Optimization of Highway Geometric Design Process for Computer-based Design

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ABSTRACT

In the design process, a virtual model, which can be called an information structure, is built up using information in a virtual space. The information structures used in construction are propagated as a design progresses. However, this process has not been sufficiently analyzed and optimized for computer-based design. This paper summarizes the concept of information propagation in the construction process and analyzes the information flow in the process of highway design. The analysis of the highway design process clarifies the problems with the conventional paper-based method of highway design. The systematic flow of a computer-based highway geometric design method is shown, and the need for a paradigm shift in the highway design method and the relationships between designers, system developers, and verifiers are discussed.

INTRODUCTION

With the current infrastructure life-cycle, much information on design, construction, and maintenance is produced and circulated. In the design process, a virtual model, which can be called an information structure, is built up using information in a virtual space. Eastman (1999) depicted this structure as a cone diagram with abstract and concrete information at the top and bottom, respectively, and we use the same abstract–concrete pyramid structure. Through an analysis of the information structure, it is clear that the information flow of the conventional design process is fragmentary and should be optimized for computer-based design.

In this paper, we first summarize the information structure concept and show the information propagation in highway design processes from previous studies (Makanae 2010; Makanae 2012). Then, we review the highway geometric design process and clarify the problems with the conventional design method. After these analyses, we discuss the optimization of the highway geometric design process for computer-based design.

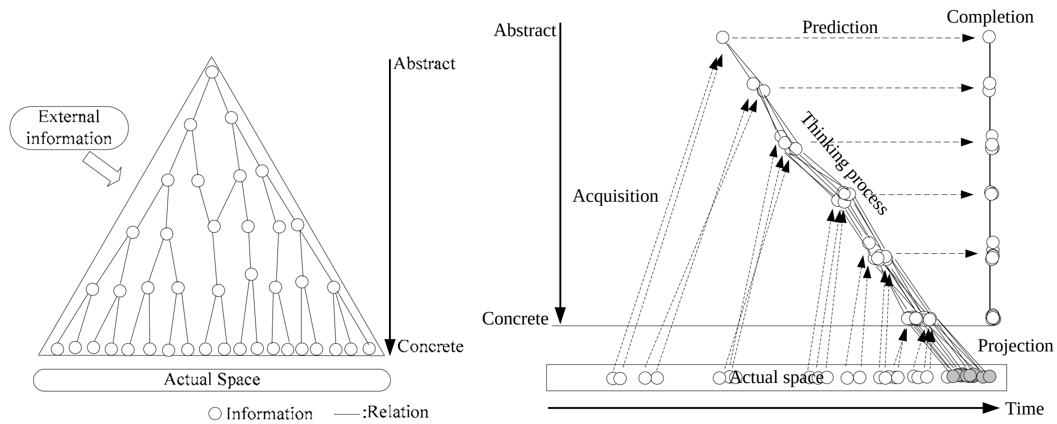
CONCEPT OF INFORMATION STRUCTURE IN DESIGN PROCESSES

In the initial stages of the construction process, highly abstract information is first defined, such as the concept and objective of the construction. Then, the information becomes less abstract in the planning and design phases, and more concrete information is projected into the actual space. The pyramid-scheme design information structure used in the previous studies is shown in Figure 1 (a).

Information is produced by obtaining various types of external information, including actual space information, and abstract information is related to concrete information in the pyramid scheme, which expands downward from the top regardless of the shape of its base.

The relationship between the pyramid scheme and time is considered here. Figure 1 (b) shows the relationship between the pyramid scheme and time by reproducing Figure 1 (a) as seen from the side. Pieces of information are related to each other in the design and construction phases. In these processes, information is produced, while information in the actual space is being obtained. The time efficiency of the construction process is represented by the slope of the entire pyramid.

Abstract information becomes concrete over a period that can span a few years or decades, although this period varies according to the type and scale of the infrastructure. The natural and social environments around the scheme vary during the period, and the information varies accordingly. Information variations may cause the information pyramid scheme to collapse. Continuity from the abstract to concrete information should be ensured in the construction process of the scheme.



a) pyramid scheme (b) relationship between the pyramid scheme and time

Figure 1. Pyramid scheme for construction information.

INFORMATION PROPAGATION IN HIGHWAY DESIGN PROCESS

The information propagation in a highway design process was analyzed in the previous study (Makanae 2012). Figure 2 shows the propagation process for highway design. In the first highway design stage, an origin, a destination, and the traffic volume between them are defined based on the traffic management policy in the targeted areas. At the next stage, basic cross-sectional profiles and design speeds are defined to correspond with the features of these areas. According to these basic conditions, more precise conditions such as grade and curve limitations, and their rates, are considered and defined. In the next stage, control points derived from the results of surveys are plotted on the maps. These control points include natural environmental factors such as geological, meteorological, and ecological control points, along with social environmental factors such as the positions of existing highways, residential areas, and public facilities. After this stage, some routes are drawn on the map to match the controls, and the most appropriate route is selected. After this route is defined, alignments and structures are designed, and three-dimensional virtual models can be defined.

