing from impacts such as intersections and traffic congestion.

So far, many criteria for classifying highway design consistency are used in Europe and North America. They include criteria for safety consistency measurement, driver workload consistency measurement, highway geometry consistency measurement, and operating speed consistency measurement.

Safety Consistency

The most valuable tool for evaluating geometric design consistency is actual collision experience, which should, for any existing facility, be used as a basis for the design consistency review (TAC 1999a). Safety consistency considers those factors that have most obvious relationships with traffic safety. Such factors include collision or accident rate, vehicle stability, etc. Lamm et al. (1988a) presented a criterion for design consistency evaluation. It was based on accident rates as following:

1. Good design: accident/10^6 vehicle-km ≤ 2.27.
2. Poor design: $2.27 <$ mean accident rate (accident/10^6 vehicle-km) ≤ 5.00.
3. Poor design: accident/10^6 vehicle-km > 5.00.

Regarding the consideration of the impact of accident rate on highway safety, researchers have also developed several models to predict accident rate on highways based on their relation to highway geometric conditions. For example, Silyanov (1973) established an equation to define the relationship between pavement width and accident rate:

$$N = 1/(0.173W - 0.21) \qquad [1.1]$$

where N = number of accidents per million vehicle kilometer and W = pavement width. Besides, the relationship between accident rate and ADT (ADT=Average Daily Traffic) was also studied and several equations were also developed (Eq. 1.2, Hauer 2000, Eq. 1.3, Council and Stewart 1998, Eq. 1.4, Belmont 1954):

$$N = 0.003 \times ADT^{0.8} / (ADT \times 365 \times 10^{-6}) \quad [1.2]$$

$$N = \alpha(ADT)^{\beta} \quad [1.3]$$

$$N = 0.0019 \times ADT^{1.028} \times (1\text{-}34.04/PW + 383.4/PW^2) \quad [1.4]$$

In Silyanov (1973), the impact of vertical alignment on accident rate was also accounted by establishing the relationship between accident rate and vertical grade (G, grade in %):

$$N = 0.265 + 0.105G + 0.023G^2 \quad [1.5]$$

Lamm et al. (1995) suggested another evaluation criterion which considers the difference between f_R and f_{Rd} ($\Delta f_R = f_R - f_{Rd}$), where f_R and f_{Rd} are respectively the actual and design friction coefficient of the road.

1. Good design: $\Delta f_R \geq +0.02$ (no improvements are required).
2. Fair design: $+0.02 > \Delta f_R \geq -0.02$ (superelevation rate must be related to operating speed to ensure that side friction supply will accommodate side friction demand).
3. Poor design: $\Delta f_R < -0.02$ (redesign is recommended).

Models presented by Gibreel et al. (1999) can be used to calculate f_R and f_{Rd}:

$$f_R = 0.082 + 4.692 \times 10^{-8} V_{85} - 7 \times 10^{-8} V^2_{85}, R^2 = 0.74 \qquad [1.6]$$

$$f_{Rd} = 0.253 + 2.330 \times 10^{-8} V_{85} - 9 \times 10^{-8} V^2_{85}, R^2 = 0.56 \qquad [1.7]$$

where V_{85} = 85th percentile speed (the speed that 85% of the drivers do not exceed).

Driver Workload Consistency

The major goal of highway design is to achieve comfortable, efficient and safe traffic operation. Too high or too low workload and sudden changes of workload are usually the reason for road collisions. Locations of high driving workload of those that do not coincide with driver's anticipation usually show poor design (Gibreel et al. 1999). To evaluate highway design consistency precisely, factors such as workload and driver anticipation should also be considered. Here is a model for workload calculation introduced by Gibreel et al. (1999):

$$WL_n = (U \times E \times S \times R_f) + (C \times WL_p) \qquad [1.8]$$

where WL_n = expected workload value for the specific feature, U = driver unfamiliarity factor (depends on highway classification and location), E = feature expectancy factor ($E = C - 1$ if the feature is similar to the previous one, otherwise $E = 1$), S = sight distance factor (which depends on the available sight distance to the feature), R_f = average workload potential value for the general feature, C = carryover factor (which depends on the separation distance between features), and WL_p = workload value of the previous feature.

Another workload regression model was developed by Shafer et al. (1994, Krammes et al. 1995) as:

$$WL = 0.193 + 0.016D,\ R^2 = 0.90 \qquad [1.9]$$

where WL = average workload of curve, and D = degree of curvature.

Cross Section Consistency

Geometric conditions have direct impacts on highway design consistency. Important geometric factors influencing the effectiveness of highway design consistency and highway safety include pavement width, horizontal curve, vertical curve, cross section, spiral, etc. Some impacts of these factors on design consistency have been examined through exploration of their relationships to such design considerations as operating speed, accident rate, and driver workload. For example, Easa (2003b) has developed an objective method that distributes superelevation by using mathematical optimization to maximize highway design consistency. In this section, only relationship between cross section and highway design consistency is extensively examined.

The cross section of a roadway is the view obtained from a section between the right-of-way lines perpendicular to the travel direction along the road. It includes features on the traveled portion of the road used by vehicular traffic as well as on the roadside.

There is strong consensus in the highway engineering community that the design of cross section elements influences a roadway's cost, operation, and safety (Hall et al. 1995). Although this consideration is definitely an important one, few cross section consistency evaluation approaches and models have been developed. The detailed design directions of important elements of cross sections have been established and summarized in many highway geometric design guides. For example, TAC (1999b) gives the minimum transition length (L) at the cross-slope change:

$$L = (100we) / (2s) \qquad [1.10]$$

where w = the width of pavement, e = the change in superelevation developed (m/m), and s = the relative slope (%).

Operating Speed Consistency

The study has shown that the safety of a road is closely linked to variations in the speed of vehicles traveling on it (TAC 1999a). In fact, the operating speed, defined as the 85th percentile speed or the speed that 85% of the drivers do not exceed, has been always a very important consideration during the procedure of highway design consistency evaluation. Meanwhile, many design standards have been developed using operating speed for design consistency judgment.

Lamm et al. (1988a, 1995) recommended the following measures of operating speed design consistency for single curved element in two-lane highways:

1 Good designs: ΔV_{85} (difference between V_{85} and design speed) $\leq$ 6mph (10 km/h),

2 Poor designs: ΔV_{85} (difference between V_{85} and design speed) > 12mph (20 km/h).

The above criteria are the design consistency evaluation criteria that aim the tuning of the relationship between design speed and operating speed on individual elements (Lamm et al. 1999). In the updated highway consistency chapter of Geometric Design Guide for Canadian Roads (Easa 2003a), the highway design consistency on individual element was defined more reasonably as local design consistency. However, since this measurement is related to operating speed, it is still included in the operating speed consistency evaluation in this thesis. Lamm et al. (1995, 1999) also recommended another series of criteria for operating speed consistency judgment between successive elements. They are:

1 Good design: ΔV_{85} (operating speed difference) ≤ 6 mph (10 km/h),

2 Fair design: 6 mph (10 km/h) < ΔV_{85} (operating speed difference) ≤ 12mph (20 km/h),

3 Poor design: ΔV_{85} (operating speed difference) > 12 mph (20 km/h).

Lamm et al. (1995) further suggested that the above three criteria should be considered equally in evaluation of design consistency. Consequently, the overall measure is:

1 Good design: 3good or 2 good/1 fair or 2 good/1 poor,

2 Fair design: 3 fair or 2 fair/1 good or 2 fair/1 poor or 1 good/1 fair/1 poor,

3 Poor design: 3 poor or 2 poor/1 good or 2 poor/1 fair.

GIS in Highway Design Consistency Evaluation

Although GIS plays an important role in transportation field, it has not been widely employed in the field of highway geometric design. Geometric design of highways refers to the design of visible dimensions of such features as curves, cross sections, sight distance, bicycle and pedestrian facilities, and intersections (Easa 2002). To meet these goals, spatially referenced data always need to be manipulated. However, most of the existing studies on the applications of GIS in highway geometric design are based on merely its functions of data storing and graphing. The GIS techniques that have been used are limited only in 2D form. Faghri and Harbeson (1999) used GIS as a data-storing tool to aid his procedure. Lamm et al. (1995) used GIS for the graphic presentation of their evaluation results. GIS application in highway design consistency evaluation has never been the focus in previous studies.

On the other hand, according to the previous research, it is very hard to evaluate design consistency based on safety and workload because they involve human factors and thus are too complicated to be measured by simple criteria. In addition, they can't be used as general criteria because it is not accurate enough to predict a highway's collision rate using data from other highways or roadways. In fact, the evaluation of operating speed can obtain the same goal with that of both workload evaluation and accident rate evaluation. Therefore, evaluating highway design consistency according to the operating speed is the most efficient method.

In this regard, this study will be a significant contribution in merging GIS in actual highway design consistency evaluation, especially operating speed consistency evaluation. This may also be a trend in the near future. Furthermore, since the advanced 3D GIS visualization exploits the original functions of 2D GIS while extends them with the third dimension, it may benefit the operating speed consistency study of 3D alignments and further benefit the whole highway design consistency field.

Chapter 2

OPERATING SPEED CONSISTENCY

2.1 Introduction

Since design consistency is directly related to road safety, achieving consistent designs is one of the key goals of road designers. It is well known that the most valuable tool for evaluating geometric design consistency is actual collision experience, and that too high or too low workload and sudden changes of workload are usually the reason of road collisions. However, researches in these two fields have never been boomed since it is very hard to accurately evaluate design consistency based on safety and workload due to difficulties in data collection and involvement of human factors.

As discussed in Chapter 1, most efforts at highway design consistency have been focused on the operating speed consistency for decades. In fact, the evaluation of speed can reflect the goodness of many other factors including workload and accident rates. It is widely accepted to use 85th percentile speed as the operating speed. The main measures of operating speed design consistency for two-lane highways have been summarized in Chapter 1. After equipped with those measures, how to predict operating speed accurately became a key challenge. Most previous works have been done on the 85th percentile speed study and, as a result, many different models have been developed considering series characteristics of the curved highways.

2.2 Operating Speed Prediction Models

2.2.1 2D and 3D Operating Speed Prediction Models

2D Operating Speed Prediction Models

During the past few decades, great efforts have been put on the forecasting of operating speed without considering vertical impacts. Consequently, many valuable 2D models have been developed. For example, based on the research on data collected from 261 road sections of two-lane rural highways in New York, Lamm and Choueiri (1987) explored the relationship between the operating speed and some geometric conditions using statistical techniques:

$$V_{85} = 34.700 - 1.005(DC) + 2.081(LW) + 0.174(SW) + 0.0004(AADT) \quad [2.1]$$

$(R^2 = 0.842, SEE = 2.814mph)$

$$V_{85} = 58.656 - 1.135(DC) \quad [2.2]$$

$(R^2 = 0.787, SEE = 3.259mph)$

where V_{85} = estimate of the operating speed expressed by the 85th percentile speed (mph), DC = degree of curve (range 0° to 27°), LW = lane width (ft), SW = shoulder width (ft), $AADT$ = average annual daily traffic (vpd), R^2 = coefficient of determination, and SEE = standard error of estimate (mph).

In the same paper (Lamm and Choueiri 1987), operating speed prediction models on horizontally curved highways with different lane widths were also developed using linear regression techniques. These models highlighted the relationships between operating speeds and curve radii or curvature change rate (CCR). Listed here are the two equations that can predict the operating speed on highways with lane width of 3.65 m:

$$V_{85} = 95.780 - 0.076\,CCR,\ R^2 = 0.84 \qquad [2.3]$$

$$V_{85} = 96.152 - (2803.769 / r),\ R^2 = 0.82 \qquad [2.4]$$

where: CCR = curvature change rate on horizontal alignment (Degree/km) and r = radius of horizontal curve (m).

The curvature change rate (CCR) in the above equation can be calculated by the following equation (Lamm et al. 1986):

$$CCR = \frac{57300}{L_t}\left(\sum \frac{L_{ci}}{r_i} + \sum \frac{L_j}{2r_i}\right) \qquad [2.5]$$

where L_{ci} = length of circular curve i (m), L_j = length of spiral curve j (m), r_i = radius of circular curve i (m), and L_t = total length of section (m).

Based on different data, Lamm et al. (1990) further studied the relationship between the operating speed and curve radius on horizontal alignments of 2-lane highways. In this study, the importance of curve radius (r) to the operating speed (V_{85}) was once again confirmed:

$$V_{85} = 94.396 - (3188.656 / r),\ R^2 = 0.79 \qquad [2.6]$$

Almost at the same time, Kanellaidis et al. (1990) developed another operating speed prediction model for horizontal alignments of two-lane highways in Greece. This is also a regression model and expressed by the next equation:

$$V_{85} = 129.88 - \frac{623.1}{\sqrt{r}},\ R^2 = 0.78 \qquad [2.7]$$

According to Eq. 2.7 itself, the operating speeds predicted with this model can be as high as 129.88 km/h (on tangent). This seems not reasonable given that the widely accepted desired speed on tangent is 100 km/h. Therefore, to achieve more accurate prediction results, the radii of the curves on the test alignments should be moderate when using this equation.

In addition, TAC (1999a) recommended the following operating speed prediction model derived using regression techniques:

$$V_{85} = 102.45 + 0.0037L - (2741.75 + 1.75L)/r \qquad [2.8]$$

where L = length of curve (m), r = radius of curvature (m)

According to Islam Senevirane (1994) and Gibreel et al. (1999), there were significant differences between the operating speeds at Point of Curve (*PC*), Point of Tangent (*PT*) and the Middle of Curve (*MC*), thus, these speeds should be predicted separately as:

$$At\ PC: \quad V_{85} = 95.41 - 1.48D - 0.012D^2,\ R^2 = 0.99, \quad [2.9a]$$

$$At\ MC: \quad V_{85} = 103.03 - 2.41D - 0.029D^2,\ R^2 = 0.98, \quad [2.9b]$$

$$At\ PT: \quad V_{85} = 96.11 - 1.07D,\ R^2 = 0.98. \quad [2.9c]$$

where D = degree of curve.

Considering the effects of approach tangent, McFadden and Elefteriadou (1997) developed two V_{85} prediction models based on the data from 78 curved sections:

$$V_{85} = 103.66 - 1.95D,\ R^2 = 0.90 \quad [2.10]$$

$$V_{85} = 41.62 - 1.29D + 0.0049L_c - 0.12\Delta + 0.95V_t,\ R^2 = 0.90 \quad [2.11]$$

where V_t = 85th percentile speed on approach tangent (km/h), L_c = length of curve, and Δ = deflection of angle.

According to the summary of Gibreel et al. (1999), models were also developed to calculate operating speed reduction (ΔV) between a tangent and its following curve (Al-Masaeid et al. 1995):

$$\Delta V = 3.30 + 1.58D,\ R^2 = 0.62 \quad [2.12]$$

$$\Delta V = 1.84 + 1.39D + 4.09P + 0.07G^2,\ R^2 = 0.77 \quad [2.13]$$

$$\Delta V = 1.54 + 1.55D + 4P + 0.00004L_v^2,\ R^2 = 0.76 \qquad [2.14]$$

where P = pavement condition, G = gradient (%), and L_v = length of vertical curve within the horizontal curve (m).

Ottesen and Krammes (2000) summarized the current regression forms (Table 2.1) that had been used to predict V_{85} percentile speeds on horizontal curves. Many previous models are reflected in this summary.

3D Operating Speed Prediction Models

Highways are 3D entities, ignoring the effects of vertical curves would of course lower the accuracy of the operating speed prediction models. Although 3D consideration of design consistency has been considered as a difficult task and few rewards have been achieved on establishing 3D-considered highway design consistency evaluation standards (Hassan et al. 1996), some vertical-impact-considered or 3D models for operating speed prediction have been developed. In the report of Fitzpatrick et al. (1999), several speed-prediction equations (these equations are called Fitzpatrick et al. equations when quoted hereinafter) representing the effects of motorist speeds on both horizontal and vertical alignments were developed. The models are listed in Table 2.2.

Although not very accurately considering vertical alignment, these equations show the effects of both horizontal and vertical alignments. They are also used to establish the speed profile of a highway to evaluate the speed reductions between successive tangents and curves or between successive curves. The speed-profile model based on these operating speed prediction equations has also been developed.

Table 2.1: 85th Percentile Speeds Prediction Model Forms on Horizontal Curves

Model Type	Model Form: V_{85} =
Linear	$\beta_0 + \beta_1 D$
Exponential	EXP $(\beta_0 + \beta_1 D)$
Inverse	$(\beta_0 + \beta_1 D)^{-1}$
Polynomial	$\beta_0 + \beta_i D_i$
Where: V_{85} = 85th percentile speed (km/h) β_i = regression coefficient for D to the *i*th power D = degree of curvature	

Table 2.2: Fitzpatrick et al. Equations for 3D Operating Speed Prediction

No.	Alignment Condition	Equation	R^2
1	Horizontal curve on grade: $-9\% \leq G < -4\%$	$V_{85} = 102.10 - \frac{3077.13}{R}$	0.58
2	Horizontal curve on grade: $-4\% \leq G < 0\%$	$V_{85} = 105.98 - \frac{3709.90}{R}$	0.76
3	Horizontal curve on grade: $0\% \leq G < 4\%$	$V_{85} = 104.82 - \frac{3574.51}{R}$	0.76
4	Horizontal curve on grade: $4\% \leq G < 9\%$	$V_{85} = 96.91 - \frac{2752.19}{R}$	0.53
5	Horizontal curve combined with sag vertical curve	$V_{85} = 105.32 - \frac{3438.19}{R}$	0.92
6	Horizontal curve combined with non limited sight distance crest vertical curve	(See note 1)	n/a
7	Horizontal curve combined with limited sight distance crest vertical curve (i.e., $K \leq 43$m/%)	$V_{85} = 103.24 - \frac{3576.51}{R}$ (See note 2)	0.74
8	Sag vertical curve on horizontal tangent	V_{85} = assumed desired speed	n/a
9	Vertical crest curve with non limited sight distance (i.e., K > 43 m/% on horizontal tangent	V_{85} = assumed desired speed	n/a
10	Vertical crest curve wit limited sight distance (i.e., K > 43 m/%) on horizontal tangent	$V_{85} = 105.08 - \frac{149.69}{K}$	0.60
Note	Where: V_{85} = 85th percentile speed of passenger cars (km/hr), K = rate of vertical curvature, P = radius of curvature (m), and G = grade (%). 1. Use lowest speed of the speeds predicted from Eq. 1 or 2 (for the upgrade) and Eq. 3 or 4 (for the downgrade). 2. In addition, check the speeds predicted from Eq. 1 or 2 (for the upgrade) and Eq. 3 or 4 (for the downgrade) and use the lowest speed. This will ensure that the speed predicted along the combined curve crest vertical curve results in a higher speed).		

In addition to the above models, Gibreel et al. (2001) developed operating speed prediction models for 3D alignments based on the consideration of five different points on the 3D combined curves. These models fall into two types (these models are called Gibreel et al. models when quoted hereinafter). The first type can be expressed in the following form:

$$V_s(i) = f(r, L_v, L_o, G_1, G_2, A, E, K,) \qquad [2.15]$$

The second type is in the following form (used when V_1 is known):

$$V_s(i) = f(V_1, L_o, G_2, A, E,) \qquad [2.16]$$

where $V_s(i)$ = predicted 85th percentile speed at point i (km/h), r = radius of horizontal curve (m), L_V = length of vertical curve (m), E = superelevation rate (percent), A = algebraic difference in grades (percent), K = rate of vertical curvature (m), G_1 and G_2 = first and second grades in the direction of travel in percent, L_0 = horizontal distance between point of vertical intersection and point of horizontal intersection (m), V_1 = measured 85th percentile speed at point 1 (km/h).

In these models, the coefficient of every variable is different in different cases (including different points, different combination of curves such as sag vertical curve with horizontal curve or crest vertical curve with horizontal curve).

2.2.2 Speed-Profile Models for Operating Speed Consistency

Speed-profile models have been considered as an efficient way of the operating speed prediction for two-lane rural highways because they can predict the operating speeds on the tangents more reasonably by tracing the operating speed changes on them. TAC (1999a) recommended a speed-profile model developed by Krammes et al. (1993), which classifies all the tangents in horizontal alignments by introducing a concept of "Critical Tangent Length" (TL_c). The TL_c is calculated based on the following equation (TAC 1999a, Krammes et al. 1993):

$$TL_c = \frac{2V_f^2 - V_{851}^{\ 2} - V_{852}^{\ 2}}{25.92a} \qquad [2.17]$$

The variables in Eq. 2.17 are defined in Table 2.3. In this equation, the acceleration and deceleration rate are assumed constantly to be 0.85 m/s^2. This value was originally given by Lamm et al. (1988b) and adopted for the speed-profile model without validation. According to the critical tangent length calculated with the above equation, every tangent is then classified as one of the three cases shown in Figure 2.1. To construct the speed profile for every case, the corresponding equations in Table 2.3 can be used.

Research on seeking a good speed-profile model for design consistency evaluation has never stopped. Based on the 3D operating speed prediction models (Table 2.2), Fitzpatrick et al. (1999) established another more refined speed-profile model (these models are called Fitzpatrick et al. speed-profile model when quoted hereinafter) to simulate the operating speed change along 3D alignments of two-lane rural highways. To build this speed-profile model, they used speed prediction equations to calculate the expected speed at horizontal, vertical, or combination curves, assumed desired speed for the roadway, TWOPAS equations to determine the performance-limited speeds at every point, acceleration and deceleration rates. Based on the studies conducted on 21 horizontal curves, they explored the acceleration and deceleration rates, which are then inputted into the equations in Table 2.4 to establish the speed profile for a highway. The different speed profile cases identified by the speed-profile model are shown in Figure 2.2 and the procedure of estimating the speed profile is shown in Figure 2.3.

