# AN INTEGRATED SYSTEM FOR AUTOMATIC BRIDGE PLANNING


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Abstract: At the early stage of bridge design, many factors are considered before determining the bridge's geometrical alignment and length of spans, which have great influence on the construction method and costs. Traditionally, the alignment and spans are determined based on the design engineer's experience. However, the resulting design, though feasible, may not necessarily be the most economical, due to the nature of the numerous possible combinations of span lengths.

This paper presents an integrated, automatic system (Automatic Bridge Planning System, ABPS) for preliminary bridge design. In ABPS, relevant site data, such as hydrological and geological conditions, as well as existing obstacles, are computerized into an object-oriented environment. In addition, code requirements for bridge design, common bridge construction methods, and expertise elicited from experts, are represented as various knowledge bases. The input to the system is a set of start/end positions of the bridge marked by the designer on a Geographical Information System (GIS) map on the computer screen. The output of the system is a set of the most feasible solutions that not only meet the site conditions and code requirements, but also bear minimum construction costs. The output solution consists of geometrical alignment and span lengths, structural units, and major beam sizes, which can serve as basic criteria for the detailed design of the bridge.



Keywords: automatic system, bridge planning, expert system, object-oriented programming, spatial analysis


## 1. Introduction

At the early stage of bridge design, the bridge’s alignment and spans need to be determined first, since they have great influence on the construction method and costs [1]. The determined bridge’s alignment should not only meet requirements in the highway design codes, but also fit into the confined site conditions, such as geographical conditions, hydrological conditions, position of obstacles, and profile of river beds [2]. The bridge's span arrangement is regulated by the same conditions but may be subject to fewer requirements in the design codes. The bridge’s alignment and spans form the geometrical appearance of the bridge and thus have great influence on the selection of the construction method. Furthermore, these two decisions set initial criteria for the bridge’s detailed design, such as height of piers, type and depth of beams and girders, etc.

Since a bridge is part of the highway, the bridge’s alignment must fit into the highway that is designed based on highway design codes. Hence, the designed features of the highway such as number of lanes, lane width, minimum curvature, etc., apply to the bridge’s alignment as well. In this research, the highway design codes are represented in an object-oriented (OO) environment via various objects, methods, and rules [3,4]. The bridge’s alignment is then designed in the same OO environment. To automate the design process, a geographical attribute knowledge base is also built in the environment that enables spatial reasoning when required by the design codes.

Once the bridge’s alignment is determined, one of the most important design tasks is to determine the location of each pier of the bridge, i.e., to perform the task of span arrangement. Theoretically, there are numerous span arrangements, depending on the length of the bridge and on how the piers are located along the alignment. However, factors such as site conditions, construction methods, construction costs, and even aesthetics, may prune many unfeasible arrangements. This research applies expertise elicited from experts such that the most economical construction method and typical span lengths are suggested for various lengths of bridges. Combined construction methods for one bridge are also considered in this research. The expertise is represented as rules in the OO environment. Again, the previous geographical attribute knowledge base is incorporated to facilitate the required spatial reasoning process.

The developed OO system, integrated with geographical features, is termed Automatic Bridge

Planning System (ABPS). The input to ABPS is a set of start/end positions of the bridge that are marked by the designer on a Geographical Information System (GIS) map on the computer screen. The output of ABPS is a set of the most feasible solutions that not only meet the site conditions and code requirements, but also bear minimum construction costs. The output solution consists of geometrical alignment and span arrangements, structural units, and major beam sizes, which can serve as basic criteria for the detailed design of the bridge.

## 2. Bridge Alignment

### *2.1 Highway alignment design codes*

A bridge is part of the highway, thus its alignment should meet the requirements of the highway design codes. A highway's alignment is determined by its service level, located district, and administration agency [5]. Alignment data, such as design speed, width of lanes, width of shoulders, and minimum curvature radius, are determined or calculated based on the design codes. Once the alignment data are obtained, the highway's alignments of plane, vertical section, and cross section can be drawn.

The formats of highway design codes can be categorized into three types:

1. Clauses: A clause is a statement that describes requirements or regulations of the highway. E.g., if the highway has only one single lane, the minimum width of the lane is 4.5 meters [6,7].
2. Tables: A table describes a corresponding value or feature for a certain factor. E.g., various minimum radii of curvature are required for different design speeds.
3. Formulas: A formula is an equation in which one design factor is calculated from several other design factors. E.g., a broaden-width on curve is calculated from design speed, number of lanes, and other design factors.