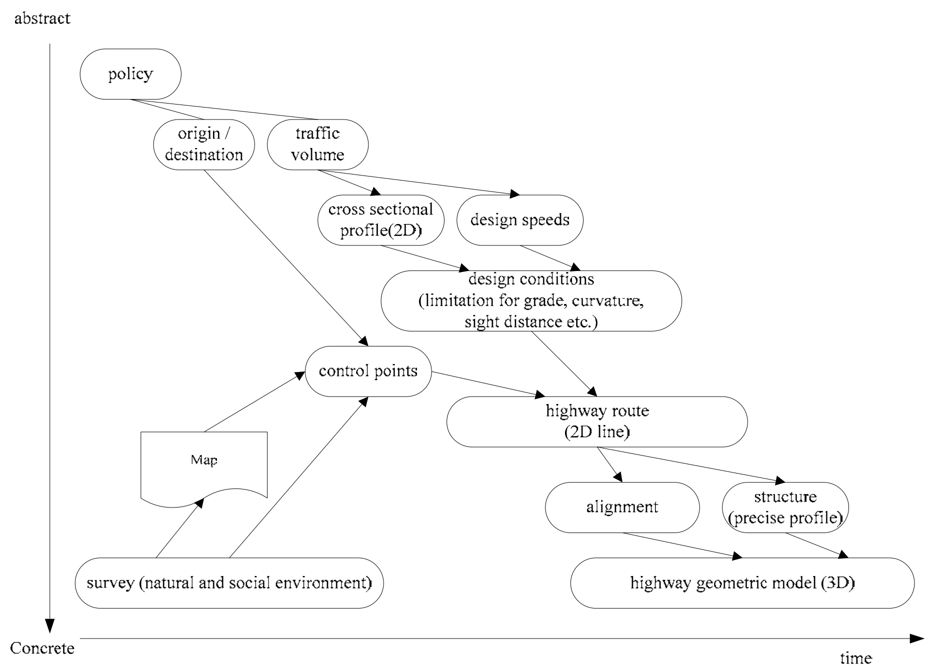


Figure 2. Information propagation in highway design process.

OPTIMIZATION OF HIGHWAY GEOMETRIC DESIGN PROCESS

The information flow in Figure 2 seems to be systematic and continuous. However, this is not always the case, especially when using the conventional geometric design system. The conventional method of highway design is mostly based on the policies and design manual that were developed for paper-based design in the 1940–1970s in many countries. Although digital and information technologies have become popular in the last few decades, the basis of these design techniques and policies has not been changed. The paper-based design system was developed to allow any designer to define geometries without the need to make calculations or have a knowledge of vehicle and road dynamics.

Figure 3 shows the conventional process for designing highway geometries based on the current design policies (e.g., ASSHTO 2011). After defining the design controls, a designer designs the alignment and cross-sections of a highway by referring to the criteria tables in the design manuals. The criteria about geometrics such as radii, grade, and so on, are shown as class tables, which are derived in advance using theory and logic in many cases. The designer simply refers to these criteria throughout the design process.

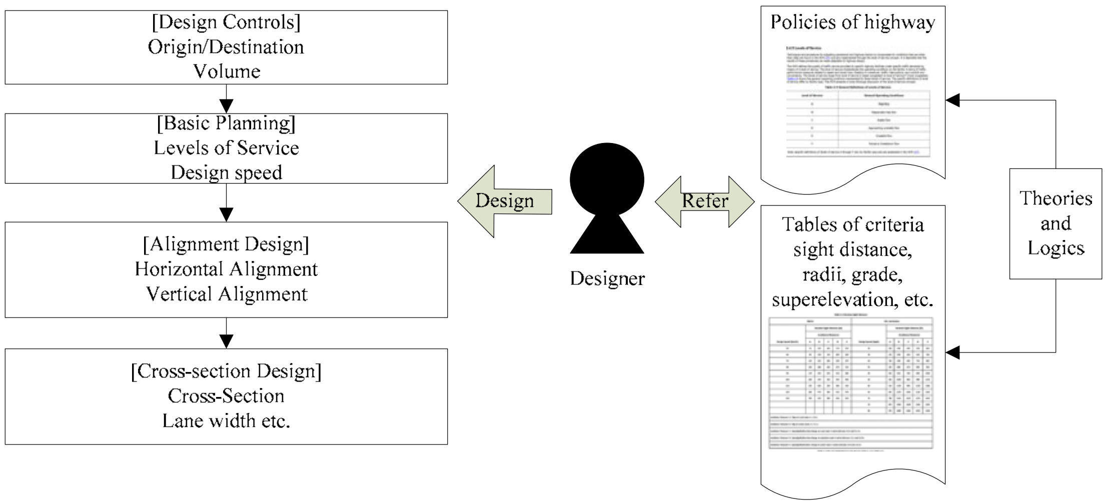


Figure 3. Conventional design process for highway design.