It should be noted that for Case B in Figure 2.2, V_a should be computed by the following equation (Easa 2003):

$$V_a = \{V_n^2 + 25.92\ [ad/(a+d)]\ (LSC_a - X_{cd})\}^{1/2} \qquad [2.18]$$

According to this equation, the equation for ΔV_a calculation in Table 2.4 should be:

$$\Delta V_a = \{V_n^2 + 25.92\ [ad/(a+d)]\ (LSC_a - X_{cd})\}^{1/2} - V_n \qquad [2.19]$$

The new version of TAC's design consistency chapter has included this speed-profile model, where the definition of segments on which speed changes occur is refined (Easa 2003a). Figure 2.4 shows the definition of speed change sections. In this figure, LSD = Limited Sight Distance, NLSD = None Limited Sight Distance, TL_n = Tangent n, and R_n = Radius of curve n. According to this definition, the sections should be considered with speed changes are tangents (horizontal tangent combined with vertical tangent) and horizontal tangents combined with NLSD vertical curves (sag curve and crest curve with none limited sight distance). Moreover, Easa (2003a) also suggested that the acceleration and deceleration rates should remain constant at 0.54 m/s^2 and 1 m/s^2 respectively.

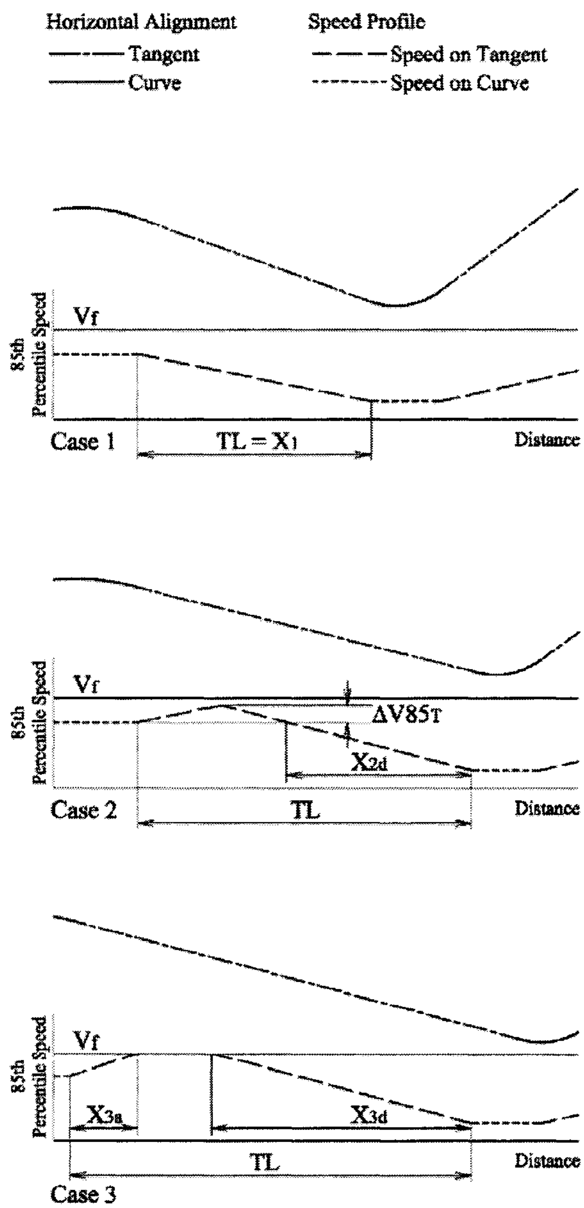


Figure 2.1: Original Speed-Profile Model
(Krammes et al. 1993)

Table 2.3: Equations for Constructing 85th Percentile Speed Profile
(TAC 1999a, Krammes et al. 1993)

Case	Condition	Equation	V_f Reached?
1	$TL = X_1$	$X_1 = \frac{V_{851}^2 - V_{852}^2}{25.92a}$	No
2.1	$TL < TL_c$	$X_{2d} = \frac{V_{851}^2 - V_{852}^2}{25.92a}$ $Max(V_{85})^*_{Tan} = V_{851} + \Delta V_{85Tan}$ $\Delta V_{85Tan} = \frac{-2V_{851} + \left[4V_{851}^2 + 44.06(TL - X_{2d})\right]^{1/2}}{2}$ Note that when calculating $Max(V_{85})_{Tan}$ the curve with the greater radius must be selected.	No
2.2	$TL = TL_c$	$X_{2a} = X_{3a} = \frac{V_f^2 - V_{851}^2}{25.92a}$ mean speed reduction (km/h)	Yes, reached but not sustained
3	$TL > TL_c$	$X_{3d} = \frac{V_1^2 - V_{852}^2}{25.92a}$ $X_{3a} = \frac{V_1^2 - V_{852}^2}{25.92a}$	Yes, reached and sustained

Where:

X1(a,d)	=	
		distance traveled for case 1 during acceleration (a) or deceleration
V_{85n}	=	(d) (km/h)
ΔV_{85}	=	85th percentile speed on curve n (km/h)
a	=	difference between the 85th percentile speeds
TL	=	acceleration/deceleration rate = 0.85 m/s^2
TL_c	=	tangent length (m)
V_f	=	critical tangent length (m)
		85th percentile desired speed on long tangent (km/h)

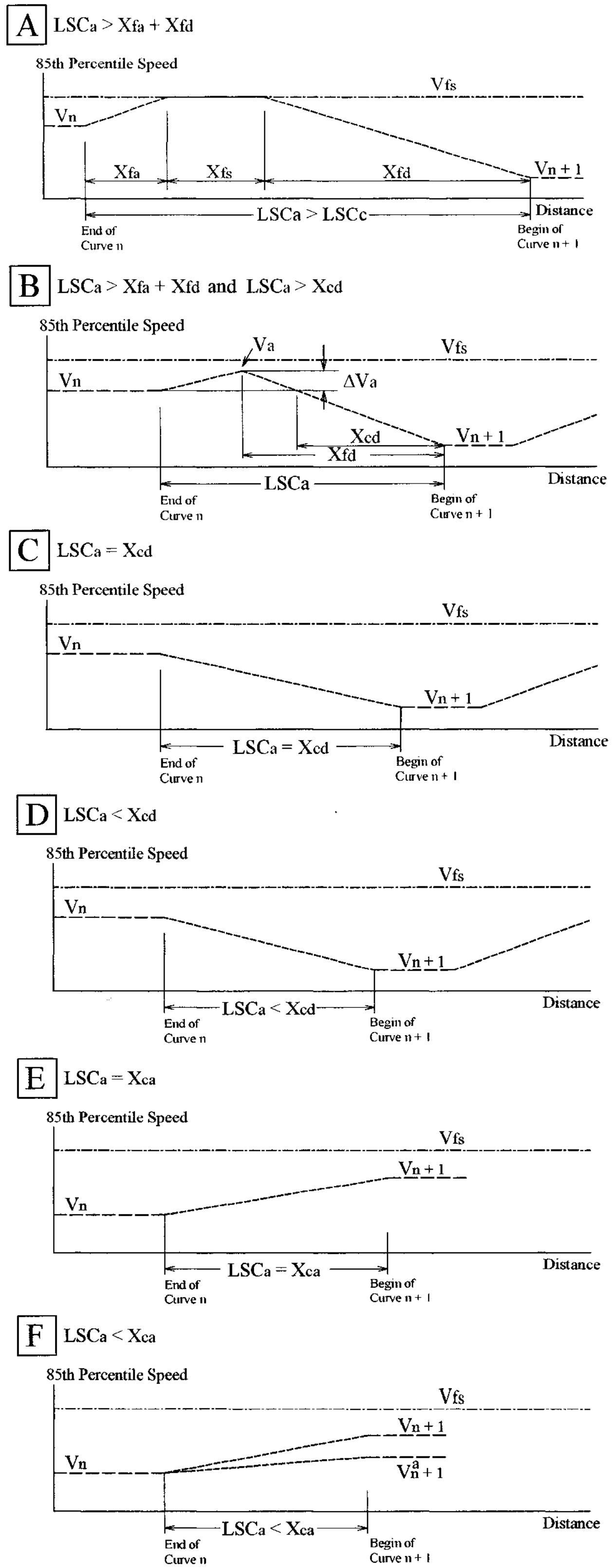


Figure 2.2: Improved Speed-Profile Model
(Fitzpatrick et al. 1999)

Table 2.4: Equations for Use in Determining Acceleration and Deceleration Distances (Fitzpatrick et al. 1999 and Easa 2003a)

$$LSC_c = X_{fa} + X_{fd} \quad (1)$$

$$X_{fd} = \frac{V_{fs}^2 - V_{n+1}^2}{25.92d} \quad (2)$$

$$X_{cd} = \frac{V_n^2 - V_{n+1}^2}{25.92d} \quad (3)$$

$$X_{ca} = \frac{V_{n+1}^2 - V_n^2}{25.92a} \quad (4)$$

$$X_{fa} = \frac{V_{fs}^2 - V_n^2}{25.92a} \quad (5)$$

$$X_{fs} = LSC_a - X_{fd} - X_{fa} \quad (6)$$

$$X_{td} = \frac{V_a^2 - V_{n+1}^2}{25.92d} \quad (7)$$

$$V_a = V_n + \Delta V_a \quad (8)$$

Note: when calculating V_a the curve with the larger radius is to be used.

$$\Delta V_a = \{V_n^2 + 25.92\,[ad/(a+d)]\,(LSC_a - X_{cd})\}^{1/2} - V_n \quad (9)$$

$$V_{n+1}^a = V_n + a(LSC_a) \quad (10)$$

Where:

V_{fs}	=	85th percentile desired speed on long tangents (m)
V_n	=	85th percentile speed on Curve_n (km/h)
V_{n+1}	=	85th percentile speed on Curve_{n+1} (km/h)
$V^a{}_{n+1}$	=	85th percentile speed on Curve_{n+1} determined as a function of the assumed acceleration rate (km/h)
V_a	=	maximum achieved speed on roadway between curves in Condition B (km/h)
ΔV_a	=	difference between speed on Curve n and the maximum achieved speed on roadway between curves in Condition B (km/h)
D	=	deceleration rate (m/s^2)
A	=	acceleration rate (m/s^2)
LSC_c	=	critical length of roadway to accommodate full acceleration and deceleration (m)
LSC_a	=	length of roadway available for speed changes (m)
X_{fd}	=	length of roadway for deceleration from desired speed to Curve_{n+1} speed (m)
X_{cd}	=	length of roadway for deceleration from Curve n speed to Curve_{n+1} speed (m)
X_{td}	=	length of roadway for deceleration from V_a to Curve n+1 speed (m)
X_{ca}	=	length of roadway for acceleration from Curve n speed to Curve_{n+1} speed (m)
X_{fa}	=	length of roadway for acceleration from Curve n speed to desired speed (m)
X_{fs}	=	length of roadway between two speed-limited curves at desired speed (m)

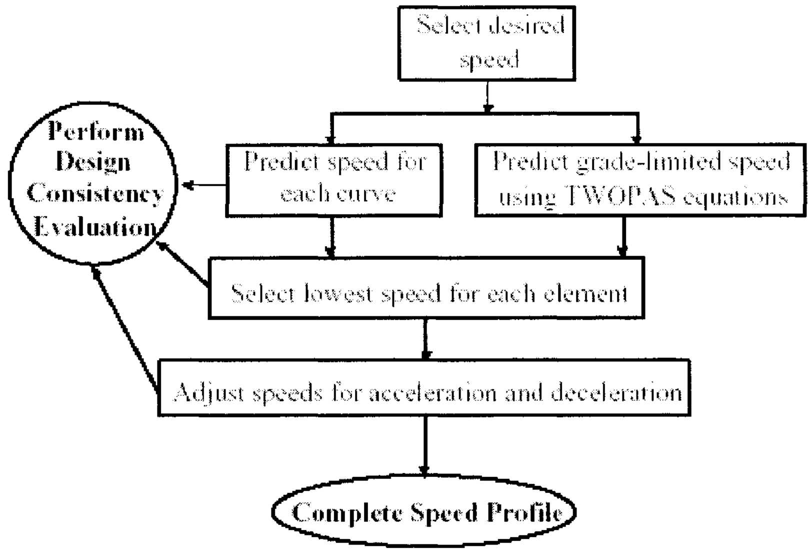


Figure 2.3: Speed-Profile Model Flowchart
(Fitzpatrick et al. 1999)

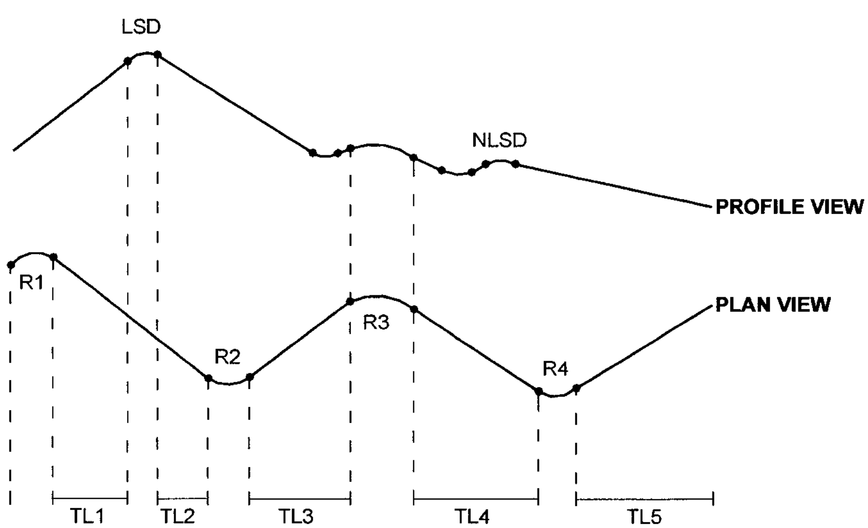


Figure 2.4: Definition of Speed-Change Segment
(Easa 2003a)

2.3 Operating Speed Consistency Evaluation Software

2.3.1 Overview

Extensive studies during the past few decades have resulted in various consistency measures and operating speed prediction models for considerations of such factors as driver workload, operating speed, and vehicle stability, etc. While being a great achievement, it also makes the evaluation of a highway's design consistency level more complicated. To solve this conflict, practical approaches to evaluate highway design consistency have been sought and some methodologies have been already published.

Current highway consistency evaluation methodologies include standard recommendations for practical evaluation procedures and software-based evaluation approaches. For the former, researchers tried to establish standard evaluation procedures and emphasized on the relationship between various consistency considerations. For the latter, designers examined the possibility of making computer software to automate the consistency evaluation procedure in order to make consistency concept more easily applied in roadway geometric design procedures.

Although the highway design consistency examination has not been widely applied into highway geometric design projects (Faghri and Harbeson 2000), some highway design consistency evaluation software programs have been developed and reported. In this section, some of them are introduced to provide the status of the development of consistency evaluation software.

Krammes et al. (1995) presented a menu-driven microcomputer software program developed for highway design consistency evaluation. This could be the beginning of automation of the consistency evaluation procedure. The program suggests the design consistency level on two-lane rural highways based on two aspects: driver workload and operating speed. Consequently, it uses two preliminary models because these two models have the same modest data requirements: the stationing of the point of curvature (PC) and the point of tangency (PT) of each horizontal curve along an alignment and each curve's radius or degree of curvature. The operating speed model used in the program is the speed-profile model developed by Ottesen and Krammes (1994) and the operating speed (V_{85}) for this model was predicted by the following equation:

$$V_{85} = 102.45 - 1.54D + 0.0037L - 0.10I \qquad [2.20]$$

where D = degree of curvature (degrees), L = length of curve (m), and I = deflection angle (degrees).

2.3.2 Interactive Highway Safety Design Model

Among the highway design consistency evaluation tools, the Interactive Highway Safety Design Model (IHSDM) is believed as the most professional one. Here is a brief introduction of this software.

IHSDM is a product of the Federal Highway Administration's (FHWA) Safety Research and Development Program. It's a suite of software analysis tools for explicit, quantitative evaluation of safety and operational effects of geometric design decisions during the highway design process. IHSDM checks designs of two-lane rural highways against relevant design policy values, estimate the crash frequency expected for a specified geometric design, and estimate other safety and operational performance measures (e.g. 85th percentile speed and percent time spent following) that help diagnose factors that contribute to expected safety performance. There are five modules in IHSDM:

- Policy Review Module (PRM) - The Policy Review Module checks a design relative to the range of values for critical dimensions recommended in AASHTO design policy.
- Crash Prediction Module (CPM) - The Crash Prediction Module provides estimates of expected crash frequency and severity.
- Design Consistency Module (DCM) - The Design Consistency Module estimates expected operating speeds and measures of operating-speed consistency.
- Intersection Review Module (IRM) - The Intersection Review Module leads users through a systematic review of intersection design elements relative to their likely safety and operational performance.
- Traffic Analysis Module (TAM) - The Traffic Analysis Module estimates measures of traffic operations used in highway capacity and quality of service evaluations.

Design consistency evaluation module helps diagnose safety concerns at horizontal curves by providing estimates of the magnitude of potential speed inconsistencies. Design consistency evaluations provide valuable information for diagnosing potential safety issues on existing highways. These evaluations also provide quality-assurance checks for both preliminary and final alignment designs. The Design

Consistency Module in the latest IHSDM, to be released in 2003, will employ Fitzpatrick et al. speed-profile model that estimates 85th percentile speeds on every element along an alignment. By applying this speed-profile model, IHSDM's consistency module can allow highway designers to estimate the impacts of horizontal curve radius and vertical grades/curvature on free-flowing passenger vehicle speeds along a two-lane highway.

In order to run the Design Consistency Module, the following data must be provided:

- Station limits for the check,
- Horizontal alignment data (begin/end tangents, begin/end of curves and curve radii),
- Vertical alignment data (tangent grades, vertical curves: begin/end, VPI, sag or crest),
- Design Speed,
- Desired Speed.

After the data collection, the Design Consistency Module creates a graph and an analysis report to show the results of the design consistency evaluation.

The DCM Graph shows results of the evaluation on the speed profile along with various geometric characteristics of the alignment analyzed. An estimated 85th percentile speed profile can be displayed for either direction of travel (increasing or decreasing stations). In addition, the user has options to display the following plots: intersections, vertical profile, K-value, horizontal curve radius, and estimated 85th percentile speed profile.

The DCM Analysis Report contains both graphical and tabular summaries of the DCM results. The graphs generated in the report will show the estimated 85th percentile operating speed profile, consistency measures and geometric characteristics for the analysis section. Tabular output provided in the DCM Analysis Report includes the following:

- V_{85} Speed Profile Coordinates: lists the coordinates denoted by a station and a predicted speed at places where the slope of the speed profile changes.
- Design Speed Assumption (Design Speed vs. Operating Speed) Check Results: illustrates the locations where a specified condition exists.
- Speed Differential of Adjacent Design Elements Check Results: compares the 85th percentile speeds between adjacent elements and specifies the condition.

In summary, IHSDM's DCM is a well-developed tool for evaluating highway operating speed consistency. However, it still has limitations. An obvious limitation is that the results of this program are presented only in 2D form. In addition, the graphs generated by the module are separated from the corresponding geometric characteristics. As a result, to identify the alignment information of some sections on the graphs, the users have to locate the sections' information manually from the original data. Hence, there is a need for the improvement of the presentational analysis function, such as the application of 3D graphic tools. There is also a need for establishing some kind of dynamic connection between graphical results and the corresponding alignment characteristics.

Chapter 3

GIS SOFTWARE USED FOR THESIS RESEARCH

With the rapid development of the modern scientific subject - GIS, many streams of GIS systems have been developed to support this practical and widely-applied technology. The most updated GIS system, ArcGIS system developed by Environmental Systems Research Institute (ESRI), is a well-developed and relatively full-functional GIS system. While retaining all functions of ESRI's former products such as ArcView and ArcInfo, which have earned wide reputation in GIS professionals, ArcGIS system has been developed with many new features and functions that make it a leading GIS software system. In this thesis research, ArcGIS is selected as the primary tool to provide the GIS platform and technical support for the development of the 3D GIS-based highway consistency evaluation methodology. Here is a general introduction of the ArcGIS system and its components.

3.1 ArcGIS System and ArcGIS Customization

3.1.1 ArcGIS System

The basic of the 3D GIS-based highway design consistency evaluation methodology is provided by ESRI's ArcGIS system. The components (functions) of the ArcGIS system include ArcGIS desktop, 3D Analyst, and ArcGIS Customization. They worked together to provide this methodology with the supporting platform to facilitate the analysis procedure of highway design consistency evaluation.

The ArcGIS system is an integrated GIS consisting of three key parts (Figure 3.1) (ESRI 2001): ArcGIS Desktop which is an integrated suite of advanced GIS tools, ArcSDE gateway which is an interface for managing geodatabases in a database management system (DBMS), and ArcIMS which is an internet-based GIS for distributing data and services and allows users to centrally build and deliver a wide range of GIS maps, data, and applications through media such as local area network (LAN) or World Wide Web (WWW).

ArcGIS provides a framework for implementing GIS for a single user or for many users. It has been developed as a scalable system with parts that can be deployed on a single desktop or distributed on a heterogeneous computer network of workstations and servers. Users can deploy various parts of this system to implement a GIS of different sizes —from a single user system to workgroups and departments, for large enterprises, and for societal GIS systems. Consequently, the works done by single user could be easily shared with other workgroups with different sizes or through the Internet with the users from all over the world provided that the proper ArcGIS system's components are used.

To develop the highway design consistency evaluation methodology reported here, the personal ArcGIS system contributed significantly. The structure and components of a personal ArcGIS system is shown in Figure 3.2. The ArcGIS includes a suite of integrated applications: ArcMap, ArcCatalog, and ArcToolbox. While working separately to meet different levels of user requirements, these applications are also designed to work together to realize ArcGIS's powerful functions.