The above design codes can be represented in an OO environment [3,4]. In the OO environment, highway related objects are first pre-defined as class objects in which relevant attributes (or properties) are defined as various slots. To design the alignment of a new highway, instance objects are created to store design data. For the requirements that are in clause form, rules are created using the pre-defined objects in "IF-THEN" form. For the requirements that are in table form, corresponding values or features are stored in pre-defined objects and can be retrieved for various conditions. The design formulas are stored in the form of "method" in relevant objects and are activated when related information or data are determined and calculated in the environment.

### *2.2 Object-oriented geographic features*

To effectively shorten the input process as well as to depict the bridge's geographical environment and planned results, functions to process geographical information are integrated into the developed ABPS. In ABPS, geographical information and its spatial reasoning functions are built and represented via a geographical attribute knowledge base [8]. The knowledge base consists of (1) objects and slots that represent geographical layers of coverage and their attributes, respectively; (2) methods embedded in the objects and slots that perform spatial reasoning functions; and (3) rules that contain suggestions from experts. Thus, the geographical functions performed by the integrated geographical knowledge base enable ABPS to fully display the geographical information such as bridge alignment and locations of piers, without assistance from external geographical information systems.

### *2.3 Bridge buffer zone analysis*

A bridge buffer zone is the area where feasible bridge alignments are located[2]. The buffer zone is confined by the start/end points of the bridge and by two opposite arcs connecting the two points. The buffer zone is determined by the following information:

1. Start/end points
   At the early stage of design, the bridge location is only roughly determined by the location of the obstacles it is to cross. However, at this stage this bridge location is only a preliminary plan in which geographical conditions and/or existing objects may have not yet been considered. Thus, ABPS must be furnished with start/end points at locations deemed by the planner most appropriate (ABPS, though, is also able to provide a bridge alignment from a set of arbitrarily determined start/end points..
2. Arcs:
   A straight line, having the minimum length among all alternatives, appears to be the ideal bridge alignment.. However, in the case of a curved highway at the proposed bridge location, or non-supporting site conditions at either bridge end (geographic/topographic constraints or existing obstacles), it is not feasible to construct a straight-line bridge. Therefore, a feasible bridge alignment must be located between two opposite arcs that are part of a simple or a complex curve, to perform a smooth transition between two ends of the bridge. According to highway design codes, the radius of the bridge alignment curve must be greater than that of the highway's minimum plane curvature. Thus, in addition to this code requirement, the planner needs to furnish ABPS with a set of two constraint points at each end of the bridge to accommodate existing site conditions. The two constraint points limit the direction of the bridge alignment; i.e., a tangent line at the end of a bridge must pass through between the two constraint

points. These two constraint points usually generate a smaller arc than that required by the code.

Once the bridge buffer zone is obtained, the planner can select or point out an alignment inside the buffer zone as desired.

# 3. Span Arrangement

*3.1 Retrieving geographical information*

After the bridge's alignment has been determined, a bridge belt can be drawn to display the strip area covered by the bridge. The bridge belt is the central line of the alignment with the calculated width of the highway. Inside the bridge belt, geographical information such as elevations, locations of obstacles, geology data and depths, and highest/normal water levels, etc., are retrieved from the previous object-oriented, geographical attribute knowledge base for a later-on arrangement of bridge spans.

*3.2 Bridge construction methods*

Five commonly used construction methods for a bridge superstructure are incorporated in this research. These are: Advanced Shoring Method (ASM, abbreviated as A); Balanced Cantilever Method (BCM, abbreviated as B); Cast-in-place Box-girder Method (CBM, abbreviated as C); Incremental Launching Method (ILM, abbreviated as I); and Simple I-girder Method (SIM, abbreviated as S). Each of these has its typical economical bridge length and span lengths that are suggested by domain experts [9,10], as shown in Table 1.

*3.3 Bridge construction sections*

Although combined methods may be used for the construction of a single bridge, their number is practically limited to three, for economical and management reasons, given the different equipment and other resources they require. Normally, unless the bridge is extremely long , two methods should be sufficient for one bridge.

Hence, a bridge is divided into three construction sections at the most, each being constructed by one single construction method. For example, if only one construction method is used, e.g., Advanced Shoring Method, then the bridge is represented as AXX, where the XX means the other two sections do not exist. In the same case, if there are two types of span lengths, both using the same construction method, then the bridge is represented as AAX, since the second construction section requires a different-size formwork. I.e., each span is identical in one construction section.