Nowadays, because every designer has their own computer, the design processes should be refined for computer-aided design. Accordingly, we need to review and reconstruct the design process theoretically and build an algorithm to define highway geometries for advanced highway computer-aided design (CAD) systems.

The author has already developed a highway geometric design system and analyzed the highway design mechanism in order to derive an optimized algorithm to build highways with three-dimensional geometries (Makanae 2005). Figure 4 shows the systematic flow used to build the highway geometries.

If basic conditions such as the design speed, cornering force coefficient, vehicle type are defined, design conditions such as the sight distance, maximum values for the gradient, curvature, and crossfall can be set. Moreover, three-dimensional geometries can be defined automatically, including a superelevation, lane widening, and crossfall for drainage, when the inflection points for the curvature and grade in a section are defined.

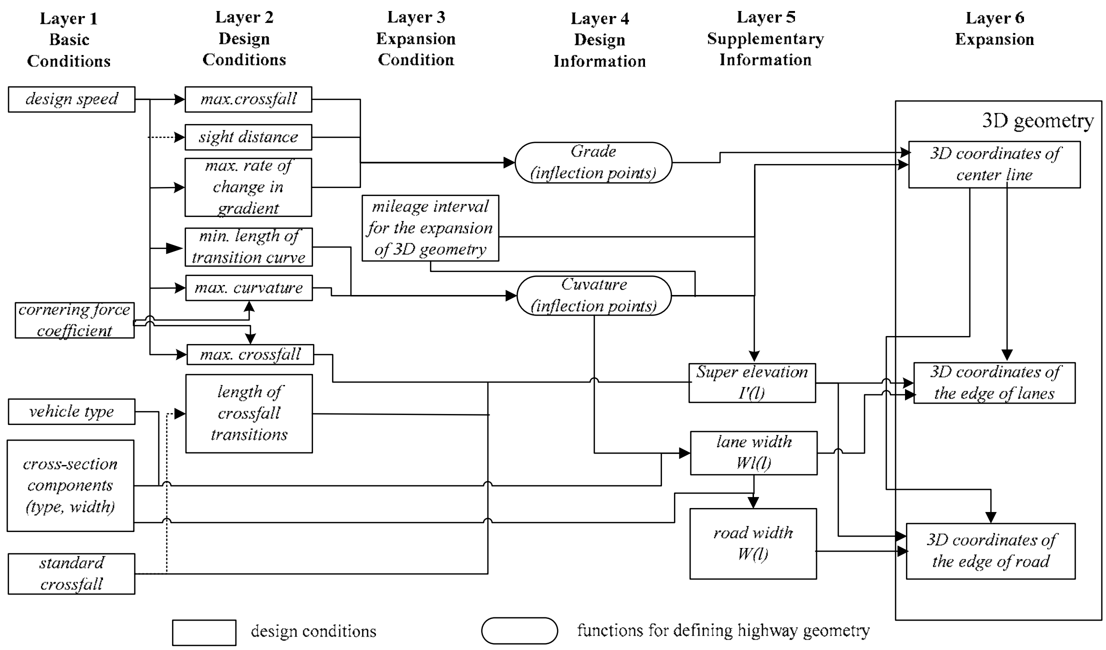


Figure 4. Systematic flow to build highway geometries.

PARADIGM SHIFT FOR COMPUTER-BASED DESIGN

As building information modeling has recently become popular in the construction field, the importance of data structures in highway engineering has also been realized (Lee et al. 2006). Although there have been several projects (e.g., Lebègue 2013) and studies (e.g., Amman et al. 2013) with the aim of building highway product models, the alignment systems have not been sufficiently improved for computer-based design. If the method proposed in the previous section is applied, a parametric highway design system can be established. However, there is a problem with how to treat the policies and criteria in the current design manuals in the new system.