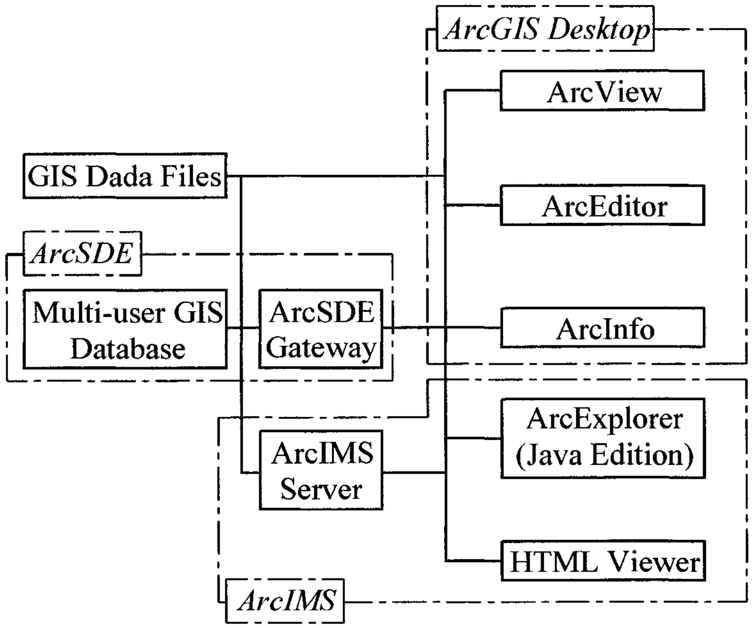


Figure 3.1: ArcGIS System Structure

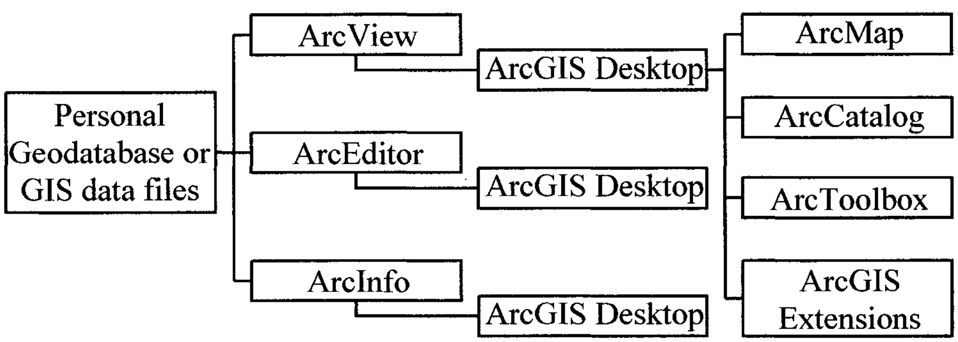


Figure 3.2: Personal ArcGIS System

ArcMap is the central application in the ArcGIS Desktop. It is one of ArcGIS' components used for many map-based tasks including cartography, map analysis, and editing. It plays the key role in the highway design consistency methodology by providing the platform for user-oriented ArcGIS customization and 3D graphing and analysis. ArcMap allows users to visualize geo-data in a straightforward way, to create map to spatially display data, to analyze the spatial relationships of geo-data, to present study results impressively, and to add customized tools to make it work in a more efficient manner.

ArcCatalog helps to organize and manage user's GIS data. It allows locating, previewing and manipulating the GIS data files in GIS databases. In addition, it gives users permissions to create and edit personal geodatabases or files in the existing personal geodatabases. ArcToolbox is a cluster of many GIS tools used for geoprocessing. There are two versions of ArcToolbox: the complete ArcToolbox that comes with ArcInfo and a lighter version that comes with ArcView and ArcEditor software.

With the same style, ArcGIS desktop can be used in three different forms, or, in other words, it can be accessed using three software products, each providing a higher level of functionality. These three software products are: ArcView (8.1), ArcEditor, and ArcInfo. ArcView provides comprehensive mapping and analysis tools along with simple editing and geoprocessing tools. It has been developed and proved as a powerful toolkit for mapping, reporting, and map-based analysis.

ArcEditor contains all the capabilities of ArcView 8.1. Plus, it adds schema management capabilities for all geodatabase models in ArcCatalog and advanced geodatabase and coverage editing in ArcMap. When users have access to a DBMS via ArcSDE, multi-user geodatabases can be edited and maintained with complete version management in ArcEditor. This includes advanced tools for version management, for example, version merging tools to identify and resolve conflicts.

ArcInfo is a system for GIS data creation, update, query, mapping, and analysis. It provides all the capabilities of ArcView 8.1 and ArcEditor. Furthermore, it also includes the complete ArcToolbox that supports advanced geoprocessing and polygon processing as well as the classical workstation applications and capabilities that are built for the proficient GIS users.

In addition, the capabilities of all three levels can be further extended using a series of optional add-on software extensions such as ArcGIS 3D Analyst. The optional extensions of ArcGIS will be introduced briefly in the latter section.

3.1.2 ArcGIS Customization

For most powerful software tools, one of the overriding principles is always extensibility. The fulfillment of this goal will make the power of the software only limited by users' imagine. ESRI's ArcGIS uses its strong customization function to realize its extensibility so to meet the requirements of different kinds of user groups. The basic of the ArcGIS customization is ArcObjects, which is the development platform of ArcGIS desktop.

ArcObjects is a framework that lets users create application-oriented tools. The ArcObjects components collaborate to serve every data management and map presentation function common to most GIS applications (Waltuch et al. 2001). ArcObjects provides an infrastructure for application customization that lets users change the interface of ArcGIS and add the customized tools developed specifically for individual projects. ArcObjects is built using Microsoft's Component Object Model (COM) technology. Therefore, it is possible to extend ArcObjects by writing COM components using any COM-compliant development language. Users may extend every part of the ArcObjects architecture in exactly the same way as ESRI developers do.

ArcObjects allows developers to use some COM programming languages such as Visual Basic and Microsoft Visual C^{++}. However, the most common way that developers will customize the ArcGIS Desktop applications is through Visual Basic for Applications (VBA), which is embedded within ArcCatalog and ArcMap. In the VBA development environment users can add modules, class modules, and user forms to the default project contained in every ArcGIS application document. A project can sometimes consist of many modules.

VBA makes it possible to change the application framework that already exists in ArcMap and ArcCatalog for general data management and map presentation tasks and extend ArcGIS with customized commands, tools, menus, and modules. More advanced developers can further extend ArcGIS Desktop with custom map layers, renderers, property pages, and data sources. For specialized applications, developers with sufficient skill even can bypass the application framework of ArcMap and ArcCatalog and to build their own-targeted applications.

In the 3D GIS-based highway design consistency evaluation methodology developed in this study, Visual Basic for Application (VBA) was the main programming tool used for customization. Several highway design consistency evaluation tools were built to work together with some existing ArcMap and ArcScene functions to form a framework to specifically benefit the consistency study. Hence, the methodology is an extension of the existing ArcGIS desktop oriented to highway consistency evaluation.

Hopefully, it will facilitate the highway geometric design field as well as the highway geometry related safety study.

3.2 ArcView Accessed ArcGIS Desktop

As explained earlier in this chapter, the ArcGIS Desktop can be used at any of three product levels: ArcView, ArcEditor, and ArcInfo. The ArcGIS desktop accessed at ArcView level is also called ArcView 8.1. ArcView 8.1 owns most of the functions of the three products levels. In addition, it was more developed to meet the requirements of personal GIS applications. Using ArcView 8.1, users may benefit from its capabilities including metadata management and data searching with ArcCatalog, simple geodatabase editing, annotation support, on the-fly projection of features and rasters between coordinate systems, and the ability to connect to and use ArcIMS services. ArcView 8.1 can also be customized using the industry standard Visual Basic for Applications (VBA) which is included with ArcView 8.1. Considering the requirements of this thesis research and the relatively powerful GIS analysis functions including its strong user-oriented customization function, the ArcView accessed ArcGIS desktop was selected as the primary GIS software basic of the highway design consistency methodology.

3.2.1 Main Functions of ArcView 8.1

ArcView 8.1 provides mapping and analysis tools along with editing and geoprocessing tools. Its functions cover many sub-fields in GIS technology. These fields include: data support, cartography, map analysis, GIS data management, editing, geoprocessing, and self-development.

- *Data support*

  ArcView 8.1 supports various data formats. It can work with: (1) shapefiles, coverages, geodatabases, and ArcIMS services, (2) geography network, (3) any database management system (DBMS), and (4) many table formats and many raster formats.

- *Cartography*

  ArcView 8.1 has strong capabilities on both advanced mapping and query and map authoring. Besides, it provides users with many map templates and different kinds of symbols and styles to make mapping easier and more professional.

- *Map analysis*

  ArcView 8.1 provides the abilities to make advanced map analysis, report writing, charting and business graphics.

- *GIS data management*

  ArcView 8.1 have been developed with many advanced GIS data management functions such as new ArcCatalog application for GIS data management, schema management for shapefiles, and metadata creation and management.

- *Editing*

  ArcView 8.1 allows users to create and edit shapefiles and personal geodatabases to meet the users' requirements for simple project-oriented personal database creating and editing.

- Geoprocessing

  Geoprocessing is defined as the creation or modification of data, which is typically spatial in nature, by a function that has one or more parameters. In this manner, geoprocessing functions include analysis functions (overlay, buffer, slope), data management functions (add field, copy, rename), and data conversion functions. Using ArcView 8.1, users can perform simple geoprocessing and data conversion, create shapefiles and personal geodatabases, and load shapefile data into personal geodatabases.

- *Self-development*

  ArcView 8.1 provides advanced ArcObjects COM library and it allows advanced self-development functions such as customization with VBA.

3.2.2 Capabilities of ArcView 8.1

In this section, the capabilities in the ArcGIS desktop accessed at ArcView level (ArcView 8.1) are described summarily. By offering this introduction, a thorough understanding of ArcGIS desktop at ArcView level will be provided.

As known, ArcView 8.1 offers users various capabilities to deal with spatial or spatially related data. Summarily, an overview of ArcView's capabilities is presented as follows:

- Map interaction: including panning and zooming, identifying, hot link/hyperlink to external application, macro, or URL, Interactive Selection tool, map tips, magnification and overview windows, spatial bookmarks, and dynamically updated selections between maps, tables, and graphs.
- Map creation: including data display (multi-layer data transparency and on-the-fly projection of features and rasters between coordinate systems, including datum transformation), data classification, symbology, labeling, and layout and printing

(inserting objects such as titles and legends, multiple data frames, wizards and predefined styles for constructing legends and neatlines, graphic export, and so on).

- Map analysis: including selection operations (interactive selection, select by attribute, select by location, and so on), analysis operations (buffer, clip, merge, intersect, union and spatial join), visualization and analysis (graphs and reports)
- Data creation: including editing shapefiles and simple personal geodatabases, rectification of images, rotating and flipping images, feature construction and editing, snapping, digitizer tablet support, geocoding and events, and dynamic segmentation.
- Data management: including importing ArcView GIS 3.x ".apr" and ".avl" files, data support tools (creating new data files, exporting and importing data, direct support of many data formats, and so on), tabular data management, metadata viewing and editing, and data search in ArcCatalog.
- Application framework: including standard Microsoft Windows look and feel, dockable toolbars, full international support for data and attributes, customizable interface, extensible functionality using COM and COM-compliant languages, creating macros using VBA, and inserting OLE objects inside ArcMap.

3.3 ArcGIS Desktop Extensions

3.3.1 Overview

Extension software is always a form for the functional extension of many outstanding software programs. Similarly, ArcGIS desktop has also several optional extensions to functionally extend itself to meet specific requirements for different user groups. Seven optional ArcGIS extensions are available currently and they can be used by each product: ArcView, ArcEditor, and ArcInfo. These extensions include:

- *ArcGIS Spatial Analyst*

  ArcGIS Spatial Analyst provides a broad range of spatial modeling and analysis features that allow users to create, query, map, and analyze vector data and cell-based raster data. Through these functions, users can derive data information, identify spatial relationships, find suitable locations, and calculate the accumulated cost of traveling from one point to another.

- *ArcGIS 3D Analyst*

  3D Analyst enables users to effectively visualize and analyze surface data. Using 3D Analyst, users can view a surface from multiple viewpoints, query a surface, determine what is visible from a chosen location on a surface, and create a realistic perspective image draping raster and vector data over a surface. The core of the 3D Analyst extension is the ArcScene application. ArcScene provides the interface for viewing multiple layers of three-dimensional data and for creating and analyzing surfaces. 3D Analyst also provides advanced GIS tools for 3D modeling such as cut–fill, line of sight, and terrain modeling.

- *ArcGIS Geostatistical Analyst*

  The power of Geostatistical Analyst lies in its ability to create a continuous surface from sparse measurements taken at sample points. It can be used to reliably predict values for surfaces using kriging. In addition, Geostatistical Analyst also includes tools for statistical error, threshold, and probability modeling.

- *ArcGIS StreetMap USA*

The ArcGIS StreetMap extension provides street-level mapping and address matching for the entire United States.

- *ArcPress for ArcGIS*

  ArcPress is the map printing extension for ArcView, ArcEditor, and ArcInfo. The role of ArcPress in a GIS environment is to render high-quality maps on a printer quickly, without requiring the addition of extra onboard memory or hardware. Instead, ArcPress turns a computer into a print processor, allowing the printer to print continuously without the need for expensive hardware upgrades.

- *MrSID Encoder for ArcGIS*

  MrSID is a high-quality, high-performance compression methodology for reducing the size of very large images. The MrSID Encoder extension provides the ability to use ArcToolbox to compress and mosaic images from 50 up to 500 MB in size (Images smaller than 50 MB can be encoded without this extension).

- *TIFF/LZW compression*

  TIFF/LZW extends ArcGIS desktop with strong image compression function.

3.3.2 ArcGIS 3D Analyst

ArcGIS 3D Analyst provides the 3D-GIS-visualization-based data analysis support for the development of the 3D GIS-based highway design consistency evaluation methodology in the thesis research. ArcGIS 3D Analyst merges itself into ArcGIS desktop by the form of providing 3D spatial data analysis and presentation functions in ArcMap and 3D spatial data exploring functions in ArcCatalog. Meanwhile, it also adds a separate component named ArcScene to ArcGIS, which provides the interface for viewing multiple layers of 3D data for visualizing data, creating surfaces, and analyzing surfaces. This generic surface-modeling package is ideal for both the novice and the advanced users, its functionality answers the needs of those performing tasks related to surface analysis and display. There are mainly four functions in ArcGIS 3D Analyst. They are:

- *Create and display scientific data in 3D form*

  Like lots of 3D GIS visualization software, 3D Analyst allows the visualization of many kinds of scientific data that are spatially related. Such data could be population (density), all kinds of process, rainfalls and so on. Figure 3.3 is a 3D graph generated for population density analysis.

- *Create and edit shapefiles*

  ArcGIS 3D Analyst displays and creates 3D shape files as well. It adds z value to 2D map to extrude objects such as lines and polygons (Figure 3.4). An ordinary shapefile stores x, y coordinates that define the position of features in planar space. A 3D shapefile stores z value as well to locate features in three-dimensional space. Z values could come from any continuous attribute of an object such as the number of stories for the visualization of a building.

- *Create and edit TIN data*

  A unique feature of ArcGIS 3D Analyst is its support for the editing and creating of Triangulated Irregular Networks (TINs) data (Figure 3.5). TINs model continuous surfaces with vector data. They represent a surface with an arrangement of continuous, nonoverlapping triangles. Unlike a grid, a TIN is a variable-resolution model. Where the sample data is dense, the surface is detailed and where the data is sparse, the surface is simpler (Ormsby 2001).

- *Analyze spatial information*

  Actually, ArcGIS 3D Analyst does much more then simply manipulating 3D data. It analyzes spatial information as well. For example, use the "Deepest Way" tool, 3D Analyst could find the stream paths from the stream source without knowing the real streams (Figure 3.6).

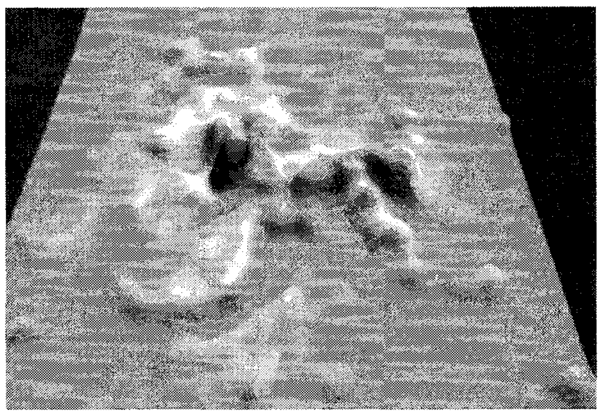


Figure 3.3: Population Density Around Minneapolis-St. Paul, Minnesota. (Peaks show concentrations of population. Source: Extending ArcView GIS)

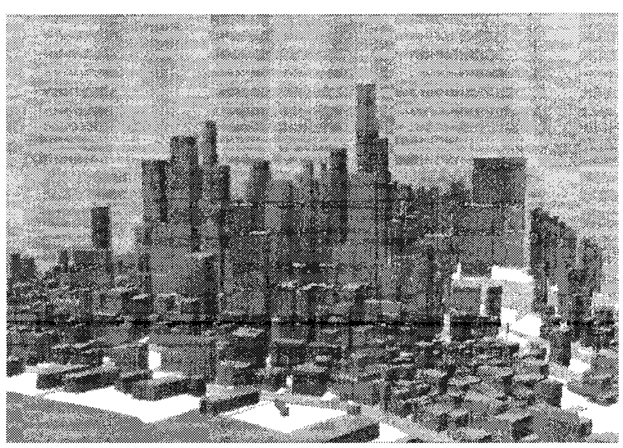


Figure 3.4: View of Downtown Seattle, Washington (Source: Extending ArcView GIS)

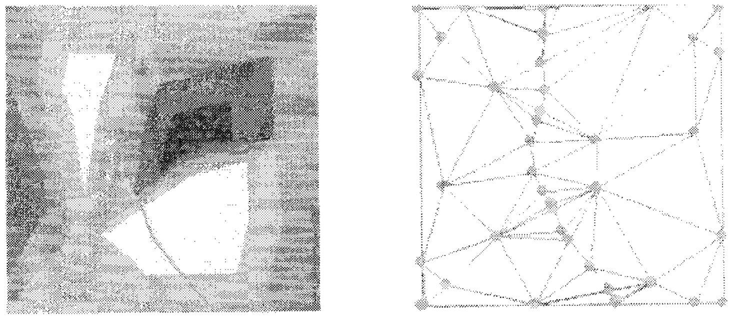


Figure 3.5: Triangulated Irregular Network (TIN) Data Form
(Source: Extending ArcView GIS)
(On the left, a free line representing a road is added to a TIN. Because triangles can't cross the breakline, the triangle structure is more complex than it would be otherwise. Slope and aspect values are affected. If the line feature has elevation information, this will also be incorporated into the TIN)

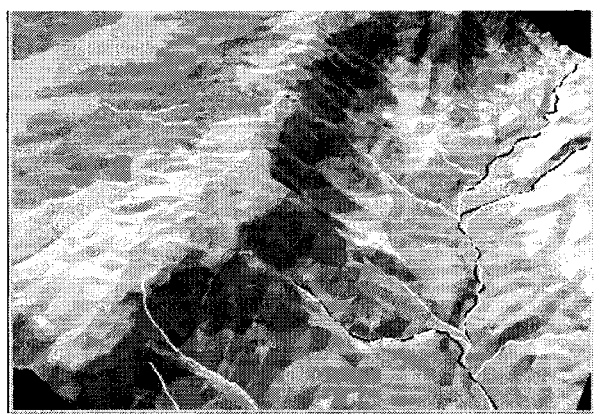


Figure 3.6: Forecasting the Stream Paths
(The green lines in the figure represent the known stream paths and the black lines are the paths forecasted by 3D Analyst. As seen from the figure, the forecasted paths almost exactly overlap with the real streams)

Chapter 4

PILOT STUDY

In this chapter, possible applications of GIS and 3D GIS visualization in highway design consistency evaluation will be explored. This step helps to determine the feasibility of further research for developing a 3D GIS-based highway design consistency methodology. For demonstration purpose, a hypothetic 3D alignment of a rural highway will be used. In addition, the two 3D operating speed prediction models mentioned in chapter 2 and two consistency evaluation criteria will be used to judge the consistency level of the fictitious alignment. The desktop GIS software, ArcGIS and its 3D Analyst extension, will be used throughout the study.

4.1 Preparation for the Exploration

4.1.1 Alignment for Exploration

The 3D alignment (Figure 4.1) used throughout the procedure in this chapter is a rural highway section with two horizontal curves and two vertical curves. It was designed according to AASHTO's "A Policy on Geometric Design of Highways and Streets" (2001). As shown in Figure 4.1, the horizontal plan contains two simple curves which are connected smoothly by a short tangent about 200m long. The parameters of these two curves are listed in Table 4.1. There are also two curves included in the profile of the alignment which shown in Figure 4.1 as well. The parameters of the vertical curves are listed in Table 4.2.

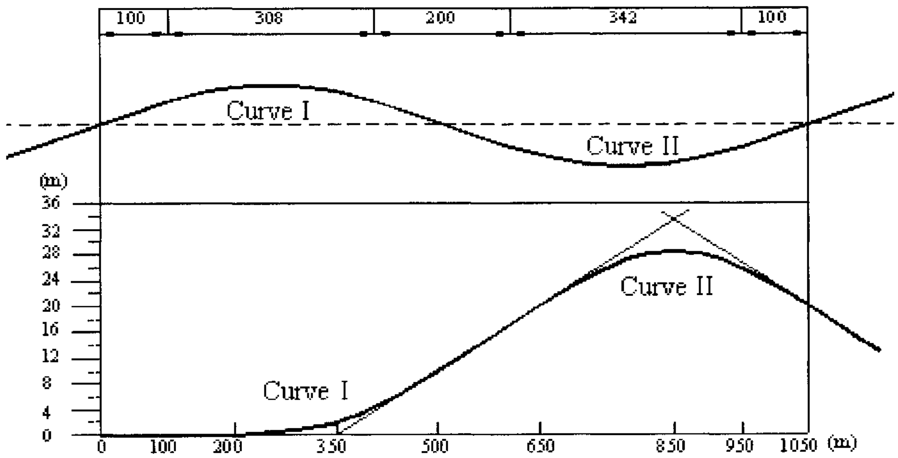


Figure 4.1: 3D curved highway alignment

Table 4.1: List of Parameters of Horizontal Curves

Parameters	R (m)	I (degree)	D (degree)
Curve I	450	40	3.881
Curve II	500	40	3.493
Note	R = Radius of curve, I = Deflection angle of curve, D = Degree of curve.		

Table 4.2: List of Parameters of Vertical Curves

Parameters	G_1 (%)	G_2 (%)	A (%)	L_v (m)	K (m)
Curve I	0	6.7	6.7	300	44.78
Curve II	6.7	-6.7	13.4	400	29.85
Note	G_1 & G_2: first and second grades in the direction of travel, A: algebraic difference in grades, L_v: length of vertical curve, K: rate of vertical curvature.				

Moreover, the superelevation rate on the horizontal curves is designed constantly and equals 6% and the design speed of the highway segment is 100 km/h or 62 m/h along the whole alignment.