After a careful consideration on the characteristics and limitations of the five bridge construction methods, there are five 1-section, twenty-five 2-section, and twenty 3-section types allowed in the proposed ABPS, as shown in Table 2.

*3.4 Determination of span arrangement*

Since every span length is the same in the same construction section, determining a feasible span arrangement must consider the following two factors before checking obstacles at the site:

1. Construction method: each method has its own typical/economical lengths and constraints during the construction process.
2. Aesthetics: symmetrical spans should be considered first [11]. The ratio between the span length and the depth of piers should also be considered [12,13]. In addition, the span ratio between two consecutive bridge sections should be limited from 0.4 to 1.0. The ratio between lengths of two construction sections should be limited from 0.25 to 1.0. The above ratios are obtained from domain experts and are subject to modifications by the planner in ABPS.

*3.5 Checking of constraints*

Once feasible span arrangements for each construction section are determined, location of each pier is drawn and checked against the existing obstacles whose geographical information was retrieve earlier. If an obstacle is located at or near a planned pier location, such that constructing the pier becomes impossible, the planner has to estimate the cost of removal. If the obstacle cannot be removed, the span arrangement for the section is abandoned. Another constraint checking is that the height of piers should meet that required by the construction method in that section. For certain construction methods, e.g., CBM and SIM, none of the planned piers should be located at the position where water of the river exist, otherwise that pier cannot be constructed by CBM or SIM. Similar miscellaneous items are also checked to meet constructability requirements.

Table 1. Typical economical bridge length and span lengths for various construction methods

| Construction Method | Abbreviation | Bridge Length (meters) | Span Length (meters) |
|---|---|---|---|
| Advanced Shoring Method | A | 400 - 3000 | 30, 35, 40, 45, 50, 55, 60, 65, 70 |
| Balanced Cantilever Method | B | 200 - 1200 | 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200 |
| Cast-in-place Box-girder Method | C | 400 - 3000 | 30, 35, 40, 45, 50, 55, 60, 65, 70 |
| Incremental Launching Method | I | 200 - 800 | 30, 35, 40, 45, 50, 55, 60 |
| Simple I-girder Method | S | 50 - 3000 | 20, 25, 30, 35, 40 |

Table 2. Allowable combinations of construction sections in ABPS

| Type | Allowable Construction Sections (X means none) |
|---|---|
| 1-section | AXX、BXX、CXX、IXX、SXX |
| 2-section | AAX、ABX、ACX、AIX、ASX、BBX、BAX、BCX、BIX、BSX、CCX、CAX、CBX、CIX、CSX、IIX、IAX、IBX、ICX、ISX、SSX 、SAX、SBX、SCX、SIX |
| 3-section | AAA、ABA、ACA、ASA、BBB、BAB、BSB、BCB、CCC、CAC、CBC、CSC、IAI、IBI、ICI、ISI、SAS、SBS、SCS、SSS |

### *3.6 Bridge structural elements*

A structural unit consists of a number of spans in a bridge. In a structural unit, the same type of structural members such as beams will have the same mechanical behavior, and will be designed and maintained as one batch. Expansion joints or similar facilities are built between two structural units. Usually, the number of spans ranges from three to five according to experts, while there is only one structural unit if the bridge is constructed by the ILM method.

In ABPS, twelve commonly used types of bridge piers and six types of abutment are stored for convenience of design. Each of the piers has an appropriate construction height, with a typical width of the beams laid on it [14]. Typical foundations for various ground conditions are also built into ABPS. Thus, after the bridge's construction sections and their span arrangements have been determined, sizes and types of these major structural elements can be automatically obtained by reasoning relevant rules in ABPS. The required information for reasoning may include span lengths, height of piers, depth of foundations, height of the abutment, and geological information extracted from the geographical attribute knowledge base. The reasoning results generate geometrical dimensions of the box-girders, I-beams, piers, and abutments. ABPS is able to print or output these dimensions for more detailed structural design.