The author proposes a paradigm shift for design manuals in order to solve this problem. As shown in Figure 4, highway geometries can be defined mathematically using several parameters and inflexion positions in horizontal and gradient alignments. Although this process requires no tables for the criteria, mathematical logic is directly required in the system. Hence, two types of criteria should be used: the criteria for designers and the criteria for CAD system developers. Table 1 lists the items in the criteria for designers and system developers.

A CAD system developer implements the mathematical algorithm and expressions to build three-dimensional geometries. A designer defines the design speed, vehicle type, and cross-section components based on the service level for the functions and capacity of the planned highway, cornering force coefficient, and standard crossfall for safety and drainage systems. After defining the conditions, the designer draws an alignment in the virtual spaces in the CAD systems. In addition, the systems should simultaneously convert the drawn alignment into curvature and grade information and ensure that the designer's drawings meet the criteria. A problem with this system is

Table 1. Criteria for designers and CAD system developers.

Geometric criteria for designers

Category	Sub-category	Items
function and capacity	service level	design speed vehicle type cross-section components (type, width)
safety and drainage		cornering force coefficient standard crossfall
alignment design		curvature and grade design

Geometric criteria for CAD system developers

Category	Items
design condition calculation	maximum crossfall (function of design speed) sight distance (same as above) max rate of change in grade (same as above) min length of transition curve (save as above) max curvature (save as above) min curvature (save as above)
geometric calculation	superelevation (function of curvature and cornering force coef.) lane width (widening) (function of curvature and cross-section components) Coordinates centerline (3D coordinates) (function of inflexion point of curvature and grade) edge of lane (3D coordinates) (function of centerline, curvature and lane width) edge of road (3D coordinates) (function of centerline, inflexion point of curvature and grade)

that designers cannot evaluate whether the systems work correctly. A verification system should be established to solve this problem.

Figure 5 shows the relationships between a designer, developer, and verifier. The verifier checks and verifies the algorithm of the highway design software. Applying this new paradigm will make highway design systems more sophisticated and improve the quality and efficiency of design work.

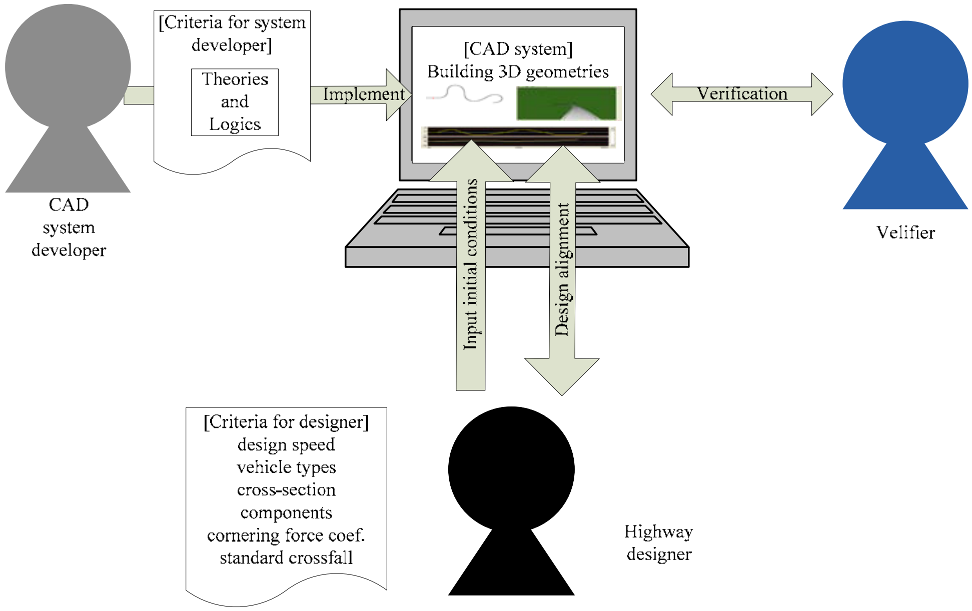


Figure 5. Relationships in computer-based highway design process.

CONCLUSION

All infrastructures and buildings in the real world are made using information structures produced by designers. Information structures are propagated as design progresses. However, this process has not been sufficiently analyzed and optimized for computer-based design. In this paper, the information flow in the highway design process was analyzed, and the problems with the conventional design method were clarified. The author showed the systematic flow of highway geometric design and proposed a paradigm shift in the policies and criteria for computer-based design. In addition, the relationships between designers, CAD system developers, and verifiers under the new paradigm were shown.

Although this paper analyzed only the geometric design process for a highway, the whole design and construction process for a highway should be analyzed and optimized for the computer-based environment in the future. Meeting this challenge would improve the efficiency of the construction processes.

ACKNOWLEDGEMENT

This research was supported by JSPS KAKENHI Grant Number 24560569.

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