Figure 4.2 shows the plan alignment of the highway segment digitized from AutoCAD in ArcMap view after being visualized together with the terrain where the alignment is assumed to be located. Figure 4.3 shows what it looks like in the perspective view. Figure 4.4 is the appearance of the alignment after its vertical dimension has been magnified five times in 3D scene where all perspectives of the highway can be explored from any angle and distance.

Figure 4.2: Plan View of the 3D Highway Alignment in GIS Form

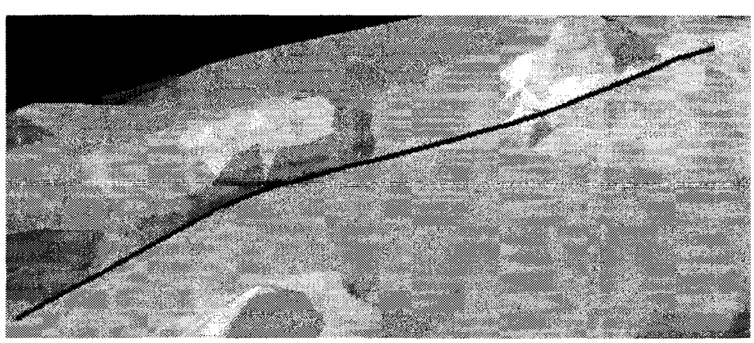


Figure 4.3: Perspective View of the Visualized 3D Highway Alignment

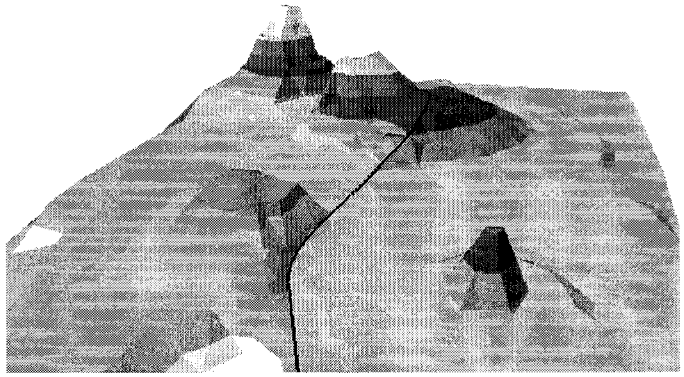


Figure 4.4: Perspective View of the 3D Alignment with Emphasis on Z Dimension

4.1.2 Highway Consistency Models and Measures

In this pilot study, two operating-speed-based consistency evaluation criteria will be used to measure the consistency level of the fictitious alignment. In addition, the two sets of 3D operating speed prediction models mentioned in chapter 2, Fitzpatrick et al. equations (see Table 2.2) and Gibreel et al. models will be used to predict operating speeds along the hypothetic 3D alignment. The criterion I and II are listed in Table 4.3:

Table 4.3: Highway Design Consistency Evaluation Criteria

Criterion I ΔV85: difference between design speed and V85.	Good designs: $\Delta V_{85} \leq$ 6mph (10 km/h) Poor design: $\Delta V_{85} >$ 12mph (20 km/h) (Lamm et al. 1988a, 1995)
Criterion II ΔV_{85}: difference between V_{85} of contiguous elements.	Good design: $\Delta V_{85} \leq$ 6mph (10 km/h), Poor design: $\Delta V_{85} >$ 12mph (20 km/h) (Lamm et al. 1995, 1999)
Where: V_{85}= 85th percentile speed	

4.2 Evaluation of Design Consistency

This study will focus on the applications of GIS and 3D GIS visualization in rural highway design consistency evaluation procedure. However, some 3D-GIS-visualization-based applications that are related to highway design consistency will also be explored. Since 3D operating speed prediction models consider the 3D natures of the analyzed highways and may more accurately reflect the design consistency status, seeking an ideal 3D GIS-integrated means for operating speed consistency evaluation for 3D alignments is the major intention for this study. As the conclusion of the pilot study, a 3D GIS-based highway design consistency evaluation approach will be recommended.

4.2.1 Predicted Operating Speeds

According to the Fitzpatrick et al. equations, the whole alignment is divided into 9 sections based on their different geometric conditions, as shown in Figure 4.5. The respective speed of each section is predicted based on its geometric condition assuming that all speeds on the tangent sections are the same as the desired speed (100 km/h) and the speeds in each driving direction are different from the other. The geometric conditions and the predicted operating speeds along the hypothetic highway section are listed in Table 4.4 where "direction I" means the driving direction from A to B (see Figure 4.5) and "direction II" means from B to A.

To analyze the prediction results, speeds are visualized with respect to locations of sections. To emphasize and clearly show the speed differences, every speed is extruded with a value of ($[V_{85}]$ - 80) x 10 km/h. This value will magnify the speed differences 10 times without making the speed profile too highway. From Figure 4.6, the distribution of speeds with respect to the alignment or varied topography is shown clearly.

Table 4.4: Predicted Speeds Using Fitzpatrick et al. Equations

Section #	Condition	R (m)	K (m/%)	Predicted V_{85} (km/h)	
				Direction I	Direction II
1	Tangent			100	100
2	Horizontal curve	450		97.74	97.74
3	Horizontal curve combined with sag vertical curve	450	44.77	97.68	97.68
4	Sag vertical curve on horizontal tangent			100	100
5	Tangent			100	100
6	Horizontal curve on grade: +-6.7%	500	29.85	91.11	95.95
7	Horizontal curve combined with non limited sight distance crest vertical curve	500	29.85	91.11	95.95
8	Horizontal curve combined with non limited sight distance crest vertical curve	500	29.85	95.95	91.11
9	Vertical crest curve with limited sight distance on horizontal tangent	500	29.85	100.07	100.07

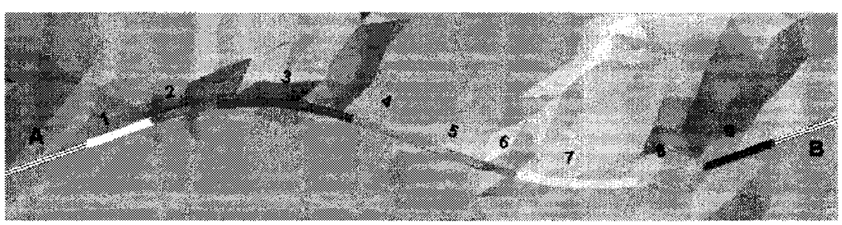


Figure 4.5: Sections Divided According to Different Conditions

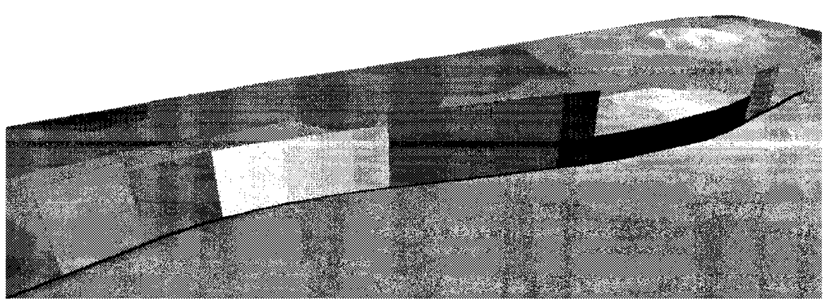


Figure 4.6: Visualized Speed Distribution with Emphasis on Differences

As seen from Figure 4.6, generally speaking, the speeds distribute relatively smoothly on different sections with different curve alignments (the maximum difference is 8.96km/h). This is mainly due to the hypothetic alignment used for the pilot study has no sharp horizontal or vertical curves and the transitions between successive elements are relatively smooth. In addition, the lowest speed is located on the alignment where horizontal curves combine with vertical curves (on uphill of the "mountain"). Furthermore, the speeds on the horizontal tangents with unlimited sight distances are not influenced by the vertical alignment, which is also in agreement with the speed prediction models.

To predict operating speeds using the models developed by Gibreel et al. (2001), the typical points are allocated along the alignment. The allocation is based on the following regulations:

1. 60-80 m on the approach tangent before the beginning of the spiral curve,
2. End of spiral curve and the beginning of horizontal curve,
3. Midpoint of horizontal curve,
4. End of horizontal curve and the beginning of spiral curve,
5. 60-80 m on the departure tangent after the end of the spiral curve.

The allocation of the points is shown in Figure 4.7 and the parameters and predicted 85th percentile speeds at the points are listed in Table 4.5 (I and II). The first table contains the operating speeds predicted based on the first horizontal curve and the second table contains the operating speeds predicted based on the second horizontal curve.

In Table 4.5: r = radius of horizontal curve, L_v = length of vertical curve, E = superelevation rate, A = algebraic difference in grades, K = rate of vertical curvature, G_1 and G_2 are first and second grades in the direction of travel in percent, L_0 = horizontal distance between point of vertical intersection and point of horizontal intersection, D_c is deflection angle of horizontal curve, direction *I* means traveling from A to B and direction *II* means traveling from B to A.

As shown in Figure 4.8, the operating speeds are also visualized with GIS visualization by extruding each test point with the value of ([Speed (Direction I)] - 90) * 10. The reason for choosing this value is that this value can magnify the differences between the operating speeds by 10 times so the differences can be analyzed better. According to the results of the Gibreel et al. models, the speeds on crest vertical curves is slightly higher then those on sag vertical curve with similar horizontal conditions. The predicted 85th percentile speeds using the Gibreel et al. models are higher than those predicted using the equations developed by Fitzpatrick et al. (1999).

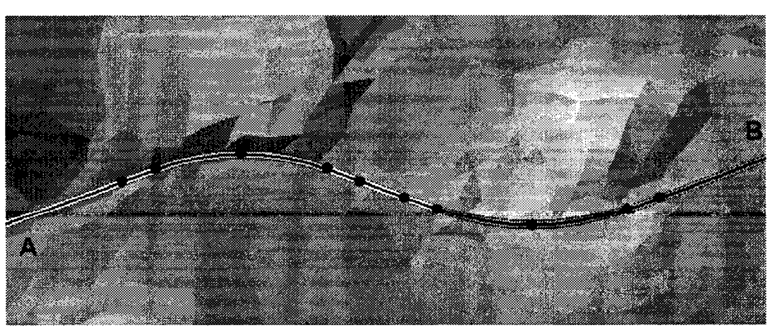


Figure 4.7: Allocation of Test Points for Gibreel et al. models

Table 4.5(I): Predicted Operating Speeds Using Gibreel et al. Models (Curve I)

	Point #	Geometric Details								Predicted V_{85} (km/h)	
		r (m)	*Lv (m)*	*E (%)*	*A (%)*	*K (m)*	*G1 (%)*	*G2 (%)*	*Lo (m)*	*Direction I*	*Direction II*
Curve I	1	450	300	6	6.7	44.776119	0	6.7	96.09	98.975022	100.7796
	2	450	300	6	6.7	44.776119	0	6.7	96.09	103.7248	105.4534
	3	450	300	6	6.7	44.776119	0	6.7	96.09	104.60877	104.60877
	4	450	300	6	6.7	44.776119	0	6.7	96.09	106.68545	109.10415
	5	450	300	0	6.7	44.776119	0	6.7	96.09	93.787558	102.20946

Table 4.5(II): Predicted Operating Speeds Using Gibreel et al. Models (Curve II)

	Point #	Geometric Details									Predicted V_{85} (km/h)	
		r (m)	*Lv (m)*	*E (%)*	*A (%)*	*K (m)*	*G1 (%)*	*G2 (%)*	*Lo (m)*	Dc	*Direction I*	*Direction II*
Curve II	1	500	400	6	13.4	29.85	6.7	-6.7	71.17	40	105.2025	105.2025
	2	500	400	6	13.4	29.85	6.7	-6.7	71.17	40	108.85257	108.85257
	3	500	400	6	13.4	29.85	6.7	-6.7	71.17	40	112.42067	112.42067
	4	500	400	6	13.4	29.85	6.7	-6.7	71.17	40	107.36762	107.36762
	5	500	400	6	13.4	29.85	6.7	-6.7	71.17	40	107.08294	107.08294

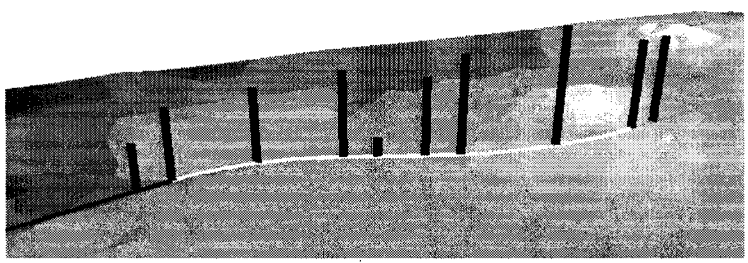


Figure 4.8: Visualized 85th Percentile Speeds Predicted Using Gibreel et al. Models

4.2.2 Evaluation of Design Consistency

Having obtained the predicted operating speeds of the alignment, the highway design consistency will be estimated with the help of GIS and 3D GIS visualization techniques. The evaluation of operating speed design consistency of the test alignment is applied based on the two criteria listed in Table 4.3.

According to the first criterion, the design consistency along the hypothetic 3D alignment is tested and the results are stored and presented with GIS. In the Figure 4.9, the consistency level of the highway alignment measured using the predicted speeds of both sets of operating speed prediction models are presented. The circles shown in Figure 4.9 are the test points based on the Gibreel et al. models. The segments are divided according to the Fitzpatrick et al. equations. The points and segments colored in red are the test sites whose consistency level is "fair design" while others (green) are those evaluated as having good consistency level.

The operating speed consistency distribution measured with the second criterion is show in Figure 4.10. In this figure, the sites with fair design consistency are represented with red circles. In this measurement, the speed differences between successive elements are analyzed. As shown from the results, the vertical alignment has significant influence on the operating speed design consistency level of the two-lane rural highway. In particular, the test points or segments that do not have good design consistency levels are mainly located on the sections where horizontal curves and vertical curves overlap.

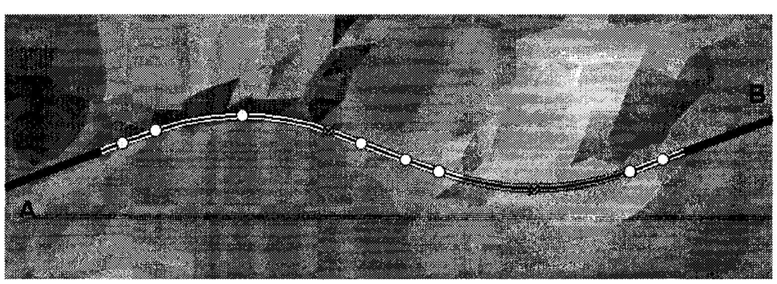


Figure 4.9: The Operating Speed Consistency Levels of the Test Alignment

In addition to graphing and presenting the evaluation results, all the data along the 3D alignment are stored and managed by the GIS. Using ArcGIS, the attribute information of all the samples can be easily checked and analyzed. For example, the results of a test point identified using the "Identify" tool is shown in Figure 4.11.

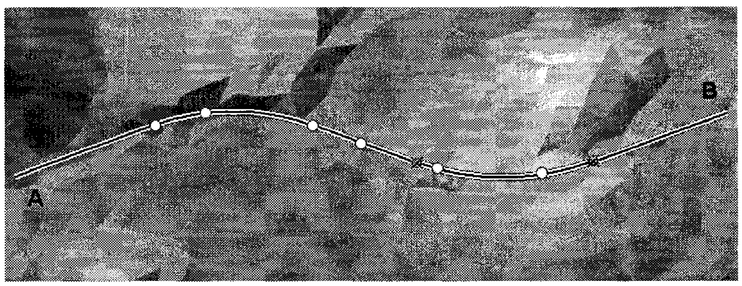


Figure 4.10: Design Consistency Evaluation Results with Criterion II

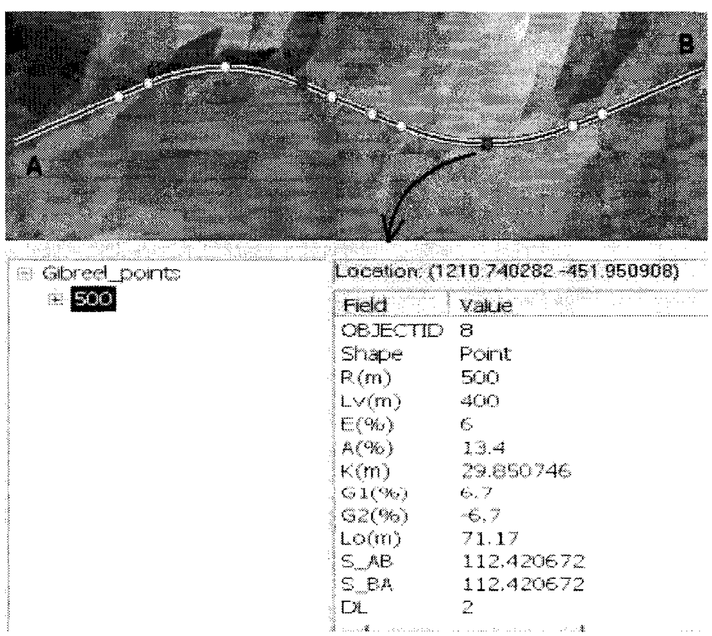


Figure 4.11: Identify Results

4.3 Other Highway Consistency Related Applications of 3D GIS Visualization

4.3.1 Determination of Sight Distances for 3D Highway Alignments

Sight distance is another important consideration in the highway design consistency evaluation procedures. Some sight distance models have been developed for 2D and 3D alignments. Designers usually compute sight distances separately and, sometimes, it takes great efforts, especially for those of 3D alignment. Fortunately, some 3D GIS visualization software such as ArcGIS with 3D Analyst has functions such as "Create Viewshed", "Create Line of Sight", and "Measure" which can measure the sight distance of 3D highway sections with simple mouse clicks.

Figure 4.12 shows the area that can be viewed from point S that is 1.05 m above ground. The area is generated by the function "Create Viewshed" in ArcGIS. Using this function, the highway sections within the sight distance can be clearly identified. Figure 4.13 shows the sight line starting from observer point S. The green sections of the sight line stand for visible areas while the red sections represent the invisible areas. It is shown in the figure that because of the "mountain" which the road winds around, the sight distance from point S is only about 190 m in the direction to A and 257 m in the direction to B.

4.3.2 Generation of Profiles for Existing 3D Highway Alignments

With help of 3D visualization techniques of GIS, highway profiles can be obtained easily. Separate design of highway profiles without the consideration of terrain effect seems unreasonable and sometimes impossible because the profiles significantly depend on the terrain where the highway will be located. This is also proved in the case study where it is shown that the profile of Highway 61 greatly depends on topography. In ArcGIS, profiles can be generated provided the horizontal view and topography data are available. Figure 4.14 contains the profile of a fictitious alignment generated in ArcGIS. Therefore, tools may be developed to generate the detailed geometric data of vertical elements of the profile to facilitate geometrically related highway studies such as consistency evaluation. A profile generation software program has also been developed as a product of this research.

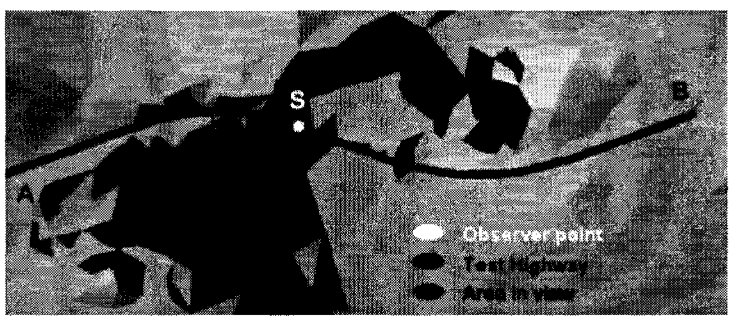


Figure 4.12: Area Viewed from Point S

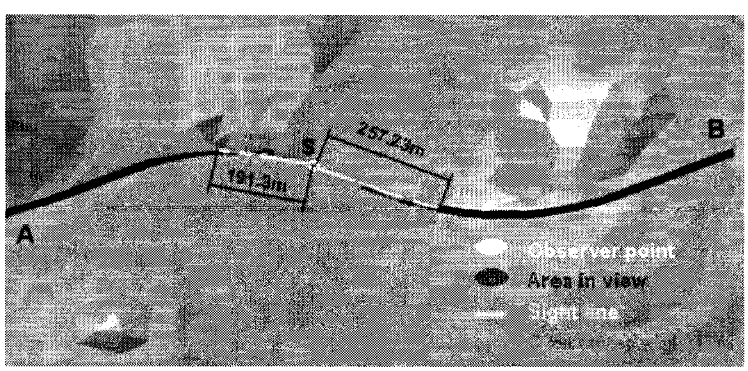


Figure 4.13: Measurement of Sight Distance from Point S

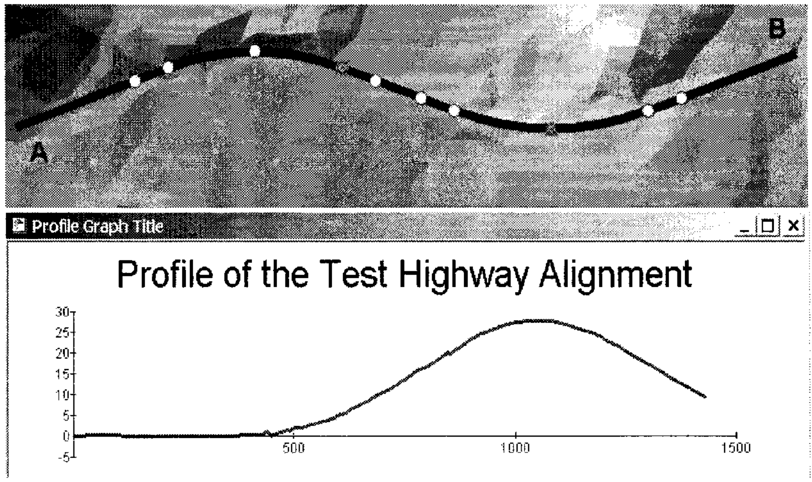


Figure 4.14: Profile of the Hypothetic Alignment Generated in ArcGIS (in meter)

Figure 4.15 shows the interface of the profile analysis program. Using this program, lots of information, such as functions for vertical tangents and vertical curves, locations of intersection points between successive vertical elements, and parameters such as grades and K-Value, can be easily generated. The analysis of the results generated by this program shows that the average error of this program is lower than 6% in most cases.