### *3.7 Construction cost and duration estimation*

The final process in the preliminary bridge design is to estimate construction costs and duration. In ABPS, rules elicited from experts are able to estimate such information based on the determined bridge construction sections (methods), span lengths, and sizes of major structural elements. Costs of the bridge's superstructure are calculated based on unit prices per square meter for various construction methods, while costs of the bridge's substructure are determined by unit prices per length for piers or foundations that vary by types. Accordingly, the total construction costs are then obtained by adding the two above costs and the cost for removing obstacles. The top ten plans with the lower construction costs are selected and ranked by ABPS as the final alternatives.

As for the duration estimation, since a bridge is a linear structure on the ground, its substructure, including foundations and piers, can be constructed at the same time if sufficient crews are provided. Hence, ABPS outputs only the duration for constructing a single foundation or pier. The construction duration for the superstructure of the bridge depends on the construction method used, and is calculated on the basis of the size of the bridge's area.

## 4. System Implementation

### *4.1 System structure*

There are twelve modules in ABPS to assist the preliminary bridge planning process. These are: (1) highway alignment design module; (2) geographical features editing module; (3) bridge buffer zone analysis module, (4) spatial information extraction module; (5) span arrangement determination module; (6) structural unit analysis module; (7) pier allocation module; (8) constraint checking module; (9) bridge element selection module; (10) bridge element geometry module; (11) cost/duration estimation module; and (12) report generation module. The information flow among these modules is shown in Figure 1.