With this program, 3D highway design consistency analysis for both newly designed highways and existing highways may become much easier. Furthermore, with the detailed GIS format terrain model, the design of a real 3D highway will be simplified to be the design of its horizontal alignment on a computer screen. This is particularly meaningful provided that the 3D elevation data can be obtained directly from spaceborne or airborne sensors such as satellites.

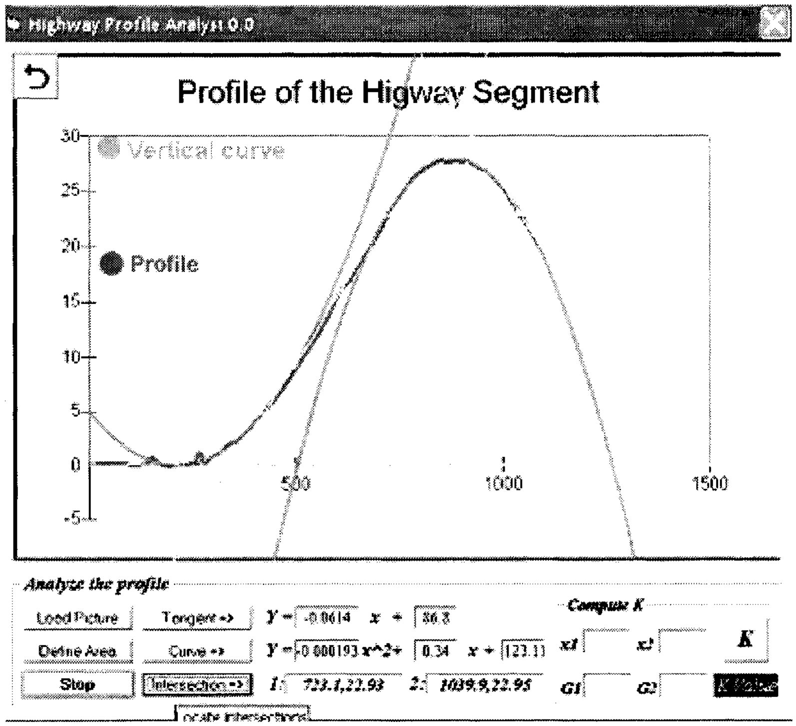


Figure 4.15: Profile Analysis Program

4.4 Need for Further Development of GIS Software

In this pilot study, ArcGIS' strong capabilities to deal with spatial or spatially related data are demonstrated. Besides, the benefits of using the two 3D operating speed prediction models for 3D highway operating speed consistency evaluation have also been verified. It should be noted that the 3D operating speed prediction models worked harmoniously with ArcGIS and ArcGIS 3D Analyst. However, as shown from this pilot study, the operating speed prediction and operating speed consistency rating procedures still involve handwork. Hence, it will be more practical to integrate 3D highway design consistency models into GIS software to automate the design consistency evaluation procedure, including operating speed calculation and design consistency rating.

The exploration of the ArcGIS software in chapter 3 has already shown the user-oriented function of ArcGIS known as customization. This function makes it possible to develop a 3D GIS-based methodology by integrating GIS and 3D GIS visualization with operating speed consistency evaluation models. Major advantages of this combination between GIS, including 3D GIS visualization, and highway consistency models include automated consistency evaluation procedure, 3D alignment based consistency level analysis, impressive evaluation result presentation, and spatially based consistency improvements. This methodology will be presented in the next chapter.

Chapter 5

DEVELOPED 3D GIS-BASED DESIGN CONSISTENCY METHODOLOGY

Although it has been realized for decades that highway design consistency is an important safety-related issue in geometric design, few designers consider it in their highway design processes (Faghri and Harbeson 1999). This is mainly due to the fact that there are many different streams of consistency evaluation models, which makes the highway design consistency evaluation a complicated task. However, the lack of an appropriate approach or tool is also an obvious obstruction to its practical application. Consequently, automating the design consistency evaluation procedure, or in other words, providing designers an easy-to-use tool, will be an incentive to the application of design consistency concept in highway design stage.

With this motivation, a few consistency evaluation tools or software programs have been developed and published in the current literatures. As mentioned in chapter 2, besides FHWA's IHSDM Consistency Module, Krammes et al. (1995) developed a highway geometric design consistency evaluation program for the consistency evaluation of two-lane rural highway horizontal alignments. Faghri and Harbeson (1999) reported a knowledge-based GIS approach to evaluation of design consistency of horizontal alignments, which uses a 2D GIS as a data-storing tool to facilitate the so-called knowledge based expert system (KBES) approach.

In this section, a 3D GIS-based highway consistency evaluation methodology is developed. In this methodology, GIS including 3D GIS visualization contribute significantly with their outstanding 3D spatial and spatially related data analysis and result presentation functions. Furthermore, the main component of ArcView accessed ArcGIS, ArcMap, and its strong adaptive function, customization, are used to program a 3D highway consistency evaluation software tool by developing functions specifically for highway operating speed consistency study based on ArcGIS.

The highway design consistency evaluation software introduced here uses ArcGIS desktop as its platform and integrates itself with the 3D operating speed prediction models and highway design consistency measures. The 3D operating speed prediction model integrated in the software is Fitzpatrick et al. speed-profile model. Consequently, the 3D GIS-based highway design consistency evaluation program "exploits" all ArcGIS' outstanding data management and presentation functions for the consistency study purpose and, of course, it should benefits the field with its unique new consistency study functions.

5.1 Programming Oriented Revision of the Speed-profile Model

Although Fitzpatrick et al. speed-profile model have been well refined to include most possible cases of acceleration and deceleration, the model does not have the convenience to present all the acceleration and deceleration conditions programmatically. It seems that the criteria of the conditions are not standard enough, which may be a shortcoming considering that the realization in computer program will automate the building routine of the speed profile. Therefore, the first step of the development is to standardize or simplify the criteria of the acceleration and deceleration conditions for the speed-profile model. This programming oriented revision to the speed-profile model will give more standardized criteria to the identification of acceleration and deceleration conditions (Figure 5.1, see Table 2.5 for the variable definitions).

Listed in Figure 5.1 are all acceleration and deceleration cases identified with the new program oriented criteria. In the table, when $V_n > V_{n+1}$, $\Delta V_{amax} = V_{fs} - V_n$, when $V_n < V_{n+1}$, $\Delta V_{amax} = V_{fs} - V_{n+1}$. Based on these criteria, the automated acceleration and deceleration determination procedure will be:

```
If LSCa ≥ LSCc Then
   Case A
Else
   If ΔVa > 0 Then Case B
   If ΔVa =0 Then Case C
   If ΔVa < 0 Then Case D
End If
```

Comparing the revised cases with Fitzpatrick et al. speed-profile model, Case A is the Case A ($LSC_a > X_{fa} + X_{fd}$) in the Fitzpatrick et al. speed-profile model, Case B is the Case B ($LSC_a < X_{fa} + X_{fd}$ and $LSC_a > X_{cd}$) in the Fitzpatrick et al. speed-profile model, Case C reflects both Case C ($LSC_a = X_{cd}$) and Case E ($LSC_a = X_{ca}$) in the Fitzpatrick et al. speed-profile model, and Case D includes both Case D ($LSC_a < X_{cd}$) and Case F ($LSC_a < X_{ca}$). Besides, according to the design consistency chapter in the new TAC's guide (Easa, 2003), the calculation of V_a for Case B (2) is different from that for Case B (1). In Case B (2):

$$V_a = \{V^2_{n+1} + 25.92[ad/(a+d)]\ (LSC_a - X_{ca})\}^{1/2} \qquad [5.1]$$

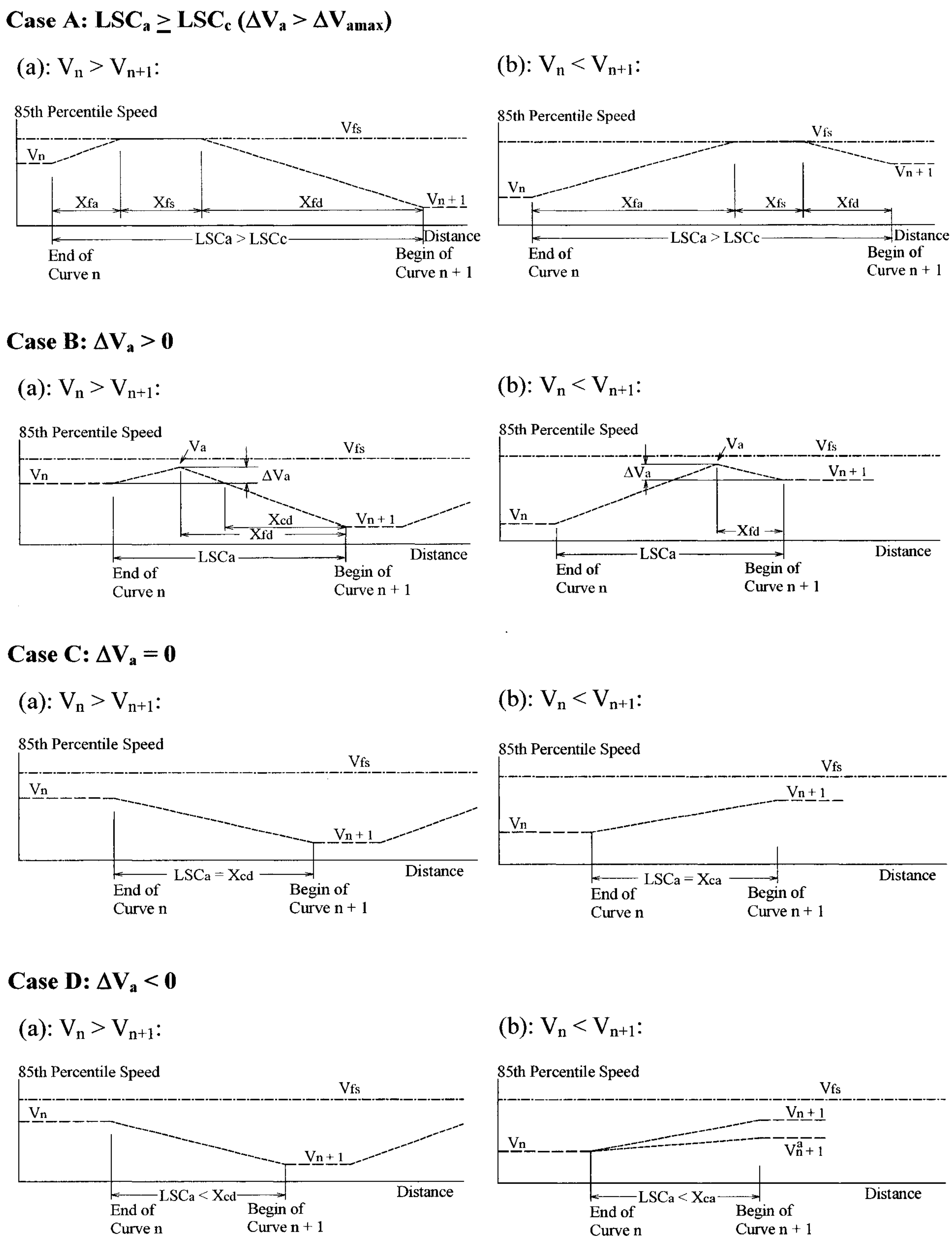


Figure 5.1: Speed Change Conditions with Standardized Criteria

By doing this revision, the identification of all acceleration and deceleration will be only based on LSC_a and ΔV_a, which will significantly simplify this procedure and make integration of the building of the speed profile in the computer software an easy routine.

5.2 Developed 3D GIS-Based Consistency Methodology

5.2.1 Conceptual Design

Based on the literature review, the following theoretical prerequisites have been discovered:

- ArcGIS has strong capabilities to deal with spatial or spatially related data;
- ArcGIS 3D Analyst extends ArcGIS with outstanding 3D spatial data analysis and graphing functions;
- ArcGIS desktop has strong application-oriented customization function;
- Highway design consistency evaluation procedure involves the spatial information of the target highways and sometimes their 3D natures are influential to their design consistency levels.

Considering all above, integrating the 3D highway design consistency module into ArcGIS to produce a 3D GIS-based highway design consistency methodology will be feasible and practical (Figure 5.2). This newly developed methodology, as a combination of GIS, especially 3D GIS visualization, and highway consistency modules, will make significant contributions in the following aspects: automated design consistency evaluation, design consistency analysis for 3D alignments, impressive evaluation result presentation, and spatially based consistency improvement suggestion.

This consistency evaluation methodology will be developed using desktop ArcGIS and its customization function. In this methodology, a set of consistency evaluation models for 3D highway alignments are integrated to ArcGIS system. Both of the two sub-routines of consistency analysis, operating speed prediction and consistency level measurement, are automated with GIS. The 2D and 3D graphing functions of GIS and GIS visualization will be used throughout the whole consistency analysis. Figure 5.3 shows the basic operation flowchart of the 3D GIS-based highway design consistency evaluation methodology.

The 3D GIS-based consistency methodology consists of three parts: data preparation, program input, and design consistency evaluation. These three parts form the frame of an ArcGIS-based consistency evaluation software, which is the core of the 3D GIS-based consistency evaluation methodology.

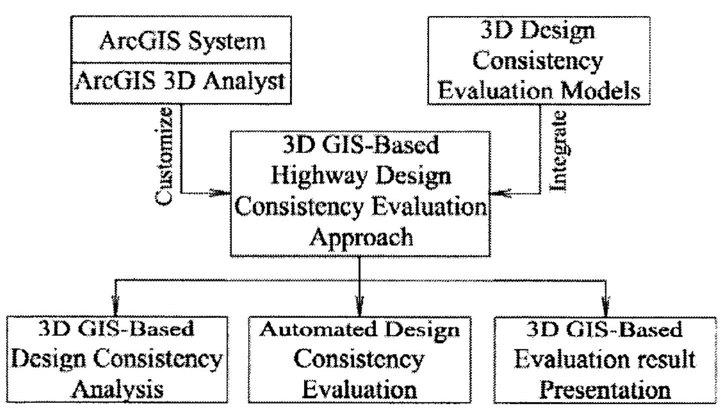


Figure 5.2: Conceptual Design of the Methodology

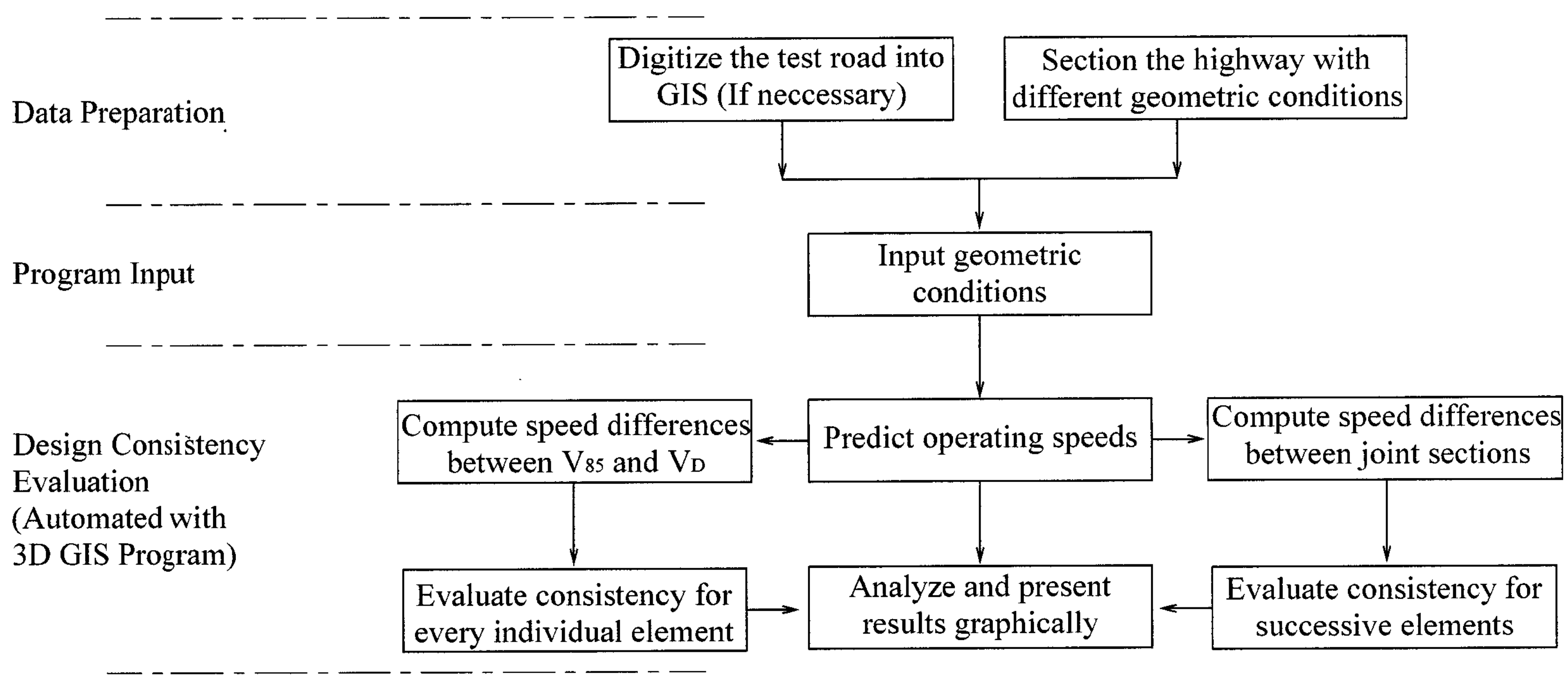


Figure 5.3: 3D GIS-Based Highway Consistency Methodology Flowchart

Data preparation includes the preparation of the GIS format test highway alignments and the pre-processing of the alignment data according to the requirements of the highway consistency models and measures. For the former, the GIS format highway alignments can be obtained by means such as satellite and airborne sensing. In addition, for those alignment data stored in other digital formats, GIS has provided strong data converting functions and many different data formats can be converted or imported into GIS software such as ArcGIS. For those alignments stored in paper format, there are also means to digitize them into GIS, for example, paper based data can be drawn in drawing software including AutoCAD and then be imported to GIS, or they can also be digitized directly using GIS facilities such as Digitizer.

For the latter, the alignments are always treated according to the consistency evaluation module and measures that are integrated in the methodology. Such treatments could be: design of the consistency study sites including planning of the test points and determination of sections according to different geometric conditions along the alignments, extraction of the geometric parameters needed in the operating speed prediction and consistency evaluation processes, and if available, the preparation of the environment data including the topography data of the test alignments and other related data, such as the sight obstructions that may influent drivers' sight distances and hence may affect the consistency levels along the test alignments. For example, to use the Fitzpatrick et al. speed-profile model, the highway alignment has to be divided into small sections using based on the definition shown in Figure 2.4.

Program input is to convey the results of data preparation to the GIS-based consistency evaluation methodology. This step needs users to input all the data needed by the consistency evaluation models integrated in the methodology including both alignments and their corresponding attribute data. This will ensure that the consistency program is ready for further evaluation.

Design consistency evaluation is the key part of the 3D GIS-based highway design consistency evaluation program. It's also the major achievement of this study. In this part, the integrated consistency models and measures work compatibly with the GIS platform provided by desktop ArcGIS and it's 3D Analyst extension. Besides, both the procedures of operating speed prediction and the consistency evaluation for the test 3D alignments are automated and supported by GIS' strong data analysis and graphical presentation functions.

The 3D operating speed prediction model integrated in the methodology is Fitzpatrick et al. speed-profile model (see Tables 2.2, 2.4, 2.5, and Figure 2.2). This is because while reflecting the 3D nature of highways, this model considers only the factors most related to operating speed so it makes the data preparation and speed prediction procedure relatively simple. It should be noted that, for the convenience of application, the acceleration and deceleration rates used in the software are constantly 0.54 m/s^2 and 1.00 m/s^2 respectively. Besides, the following assumptions were made to make the integration feasible:

- Acceleration and deceleration happen on the road sections that allow drivers to drive at desired speeds, such as tangents and sections fall into case 8 and 9 in Table 2.2.
- Since desired speed is assumed as 100 km/h, the operating speeds do not exceed the desired speed.

- Speeds on curved elements are always less than and equal to the desired speed, although according to the prediction equations the speed on some curved sections can exceed 100 km/h.

The measures used for the consistency evaluation are those listed in Table 4.3. Both of the Criteria are developed for operating speed consistency measurement. Criterion I is based on the differences between design speeds and predicted operating speeds while Criterion II is based on the operating speed differences between successive elements on the highway.

5.2.2 Main Features of the Developed Methodology

There are five tools specifically developed for highway design consistency evaluation in the 3D GIS-based methodology (Figure 5.4) (the VBA codes for these tools are attached in Appendix C). These tools are integrated with the two highway design consistency evaluation measurements as well as the 3D operating speed prediction models, which are responsible for the prediction of operating speeds and the consistency evaluation along the analyzed highway.

- *Add Fields for Highway Layer:*

  This tool allows users to add all the attribute fields that will store the highways' geometric information and the future speed and consistency study results into the corresponding numerical tables in the database of the test highways. By doing this, the data tables needed for the consistency related data storing will be created with necessary data fields automatically in order to get prepared for the input and output of the highway data. The fields that automatically added in the attribute table of the analyzed highways include:

1. SectionNo: by inputting the section numbers, the spatial sequence of the sections on the test highway determined according to their different geometric conditions (see Figure 2.4) will be defined and thus to tell ArcGIS who is in front or following whom.
2. Type: this field will store the case number of every segment divided according to the Fitzpatrick et al. speed-profile model.
3. Curve_Radius: the radii of all the horizontal curved elements along the analyzed highways will be stored in this field.
4. K_Value: the K-Value, which is a measure of the flatness of a horizontal curve on the analyzed highways (Length of vertical curve / Algebraic difference of vertical curve), will be stored in this field.
5. Design_Speed: the design speeds along the analysis highways will be stored in this field.
6. V_{85}: the 85th percentile speeds (operating speeds) predicted automatically by the program according to the Fitzpatrick et al. speed-profile model along the analyzed highways will be stored in this field.

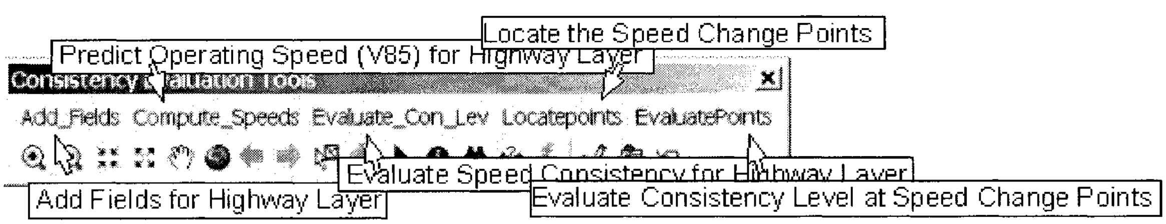


Figure 5.4: Highway Consistency Evaluation Toolbar

7. Con_Level: the levels of the operating speed design consistency along the analyzed highways will be evaluated and stored in this field.

- *Predict Operating Speed (V_{85}) for Highway Layer:*

When this tool is activated, the operating speed on every segment of the analyzed highways will be computed automatically according to the 3D operating speed prediction models and stored in the corresponding field of every segment. The operating speed prediction is the prerequisite of operating speed consistency evaluation. Figure 5.5 shows the program flowchart of this tool.

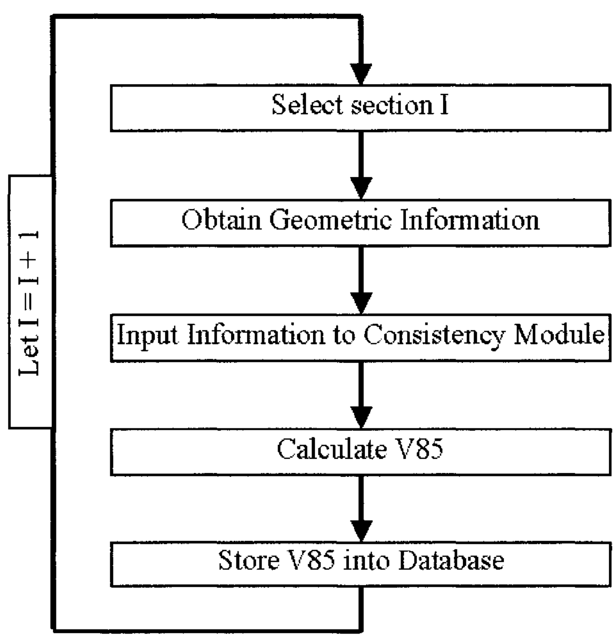


Figure 5.5: Flowchart of Predict Operating Speed Tool

- *Evaluate Speed Consistency for Highway Layer:*

  This tool can obtain both the predicted operating speeds and the input design speeds from the geodatabase of the test highways. It does the consistency evaluation according to the consistency measure based on the speed differences between operating speeds and design speeds (Criterion I, see Table 4.3). Besides, it also stores the different consistency levels along the analyzed highway into its attribute database table. There are three different levels assigned to the highway segments, in which, level 1 represents good design, level 2 means fair design, and level 3 is poor design. Figure 5.6 indicates the program workflow of this part of the program.

- *Locate the Speed Change Points:*

  This tool makes the consistency evaluation between the successive elements along the test highways possible. Study has shown that the potential speed change points are always located at the joints of successive geometric elements. With this tool activated, all the points where operating speed changes may exist will be located and generated as a new analyzed layer on the analyzed highways (see Figure 5.7). Moreover, the attribute table for operating speed difference evaluation of the highways will be created automatically in the geodatabase. The program flowchart of this tool is given in Figure 5.8.

- *Evaluate Consistency Levels at Speed Change Points:*

  By analyzing the spatial distribution and the database of every potential speed change point, this tool will find the operating speed on each side of every speed change point and store it in the attribute table of the point, and then evaluate the speed differences between every pair of operating speeds. At last, it measures the operating speed consistency between successive highway elements according to Criterion II listed in Table 4.3. Figure 5.9 shows how the consistency evaluation for successive elements programmatically performed.

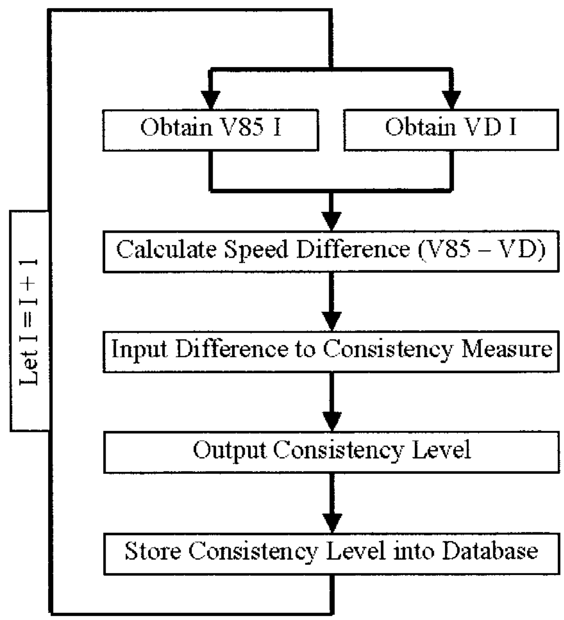


Figure 5.6: Flowchart of tool Evaluate Speed Consistency
(where VD = design speed)

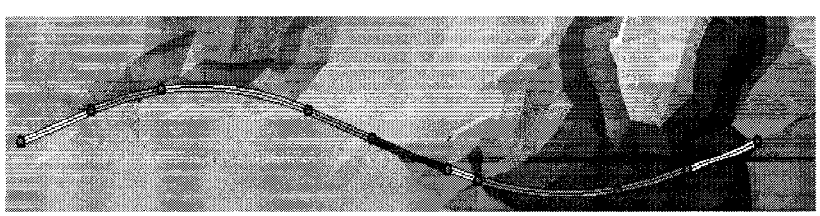


Figure 5.7: Potential Operating Speed Change Points on the Highway Segment

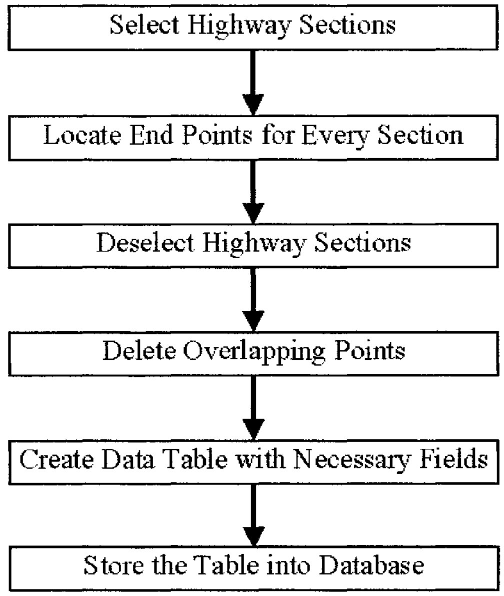


Figure 5.8: Flowchart of Tool Locate Speed Change Points

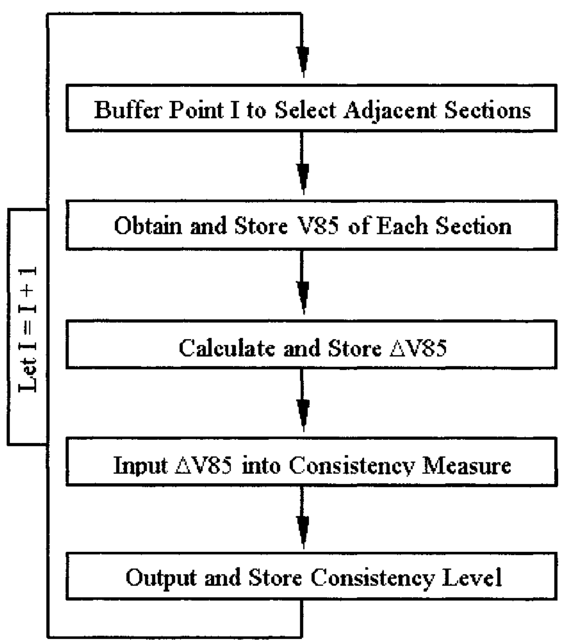


Figure 5.9: Flowchart of Evaluation Consistency Levels at Speed Change Points

5.3 Operation of the Developed Computer Software

This software is developed based on the platform of ESRI ArcGIS desktop, which provides the highway design consistency evaluation program with outstanding date management, alignment visualization, and result presentation functions. In ArcGIS platform, the alignment of highways will be exhibited and the speed and consistency results can be analyzed graphically and impressively. The main operations and customized functions of the operating speed evaluation software program will be described in this section.

5.3.1 Software Input

To study the consistency of a highway, the GIS format alignment of this highway should be first prepared. Currently, GIS is used in transportation more and more popularly and the data of highways are more likely to be stored and managed in GIS. This provides the design consistency evaluation program with much convenience. Alternatively, highway data in other formats can be easily digitized into GIS through AutoCAD or other drawing software and GIS facilities. The coordinate system of the highway could be the real world or local earth surface coordinate system or systems defined by users. The unit of the coordinate could be any metric or English units. As an example, the alignment and terrain in Figure 5.10 are digitized from AutoCAD drawing.

Some geometric design information of the highway in analysis is also needed for the consistency study. Parameters inputted in the program should be:

- ID assigned to every highway section in spatial sequence,
- Radius (R) for every horizontal curve,

- K-value for vertical curve if available,
- Case number according to Fitzpatrick et al. speed-profile model,
- Design speed for the difference measurement between design speed and operating speed.

Figure 5.11 shows the input interface and parameters inputted in the program. The highlighted areas are the fields need to be filled up.

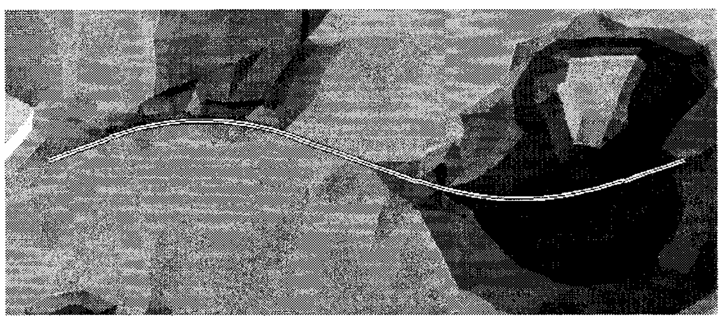
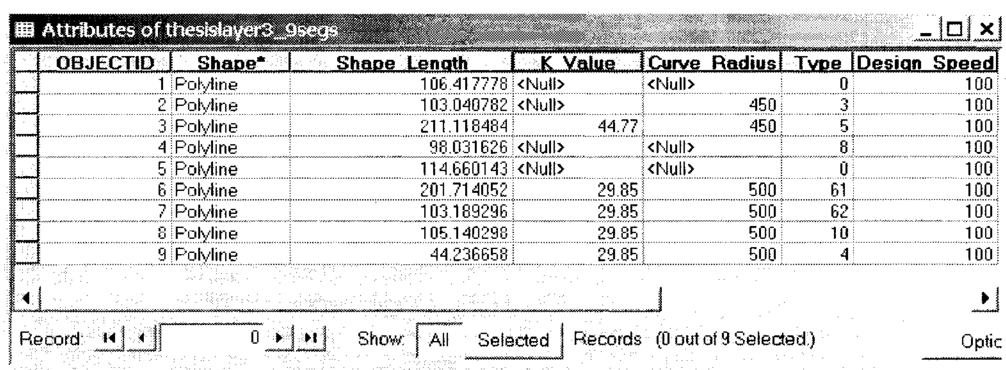


Figure 5.10: Alignment Needed in the Program



Attributes of thesislayer3_9segs

OBJECTID	Shape*	Shape Length	K Value	Curve Radius	Type	Design Speed
1	Polyline	106.417778	<Null>	<Null>	0	100
2	Polyline	103.040782	<Null>	450	3	100
3	Polyline	211.118484	44.77	450	5	100
4	Polyline	98.031626	<Null>	<Null>	8	100
5	Polyline	114.660143	<Null>	<Null>	0	100
6	Polyline	201.714052	29.85	500	61	100
7	Polyline	103.189296	29.85	500	62	100
8	Polyline	105.140298	29.85	500	10	100
9	Polyline	44.236658	29.85	500	4	100

Record: 0 Show: All Selected Records (0 out of 9 Selected.) Optic

Figure 5.11: Parameters Inputted in the Program

5.3.2 Software Output

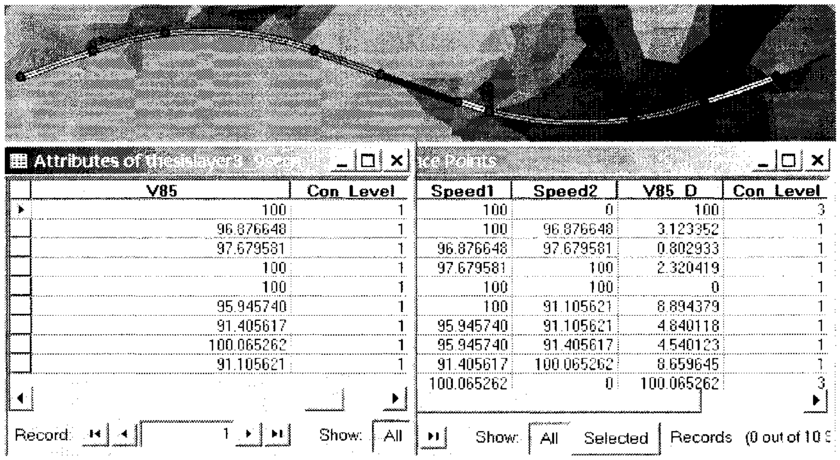
Outputs from the software fall into two categories: numerical and graphical. Graphical presentation of the output can be made using the existing 3D and 2D graphing functions of ArcMap in various forms based on the numerical results. Numerical output of the program includes:

- Predicted (V_{85}) operating speeds along the highway,
- Operating speed consistency levels along the test highway measured according to the differences between design speeds and operating speeds,
- Operating speed pairs of every joint point of successive elements on the highway,
- Operating speed differences on the joint points between successive elements along the highway,
- Consistency level on every speed abrupt change point according to differences between operating speeds on the successive elements of the highway.

In addition to the above outputs, the program also computes the length ratio between the segments with different consistency levels and the whole highway section. Figures 5.12 and 5.13 show the numerical output of the consistency evaluation program. The points in Figure 5.12 represent the locations where speed abrupt changes may occur.

The graphic output of the 3D GIS-based highway design consistency evaluation software is the other important analysis assistance. The program's graphic output falls into two groups: 2D and 3D graphs.

The 2D form graphic output functions include colorful symbology and labeling.



V85	Con Level
100	1
96.876648	1
97.679581	1
100	1
100	1
95.945740	1
91.405617	1
100.065262	1
91.105621	1

Speed1	Speed2	V85_D	Con Level
100	0	100	3
100	96.876648	3.123352	1
96.876648	97.679581	0.802933	1
97.679581	100	2.320419	1
100	100	0	1
100	91.105621	8.894379	1
95.945740	91.105621	4.840118	1
95.945740	91.405617	4.540123	1
91.405617	100.065262	8.659645	1
100.065262	0	100.065262	3

Figure 5.12: Numerical Output of the Consistency Evaluation Program

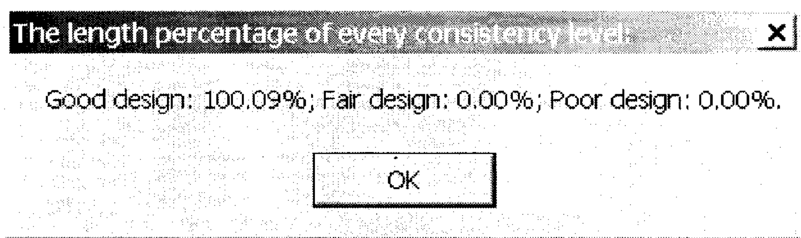


Figure 5.13: The Length Percentage of Every Consistency Level

- *Colorful symbology*

The symbology function allows users to adjust the symbols of features in analysis. It allows both single symbol and multiple symbols to present features. Using this function, users can present features with important attributes with bright color to attract viewers and highlight the attributes. Besides, by presenting features in different colors, people can easily distinguish features from others especially when the quantity of analysis features is massive. Figure 5.14 shows the symbology window and Figure 5.15 shows the highway sections presented with different colors.

- *Labeling*

The labeling function allows people to show features labeled with the attributes that need to be highlighted. Using labeling function, users can show the information of any field in the features' database spatially together with the features. Figure 5.16 shows the operation window of labeling function and Figure 5.17 gives an example of labeled features.

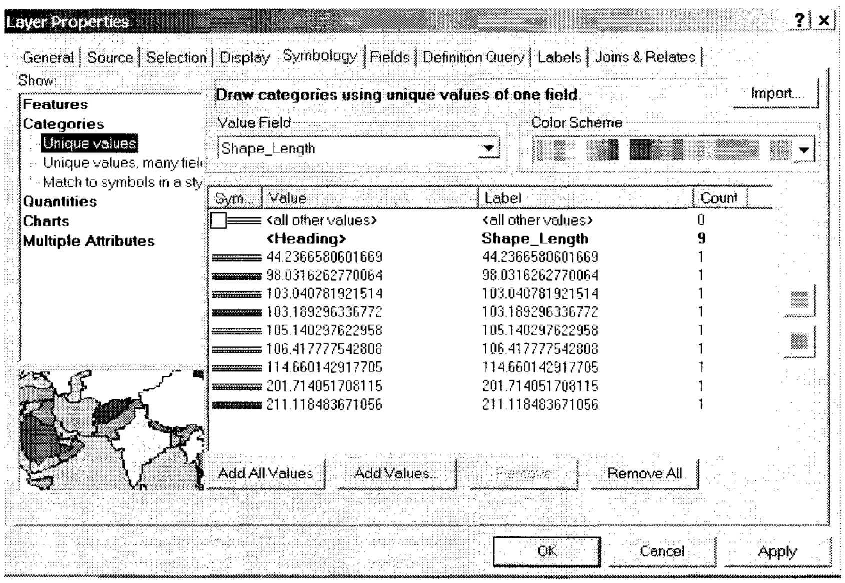


Figure 5.14: Symbology Function

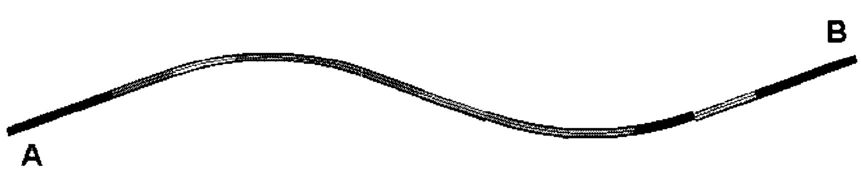


Figure 5.15: Highway Sections Presented in Different Colors

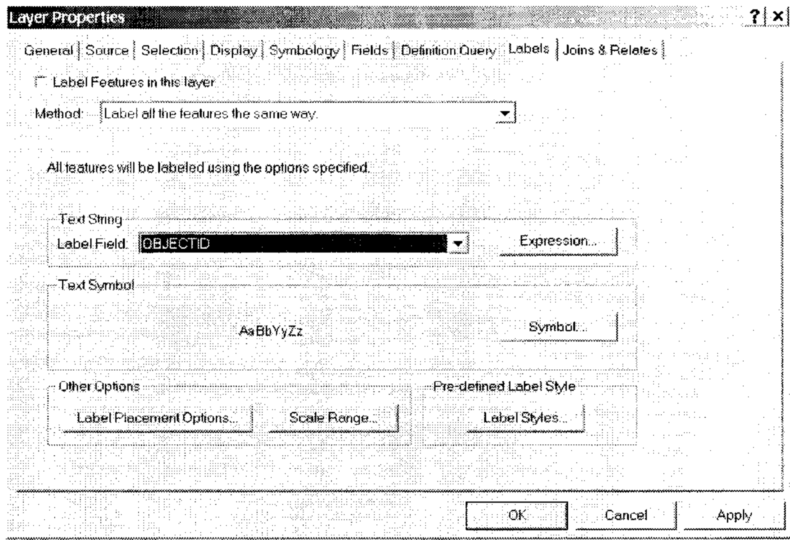


Figure 5.16: Labeling Function

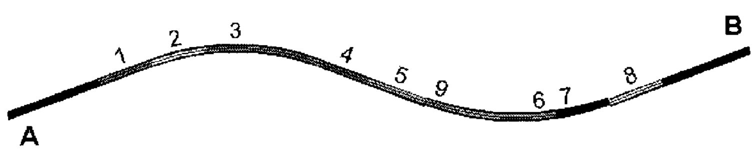


Figure 5.17: Highway Sections Labeled with Object ID

The 3D graphic output forms include 3D colorful charting and attribute visualization.

- *3D colorful charting*

  ArcGIS provides powerful graphing functions including the generation of pie chart, column chart, and stacked chart. These different charting functions allow users to compare and present different attributes of features according to their own preferences. Figure 5.18 shows the operation of this function and Figure 5.19 shows the form of every chart type.

- *Attribute visualization*

Attribute visualization is also called extrusion in ArcGIS. It allows users to visualize important attribute of analyzed features. By visualizing feature attributes that need to be emphasized, the more impressive analysis way will be available to analysts. Figure 5.20 shows the operation window of the Extrusion function and Figure 5.21 shows the test 3D highway with visualized operating speeds.

With helps from some other existing tools in ArcMap and 3D Analyst, highway design consistency can be analyzed easily and the evaluation results can be presented impressively in this highway consistency program. In next chapter, the verification of this newly developed 3D GIS-based highway design consistency evaluation approach will be conducted with a study of a real case.

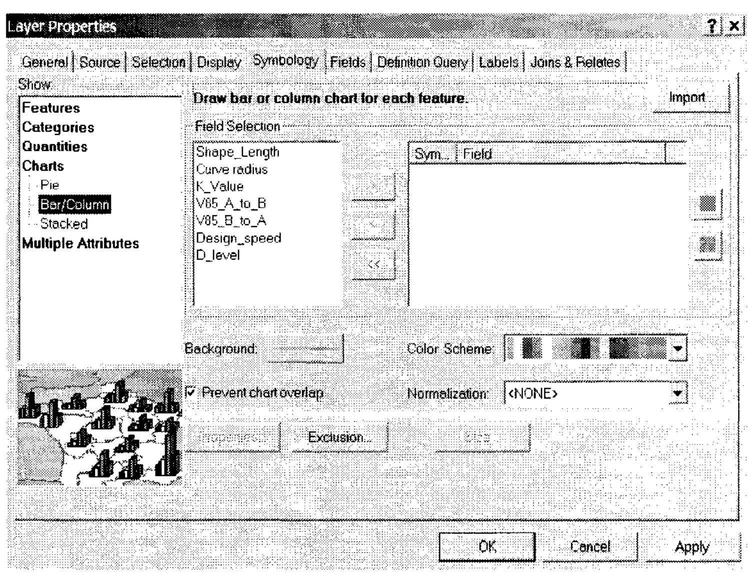


Figure 5.18: 3D Charting Function

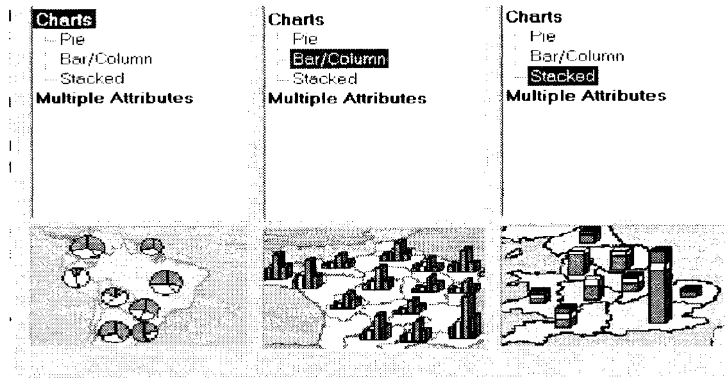


Figure 5.19: Different Types of 3D Charting

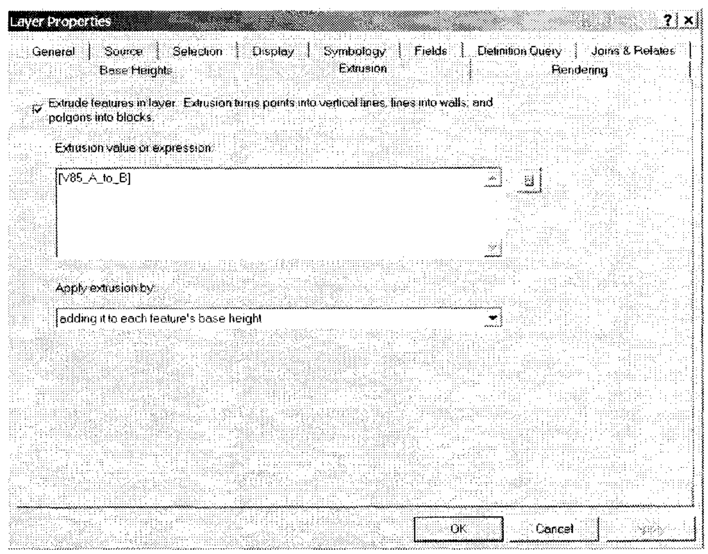


Figure 5.20: Extrusion Function

Figure 5.21: 3D Highway Sections with Visualized Operating Speeds

Chapter 6

CASE STUDY

In this chapter, for verification purposes, the newly developed 3D GIS-based highway design consistency evaluation methodology discussed in Chapter 5 will be applied to a two-lane highway segment in Ontario.

6.1 Highway Segment for Case Study

The highway segment used for this case study is a 17 km two-lane rural highway section from station 10+000 to station 27+000 on the Highway 61 in Ontario (see Figure 6.1). The direction from Pigeon River to Thunder Bay is the direction analyzed in this study.

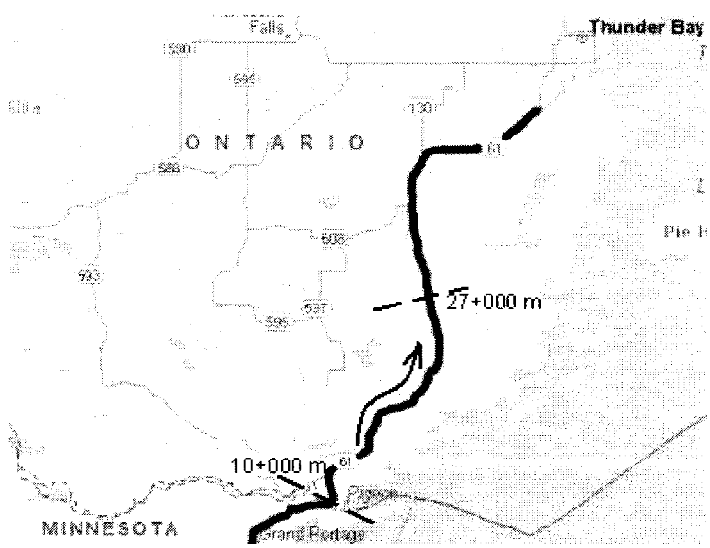


Figure 6.1: Location of Highway Segment on HW61 for Case Study

Figure 6.2 shows the horizontal and vertical alignments of the studied highway segment. This segment of Highway 61 is apparently a typical 3D alignment of two-lane rural highway and fully qualified for the highway operating speed consistency study.The study of the original alignment data shows that:

1. The radii of the curves on the original horizontal alignment vary from 430 m to 1800 m and there are no sharp curves. In addition, the study shows that the sight distances decided by the curves do not affect the expectancy of drivers.
2. The vertical alignment of the highway segment containing sag and crest vertical curves and the elevations along the segment fall into the interval from 200 m to 290 m.
3. The grades along the highway segment's profile are mostly between $\pm$ 9% and sight distances on the vertical curves are all unlimited (K > 43 m/%).

To illustrate the application of the developed highway design consistency software, especially its problem identification, one of the horizontal curves in the highway alignment is intentionally made sharper. As seen from Figure 6.2, the radius of an original horizontal curve (580 m) is sharpened to 150 m. By doing this, the practicality of the problem identification and solution of the highway design consistency software will be tested.

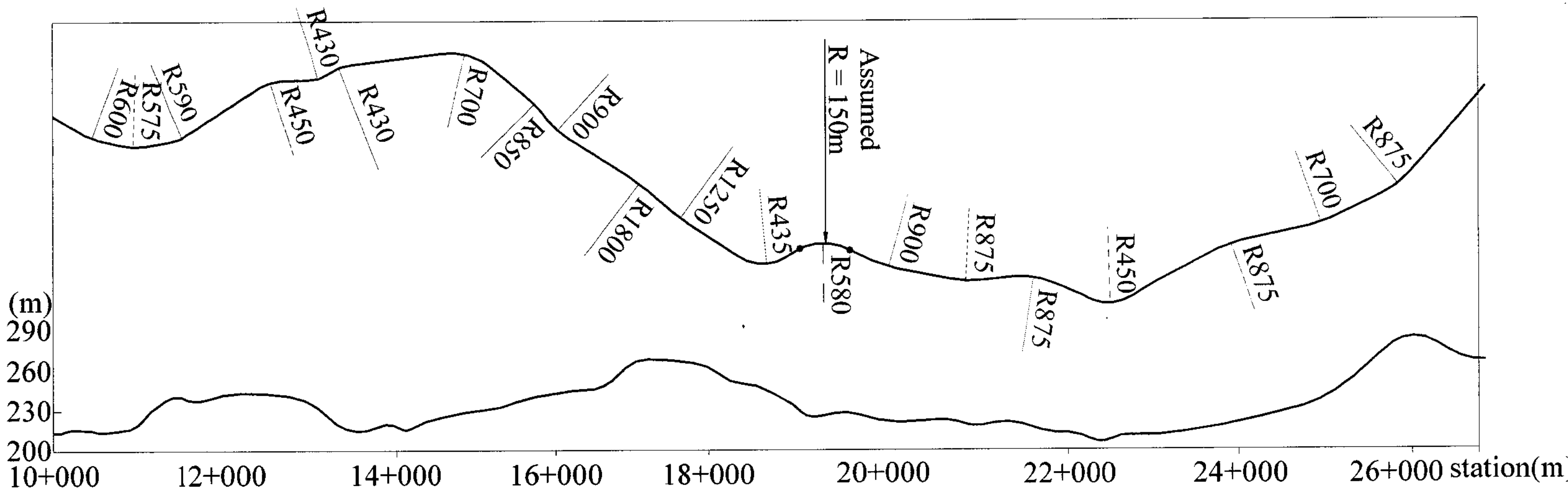


Figure 6.2: Horizontal and Vertical Alignments of the Study Highway Segment

6.2 Operating Speed Prediction and Highway Consistency Evaluation

6.2.1 Data Preparation

To analyze the design consistency of the highway segment, the alignment is digitized in AutoCAD 2000 and imported into GIS. During the importing procedure, ArcGIS will obtain the lengths of elements on test alignment such as tangents and curves and assign them with unique object IDs.

Figure 6.3 shows the horizontal alignment of the highway segment that is measured in metric units. Figure 6.4 shows the 3D alignment (in yellow) of the highway section together with its plan (in red). The variation of elevations from the plan along the alignment is clearly shown from this figure. The alignment in Figure 6.5 is divided into small sections according to their different geometric conditions that are defined in Fitzpatrick et al. speed-profile model. In this case, the GIS terrain data are not provided with the alignment. Therefore, the analysis will be applied only on the alignment itself.

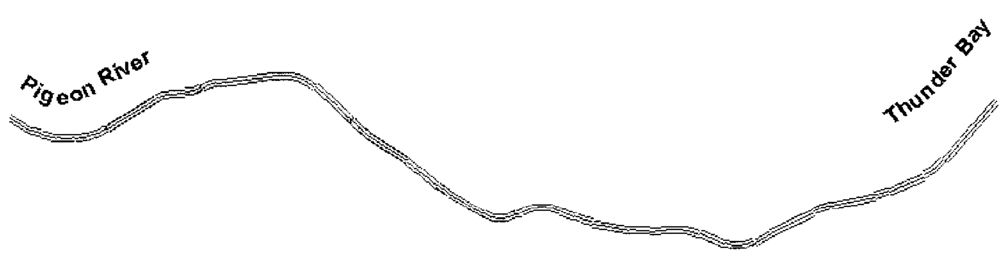


Figure 6.3: Horizontal Alignment Digitized for the Study

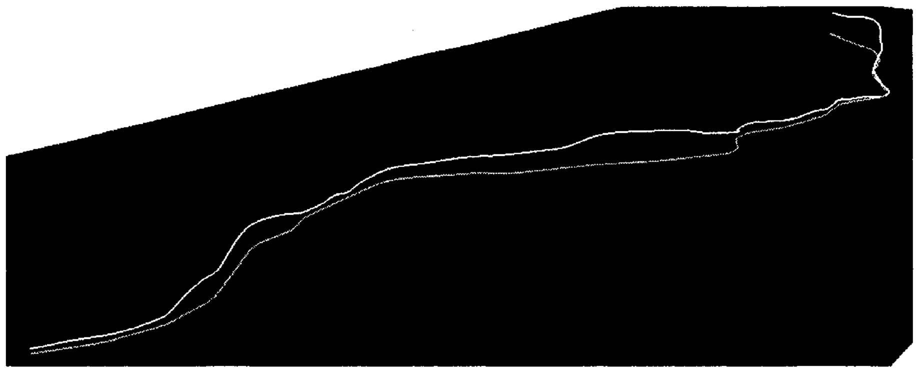


Figure 6.4: The 3D Alignment of the Highway Segment and Its Plan

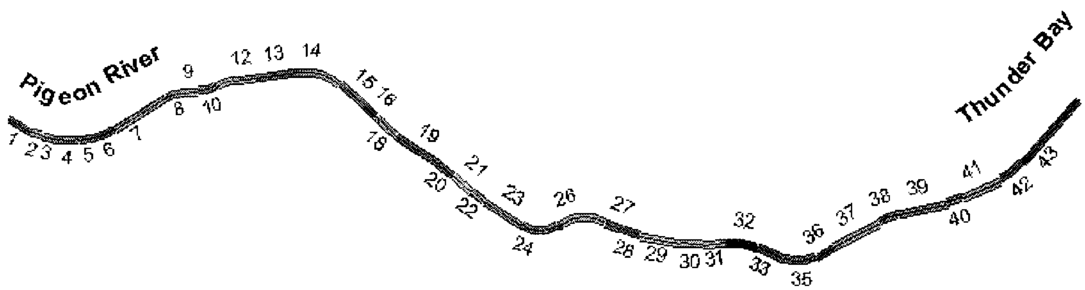


Figure 6.5: Different Sections Divided Based on the Speed-Profile Model

After the alignment was digitized into ArcGIS, inputs are needed for the geometric information, including radii of horizontal curves, K Values of vertical curves, and case number of every segment divided according to Fitzpatrick et al. speed-profile model. The operating speed study is based on the following assumptions:

1. The vehicles on the test highway travel in a free flow and their speeds are only influenced by the geometric conditions of the highway segment. Effects from other

factors such as intersections and climbing lanes on drivers' operating speeds are ignored.

2. The sight distances such as stop sight distance and passing sight distance along the highway are only affected by the 3D highway alignment and the disturbing of unexpected obstructions to sight distances is ignored.
3. Based on the study of the highway alignment, the transitions between horizontal curves and tangents are mostly shorter than 50 meters. Consequently, the transitions will be considered as parts of their connected curves.
4. The desired speed on highway 61 is 100 km/h while its design speed is considered to be 90 km/h (speed limit on highway 61), although speed limit on a highway is usually lower than its design speed.

Table 6.1 is the attribute table of the highway layer exported from the developed software. It contains all input data and the results (operating speed and consistency level of individual sections) generated by the highway design consistency software and the consistency levels are evaluated based on the following measure (ΔV_{85} = difference between design speed and V_{85}):

Criterion I (Lamm et al., 1988a, 1995)

Good designs: $\Delta V_{85} \leq 6$ mph (10 km/h)

Poor design: $\Delta V_{85} > 12$ mph (20 km/h)

Table 6.1: Operating Speed Consistency Evaluation Data Table of the Test Highway

OBJECTID	SHAPE_LENG	SectionNo	TYPE	DESIGN_SPEED	CURVE_RADII	K_VALUE	V_{85}	CON_LEVEL
1	410.78	1	9	90.00			100.00	1
2	243.61	3	9	90.00			100.00	1
3	142.82	2	3	90.00	600.00		98.86	1
4	231.70	5	9	90.00		66.00	100.00	1
5	288.86	4	61	90.00	575.00	45.00	96.75	1
6	876.83	7	0	90.00			100.00	1
7	290.69	6	5	90.00	590.00		99.49	1
8	254.31	9	9	90.00			100.00	1
9	226.42	8	2	90.00	450.00		97.74	1
11	274.24	10	5	90.00	430.00	70.00	97.32	1
12	312.86	12	8	90.00			100.00	1
13	258.59	11	5	90.00	430.00	60.00	97.32	1
14	624.49	13	9	90.00			100.00	1
15	460.80	15	9	90.00			100.00	1
16	635.14	14	3	90.00	700.00		99.71	1
17	70.50	17	9	90.00			100.00	1
18	236.72	16	3	90.00	850.00		100.00	1
19	732.67	19	8	90.00		45.00	100.00	1
20	326.07	18	3	90.00	900.00		100.00	1
21	327.40	21	9	90.00			100.00	1
22	272.45	20	61	90.00	1800.00		100.00	1
23	642.27	23	9	90.00		50.00	100.00	1
24	210.45	22	62	90.00	1250.00		94.71	1
25	65.05	25	9	90.00		60.00	100.00	1
26	548.39	24	2	90.00	435.00		97.45	1
27	232.41	27	9	90.00			100.00	1
28	666.07	26	61	90.00	150.00	84.00	81.25	1
29	581.23	29	9	90.00			100.00	1
30	284.14	28	2	90.00	900.00		100.00	1
31	318.61	31	8	90.00			100.00	1
32	322.26	30	5	90.00	875.00		100.00	1
33	328.63	33	9	90.00			100.00	1
34	467.70	32	5	90.00	875.00		100.00	1
35	79.37	34	8	90.00			100.00	1
36	280.87	36	9	90.00			100.00	1
37	498.30	35	3	90.00	450.00		96.88	1
38	735.12	37	9	90.00			100.00	1
39	727.82	39	9	90.00			100.00	1
40	273.96	38	3	90.00	875.00		100.00	1
41	580.62	41	9	90.00		120.00	100.00	1
42	225.45	40	5	90.00	700.00		100.00	1
43	1218.22	43	9	90.00			100.00	1
44	410.28	42	61	90.00	875.00		98.58	1

In Table 6.1: TYPE = case number according to Fitzpatrick et al. speed-profile model, where 61 and 71 are cases 6 and 7 on upgrade respectively, 62 and 72 are cases 6 and 7 on downgrade respectively, DESIGN_SPEED = design speed of the highway segment in km/h, CURVE_RADII = radius of horizontal curve on the highway segment in meter, K_VALUE = the K value of the vertical curve on the highway segment, V_{85} = predicted operating speed (85 percentile speed) in km/h, CON_LEVEL = operating speed consistency levels along the test highway, where level 1 = good design, level 2 = fair design, and level 3 = poor design. To manage the tremendous features and their attributes in database, every geometric element is identified in ArcGIS by adding a unique OBJECTID. However, this OBJECTID is not assigned exactly following the spatial sequence along the alignment. To facilitate the consistency analysis, a SectionNo is assigned to every section according to its spatial distribution on the alignment (See Figure 6.5).

6.2.2 Analysis Results

The predicted operating speeds along a portion of the test highway segment are labeled in Figure 6.6. The visualized speed profile is presented in Figure 6.7. In this figure (Figure 6.7), the operating speeds along the highway are magnified by a factor of two. Consequently, the differences between operating speeds and desired speed (100 km/h shown in Figure 6.7) are also magnified by a factor of two. To analyze the relationship between the operating speed distribution and vertical alignment, the profile of the test segment on Highway 61 is added through the speed profile (see Figure 6.7).

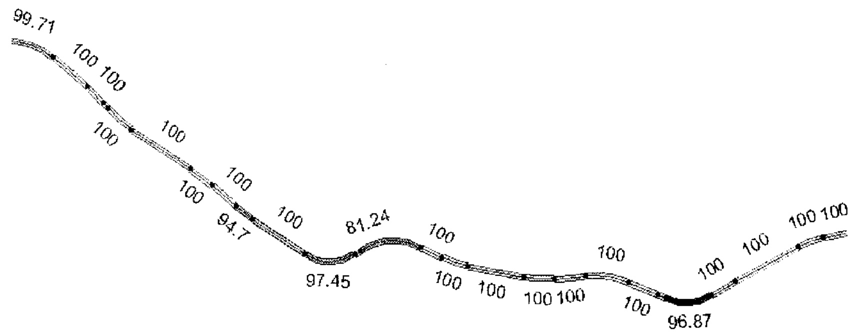


Figure 6.6: Operating Speeds (V_{85}) along a Portion of Test Highway (km/h)

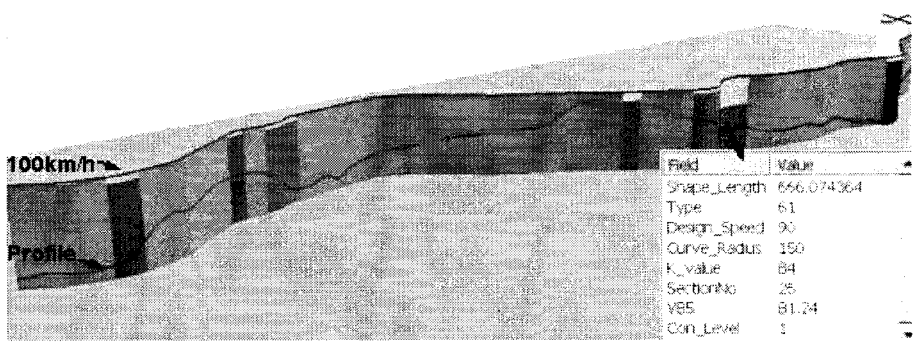


Figure 6.7: Visualized Operating Speed Profile of the Test Highway

Figure 6.6 and 6.7 clearly indicate that because there are no vertical curves with limited sight distances or horizontal curves combined with steep grades, the predicted operating speeds are generally distributed smoothly along the alignment. In addition, those sections with small-radius curves or where horizontal and vertical curves coincide are predicted with the lowest operating speeds. It is noted that, the curve, whose radius is intentionally sharpened to 150 m from 580 m, has the lowest operating speed of 81.24 km/h. This is clearly identified and presented in the figures by the developed software.

Moreover, ArcGIS system provides users another very useful analysis tool: Identify. With this tool, users can check the attribute information of every object by a simple mouse click. This function provides analysts with the dynamic connection between graphs and their numerical data and, thus, makes the analysis convenient. The identification window in Figure 6.7 shows the information of the highway section with the lowest speed, which is, as mentioned before, a horizontal curve with the shortest radius of 150 m.

The differences between design speed (speed limit) and predicted operating speeds along a portion of the test highway segment have been visualized in Figure 6.8. As shown from this figure (also see Table 6.1), most predicted operating speeds are higher then the speed limit by approximate 8 – 10 km/h. This point is also indicated from the speed measurements on straight segments of Highway 61 with favorable pavement conditions that show an average operating speed of 102.0 km/h (Hassan et al. 2000). However, the operating speed on the sharpest horizontal curve, which has a radius of 150 m, is much lower (about 8.7 km/h) than the speed limit. Hence, drivers traveling on this curve have to lower their speeds significantly to meet the requirements of the geometric conditions, which may cause collisions.

Joint points between successive elements (for example, the points in the plan view in Figure 2.3) on the test highway segment where potential abrupt speed changes may happen have been located by the developed software. The consistency studies at these points have been performed automatically as well. The operating speed consistency evaluation at these points will be the estimation of the speed consistency between successive elements and this evaluation will indicate the goodness of the design for avoiding abrupt speed changes along the test highway. The consistency measure used for the operating speed consistency evaluation between successive elements is the Criterion I in Table 4.3.

Figure 6.9 shows the potential speed change points on a portion of the test Highway segment that were generated by the software automatically. Table 6.2 contains the evaluation results for the joint points between successive elements on Highway 61. According to the evaluation results from the highway consistency software, most speed differences between successive elements vary from 0 to 5.3 km/h, which consequently means that the consistency level at these points are level 1 (good design). However, due to the low predicted operating speed on the curve that was intentionally sharpened, the speed differences at point 47 and 52 (see Table 6.2) are as high as 18.75 km/h. In other words, the operating speed consistency levels at these points are almost poor designs and the geometric conditions at these points definitely need to be improved.

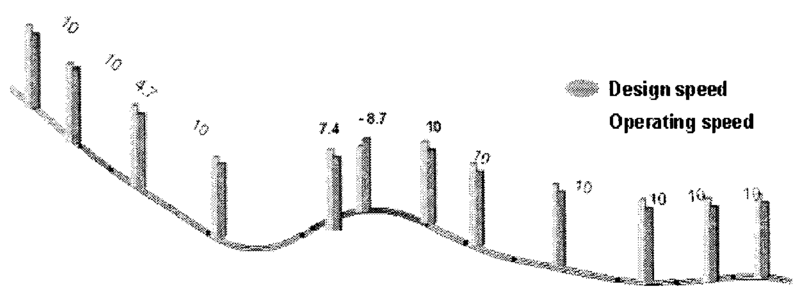


Figure 6.8: Difference between Design Speed and Operating Speed on a Portion of Test Highway (km/h)

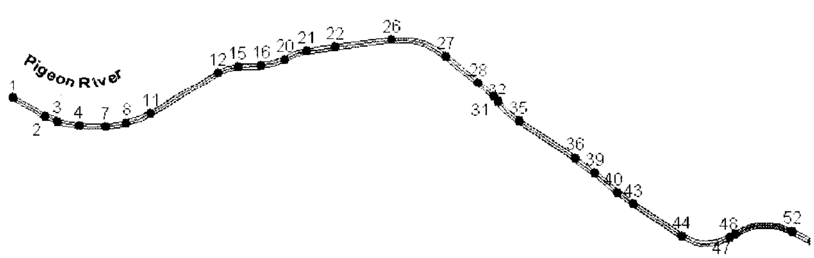


Figure 6.9: The Joint Points and Their OBJECTID on a Portion of Test Highway

Table 6.2: Consistency Evaluation Results at Speed Change Points

OBJECTID	Speed1	Speed2	V85_D	Con_Level
1	100.00	N/A	100.00	N/A
2	100.00	98.86	1.14	1
3	100.00	98.86	1.14	1
4	100.00	96.75	3.25	1
7	100.00	96.75	3.25	1
8	100.00	99.49	0.51	1
11	100.00	99.49	0.51	1
12	100.00	97.74	2.26	1
15	100.00	97.74	2.26	1
16	100.00	97.32	2.68	1
20	97.32	97.32	0.00	1
21	100.00	97.32	2.68	1
22	100.00	100.00	0.00	1
26	100.00	99.71	0.29	1
27	100.00	99.71	0.29	1
28	100.00	100.00	0.00	1
31	100.00	100.00	0.00	1
32	100.00	100.00	0.00	1
35	100.00	100.00	0.00	1
36	100.00	100.00	0.00	1
39	100.00	100.00	0.00	1
40	100.00	94.71	5.29	1
43	100.00	94.71	5.29	1
44	100.00	97.45	2.55	1
47	100.00	81.25	18.75	2
48	100.00	97.45	2.55	1
51	100.00	100.00	0.00	1
52	100.00	81.25	18.75	2
55	100.00	100.00	0.00	1
56	100.00	100.00	0.00	1
59	100.00	100.00	0.00	1
60	100.00	100.00	0.00	1
63	100.00	100.00	0.00	1
64	100.00	100.00	0.00	1
68	100.00	96.88	3.12	1
69	100.00	96.88	3.12	1
70	100.00	100.00	0.00	1
74	100.00	100.00	0.00	1
75	100.00	100.00	0.00	1
76	100.00	100.00	0.00	1
79	100.00	100.00	0.00	1
80	100.00	98.58	1.42	1
83	100.00	98.58	1.42	1
84	100.00	N/A	100.00	N/A

In Table 6.2: OBJECTID = ID of speed change points along the highway segment (see Figure 6.9), Speed1 and Speed2 = the speeds on each side of a joint point respectively in km/h, V85_D = Differences between Speed1 and Speed2 in km/h, Con_Level = level of operating speed consistency measured based on the predicted operating speed differences between successive elements.

The visualized operating speed differences between successive sections along the test highway with reference to its profile are shown in Figure 6.10. As seen from this figure, the differences on the smooth terrain where horizontal alignments are flat are mostly small while the speed differences between those segments on sharp curved parts or sections where horizontal and vertical curves overlap are relatively large. Furthermore, as mentioned before, the points connecting the sharpest curve (R = 150 m) have the greatest speed differences. Meanwhile, operating speed differences at other points on the test alignment are generally insignificant. Figure 6.11 shows that most speed differences are lower than 5%.

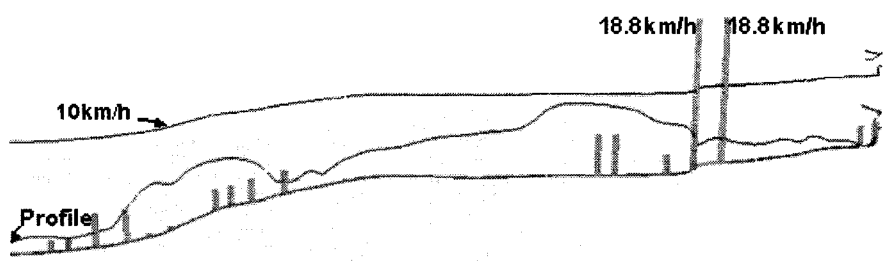


Figure 6.10: Visualized Speed Differences (km/h) on Test Highway Segment

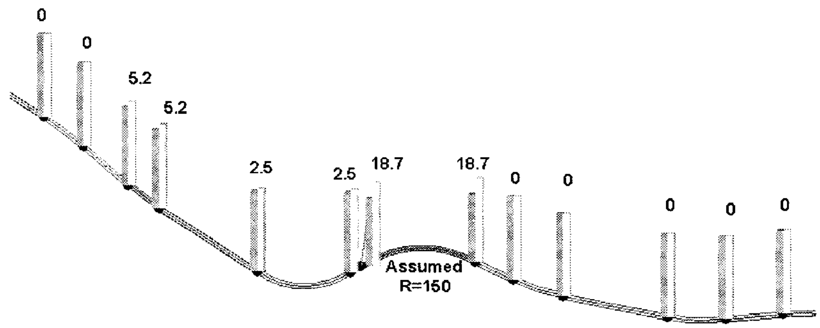


Figure 6.11: Operating Speed Differences (km/h) at Joint Points on a Portion of Test Section

In addition, a report of the length percentage of every consistency level is also generated automatically when the evaluation process is finished. The length percentage report window is shown in Figure 6.12. Known from the report, there are no sections with poor consistency level on the test highway segment and the percentage of good design is as high as 100%, which indicates that the operating speeds on all sections of the test highway fall between 80 km/h and 100 km/h. This is mainly because the program assumes that the operating speeds along the test highway will not exceed the desired speed (100 km/h) and the design speed is 90 km/h. In fact, according to the operating speed prediction equations themselves, the operating speeds on some sections do exceed the desired speeds.

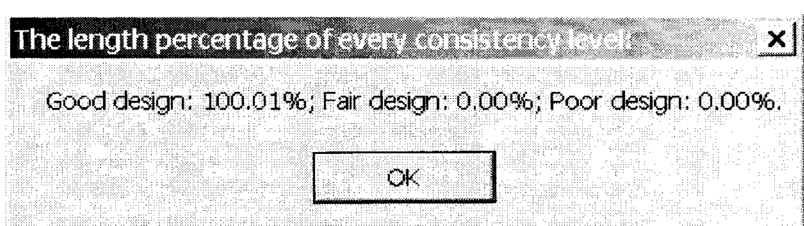


Figure 6.12: Operating Speed Consistency State Reported by the Program

6.3 Discussion and Conclusions

6.3.1 Discussion of Results

As seen from the case study results from the newly developed 3D GIS-based highway design consistency evaluation software, highway geometric condition has direct impact on the speed that a driver chooses to drive. According to the case study, the radius of a horizontal curve is an important factor influencing a driver's decision. As identified clearly by the developed software, the operating speed on the horizontal curve, whose radius was intentionally sharpened from 580 m to 150 m, is much lower than the desired speed (see Figure 6.8, Table 6.1). This directly resulted in the differences between the operating speeds on this curve (R = 150 m) and on the adjacent elements being as high as 18.7 km/h (see Figure 6.11 and 6.12). This means that the design consistency levels at the points between this curve and its adjacent elements are almost poor.

To make the operating speeds on the curve and its adjacent elements more consistent, the ideal radius has been sought by assigning different radius values to the curve. The radii of the alternative curves are: R = 250 m, R = 350 m, R = 450 m, and R = 580 m. These radii were inputted to the developed highway consistency software to predict the corresponding operating speeds. The results are listed in Table 6.3.

Table 6.3 shows that, when other geometric conditions remain unchanged, the horizontal curve radius can significantly affect the operating speed (Figure 6.13). When R > 250 m, the operating speed difference between the horizontal curve and its adjacent sections will be less than 10 km/h. When the curve has the original radius of 580 m, the operating speed difference will be reduced to 3.2 km/h (Figure 6.14), which means drivers can travel from the adjacent section to the curve without changing their speeds significantly. That also reflects that the original design of this section is reasonable.

Table 6.3: Operating Speed and Consistency Level of the Test Curve With Different Radii

R[1]	V85[2]	V85 Difference[3]	Consistency Level[4]
150	81.2	18.8	Fair
250	89.8	10.2	Fair
350	93.3	6.7	Good
450	95.3	4.7	Good
580	96.8	3.2	Good

Note:
1. Alternative curve radii in m,
2. Operating speed in km/h,
3. Difference between operating speeds of successive elements in km/h,
4. Operating speed consistency level based on operating speed difference.

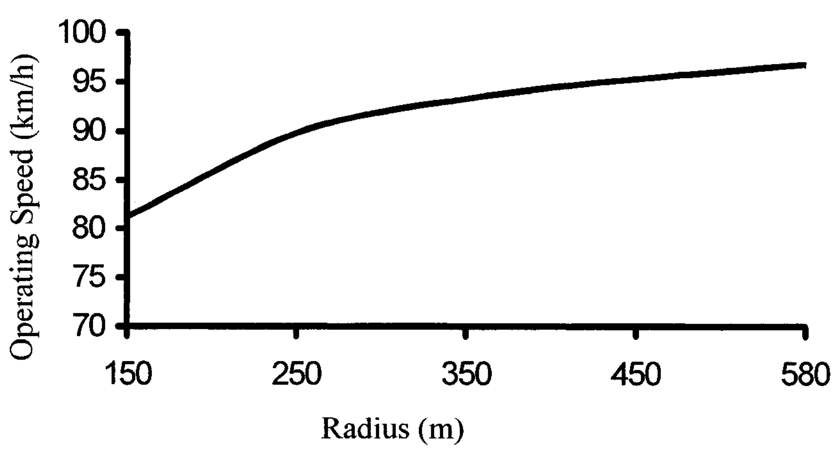


Figure 6.13: The Influence of Horizontal Curve Radius on the Operating Speed

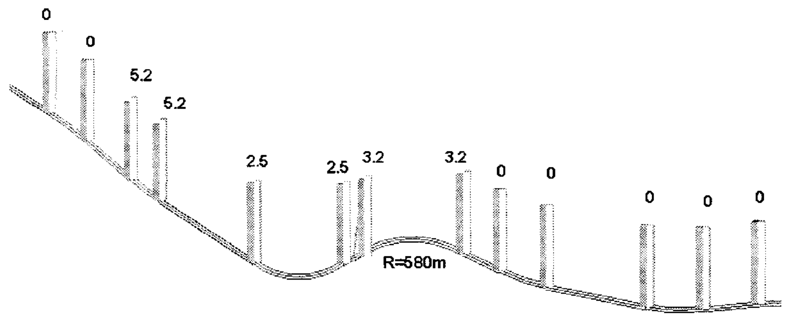


Figure 6.14: Operating Speed Differences (km/h) when the Curve Radius is Increased to 580 m

6.3.2 Case Study Conclusions

In this case, the operating speed consistency of a segment on Highway 61 is studied using the newly developed 3D ArcGIS-based highway consistency evaluation software. This case study is also considered as a verification of the developed software. Through the automation of the developed 3D GIS-based highway consistency evaluation approach, the operating speed consistency of this real case is studied with Fitzpatrick et al. speed-profile model. Major conclusions from this case study are:

1. Since the terrain, where the 17 km test segment from station 10+000m to station 27+000m of Highway 61 is located, is smooth (reflected from vertical alignment) and the horizontal alignment is curved relatively fluently, there are no abrupt speed changes and, consequently, the consistency along the highway section has been achieved successfully. According to the predicted operating speeds and operating speed based highway design consistency evaluation, this segment was designed consistently and the 3D alignment of the highway segment is assigned properly.
2. In this case study, one horizontal curve was intentionally sharpened to test the problem identification and solution capabilities of the developed operating speed

consistency software. The verification indicates that the highway design consistency evaluation program is well developed and applicable to series of 3D rural highways regardless of their lengths and numbers of sections. In addition, the software can identify design consistency problems related to operating speeds. Hence, this software will be a significant contribution to the 3D consistency study, especially for 2-lane rural highways.

3. From this case study, it is also clearly proven that geometric alignment of a highway, especially the curve radii, have significant influence on the operating speeds on it. For example, when the curve in the case study was sharpened from 580 m to 150 m, the predicted operating speed on this curve is decreased by 15.6 km/h (Table 6.3). Hence, in most cases, the proper control of horizontal geometry including the selection of curve radii will affect the level of design consistency of a highway.

Chapter 7

SUMMARY AND CONCLUSIONS

7.1 Summary

As one of the most safety-related subjects in highway geometric design, highway design consistency evaluation has been attracting more and more attention from the transportation engineering community. The in-depth literature review of this study has revealed that considerable research works have been done on highway design consistency evaluation. Many models and corresponding measures have been developed during the past few decades. However, in previous studies, GIS was used merely as a data storing/managing tool or as a presentation tool. It has not been addressed in previous studies that GIS has merged into the core of the procedure for highway design consistency evaluation. In contrast, this is the primary objective of this thesis project. In this study, based on the currently available knowledge on consistency evaluation and the latest advanced GIS techniques, a 3D GIS-based highway design consistency evaluation methodology is developed. The GIS functions involved in this thesis include spatially related data manipulation, especially 3D graphing and modeling. Motivation for this study primarily came from GIS' popularity on dealing with spatial or spatially related data and the extensive involvement of spatial conditions in the procedure of highway design consistency evaluation.

With the rapid development of GIS techniques, more and more traffic data, such as highway alignment information and elevation information are likely stored in GIS data format. The latest advanced 3D GIS visualization techniques allow traffic engineers to work on the real terrain in front of computers, instead of traveling all around the sites. Therefore, GIS or 3D GIS-based approaches are definitely a promising trend for design consistency analysis in the future. Results from this study, in particular, the newly developed 3D GIS-based highway design consistency evaluation methodology and associated software, will be a significant contribution to the promising trend.

Previous studies on design consistency evaluation have been focused on two-lane rural highways. This is mainly because two-lane rural highways consist a big portion of many countries' transportation networks and they have the typicality of various 2D and 3D alignments while their interruptions on drivers' operating speeds are less than other types of highways. Such interruptions include congestion, traffic signal, and intersections. It is exciting to see that there are few arguments on highway design consistency evaluation criteria, which are cited in current publications.

The thorough literature review also shows that previous studies on highway design consistency evaluation fall into several groups, such as operating speed consistency, driver workload consistency, safety consistency, and cross section consistency. Among these groups, operating speed consistency evaluation has been accepted as the most straightforward way to estimate a highway's design consistency. Various streams of research have resulted in many operating speed prediction models in different styles in terms of consideration of 2D and 3D alignments. However, few studies show practical significance. Therefore, unified operating speed prediction models with both accuracy and simplicity should be introduced to highway designers, in order to make highway consistency evaluation easily applicable at the design stage.

GIS has been widely applied in many fields including transportation engineering. Traffic engineers have benefited a lot from the implementation of GIS in such areas as safety study and transportation planning. However, further potential contributions of GIS to the field of highway geometric design are still under exploration. The understanding of previous studies and the latest advanced 3D GIS visualization techniques shows great feasibility of applying GIS in highway geometric design, more specifically, in highway design consistency evaluation. Of course, to get more familiar with the latest GIS techniques is a key challenge to highway designers. This study began as an attempt to this challenge and turn out to be a valuable contribution to design consistency evaluation and, thus to the highway geometric deign field.

This study has focused on exploring potential GIS and 3D GIS visualization applications in highway design consistency evaluation. It has resulted in a valuable contribution to the highway geometric design, a newly developed 3D GIS-based highway design consistency evaluation methodology and associated software. The software consists of five customized tools and their ArcGIS platform. The set of tools has been specifically built for highway design consistency evaluation, including operating speed prediction and consistency level evaluation. Two consistency evaluation measures and a speed-profile model for 3D two-lane rural highway alignments are integrated into this program. This program considerably improves the automation of highway operating speed consistency evaluation procedure. To verify this methodology and software, a case study was done on a 17 km segment of a two-lane rural highway, known as Highway 61 in Ontario.

7.2 Conclusions

Based on this thesis research, the following conclusions are drawn:

1. The most significant contribution from this thesis research is a newly developed 3D GIS-based highway design consistency evaluation methodology and associated software. This newly developed methodology, as a combination of GIS and highway consistency modules, offers highway designers the following unique features: automated consistency evaluation procedure, GIS based 3D-alignment consistency analysis, impressive evaluation result presentation, and spatially based consistency improvement suggestion.
2. Both operating speed models explored for 85th percentile speed prediction in the pilot study have considered the 3D natures of highways. The Gibreel et al. models contain possible influences of most highway geometric factors in order to predict the operating speeds as accurately as possible. In contrast, the Fitzpatrick et al. speed-profile model considers impacts from only the most important parameters intending to keep the equations easy to use. Therefore, while pursuing the accuracy of prediction, the Gibreel et al. models seem too complex to be deployed into the consistency evaluation procedure. On the contrary, Fitzpatrick et al. speed-profile model is simple for implementation but with low accuracy. Since it seems impossible to obtain both high simplicity and high accuracy simultaneously, a trade-off should be sought and more easy-to-use models need to be developed. In addition, more general and widely accepted models need to be developed and be applied to the highway design procedure.

3. In this research, the speed-profile model integrated in the consistency evaluation program is for operating speed consistency evaluation. In fact, many other models, including driver workload based models, safety based models, and other operating speed prediction models can be integrated into the program either separately or simultaneously as long as the data needed for the models are available. Therefore, the 3D GIS-based methodology and software developed in this study will be able to fulfill requirements from different users in different cases.
4. An advantage of this newly developed 3D GIS-based methodology is that, since ArcGIS manages different data in different layers, it can study several highway alignments or highway sections simultaneously. This is particularly important when several alternative routes of a highway need to be investigated. This feature is also important when highway consistency is studied with different considerations. For example, if users want to study highway consistency based on the operating speed consideration and vehicle stability consideration simultaneously, they just need to duplicate the highway layer and apply different consistency models.
5. One limitation of this methodology is that the geometric information of the test highway has to be inputted into the program manually. However, using remote sensing techniques, this work will be much more eased because it will become part of the automated data preparation in which highway geometric information such as grades, K values, and curve radii will be automatically generated and stored together with highway alignments in GIS database. Alternatively, with some customized functions or tools, highway geometric information digitized into ArcGIS can be generated using similar techniques for generations of highway profiles or sight

distances. Consequently, the procedure of highway design consistency evaluation will be equal to simple clicks on buttons in the newly developed 3D GIS-based consistency evaluation program.

6. Although not as professional as many CAD software programs, some GIS software (e.g. ArcGIS) have been developed with strong drawing functions. With the rapid development of the associated software, it is possible to design a highway completely in GIS platform. Here are some potential benefits from doing so: first, based on land use and topography information that imported into GIS software, highway design can be preformed on the simulation of real terrain in font of computers. Second, highway consistency evaluation can be applied at the design stage and this can help to avoid inconsistent design before actual constructions of highways. Finally, if other considerations such as economical and environmental data are integrated into the program, highway consistency will contribute with these factors for the selection of alternative routes of highways during the planning and design course.
7. More specifically, the study of the operating speed-profile model integrated in this developed methodology has shown that the insufficient length of a speed change segment on a highway may force drivers to change the acceleration or deceleration rates which they feel comfortable with (for example, case D in Figure 2.2). Then sometimes the unusual acceleration or deceleration may cause collisions. Hence, the further customized tools may be added into the developed methodology so the acceleration and deceleration rates can take part in the operating speed consistency evaluation procedure as an important consideration for the consistency level rating.

8. Lastly, graphs are always the most valuable language for presentation. With the outstanding graphing functions in GIS visualization software, it is easy and impressive to present the analysis results. This will allow the work to be accepted easily by the public. What may be more exciting is that, with the boom of the current Internet technology, the persuasive presentations of 3D GIS-based research work can be easily shared with users all over the world.

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APPENDIX

LIST OF TRADEMARKS

3D Analyst™	Trademark of Environmental Systems Research Institute, Inc.
3D Studio MAX™	Trademarks of Autodesk.
ArcExplore™	Trademark of Environmental Systems Research Institute, Inc.
ArcGIS™	Trademark of Environmental Systems Research Institute, Inc.
ArcIMS™	Trademark of Environmental Systems Research Institute, Inc.
ArcInfo™	Trademark of Environmental Systems Research Institute, Inc.
ArcObjects™	Trademark of Environmental Systems Research Institute, Inc.
ArcMap™	Trademark of Environmental Systems Research Institute, Inc.
ArcPress™	Trademark of Environmental Systems Research Institute, Inc.
ArcSDE™	Trademark of Environmental Systems Research Institute, Inc.
ArcScene™	Trademark of Environmental Systems Research Institute, Inc.
ArcView™	Trademark of Environmental Systems Research Institute, Inc.
Auto CAD™	Trademarks of Autodesk.
GeoView 3D™	Trademark of GeoAnalytika.
MrSID™	Trademark of lizardtech, Inc.
SiteBuilder 3D™	Trademark of MultiGen-Paradigm, Inc.
Softimage™	Trademark of Softimage Inc.