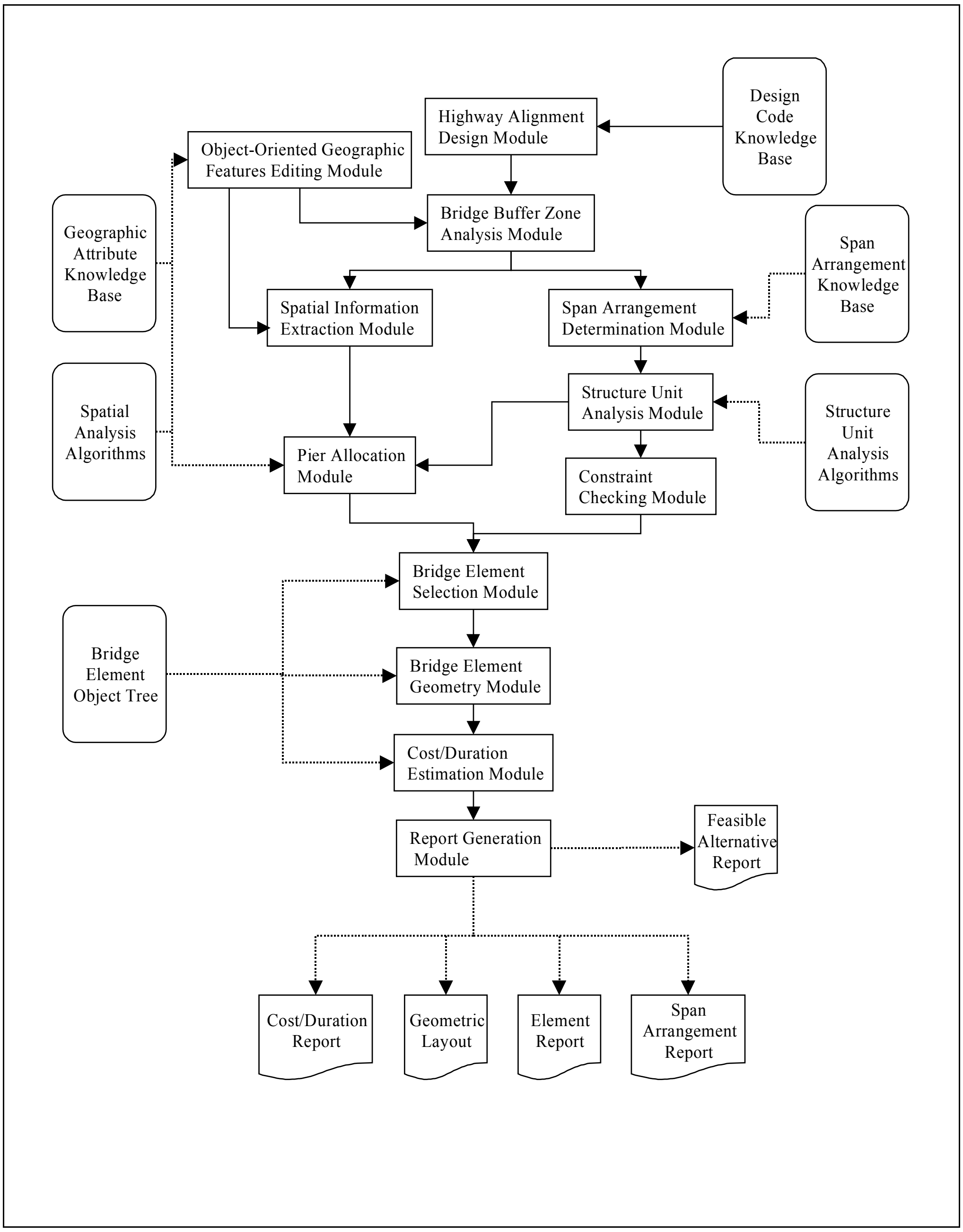


Figure 1. Information flow among twelve modules in ABPS

Table 3. Input and output factors for the demonstration example

| Input Factors | Value | Output Factors | Value |
|---|---|---|---|
| Administration of highway | interstate | Design Velocity | 120 km/hr |
| Function of highway | freeway | Width of one lane | 3.75 m |
| Located zone and terrain | rural_plain | Width of outside shoulder | 3.0 m |
| Climate | normal_area | Width of inside shoulder | 1.0 m |
| Level of highway | level_1 | Normal Crown (NC) | 3% |
| Design vehicle | WB50 | Normal Shoulder Slope (NSS) | 4% |
| Two way? | yes | Maximum superelevation rate (emax) | 0.10 |
| Lane # of right side | 4 | Superelevation rate (e) | 0.08 |
| Lane # of left side | 3 | $R_{min}$ | 560 m |

*4.2 Implementation platform*

ABPS is implemented in KAPPA PC 2.4™, a windows-based, OO expert system shell running on personal computers. The shell is selected due to its powerful system functions that provide the flexibility to establish geographical information system functions inside a user-friendly, OO environment [15,16].

## 5. Example

An example is presented herein to demonstrate the capabilities of ABPS. The planned bridge is roughly 700 meters in length. Input and output factors for the bridge are shown in Table 3.

As shown in Figure 2, the bridge's buffer zone is enclosed by the two outer arcs that are drawn based on code requirements. The bridge's alignment is selected inside the smaller buffer zone, which is enclosed by two smaller arcs that are generated by two constraint points at each bridge end. The selected bridge alignment is 720 meters in length with a radius of 3000 meters.

After the bridge alignment is determined, ABPS automatically generates the top ten alternatives, as shown in Table 4, and ranks them by construction costs. For each alternative, construction sections as well as their span arrangements and construction costs are determined by ABPS. For the best alternative proposed by ABPS, Figure 3 shows the construction method, structural units, and spans, and Figure 4 displays geometrical details of the proposed piers and girders.

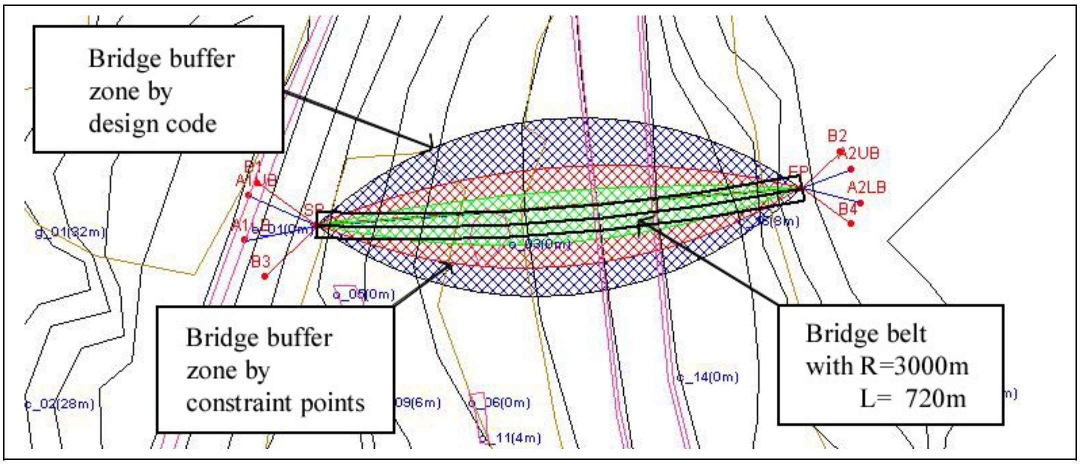


Figure 2. Output of bridge alignment for the demonstration example

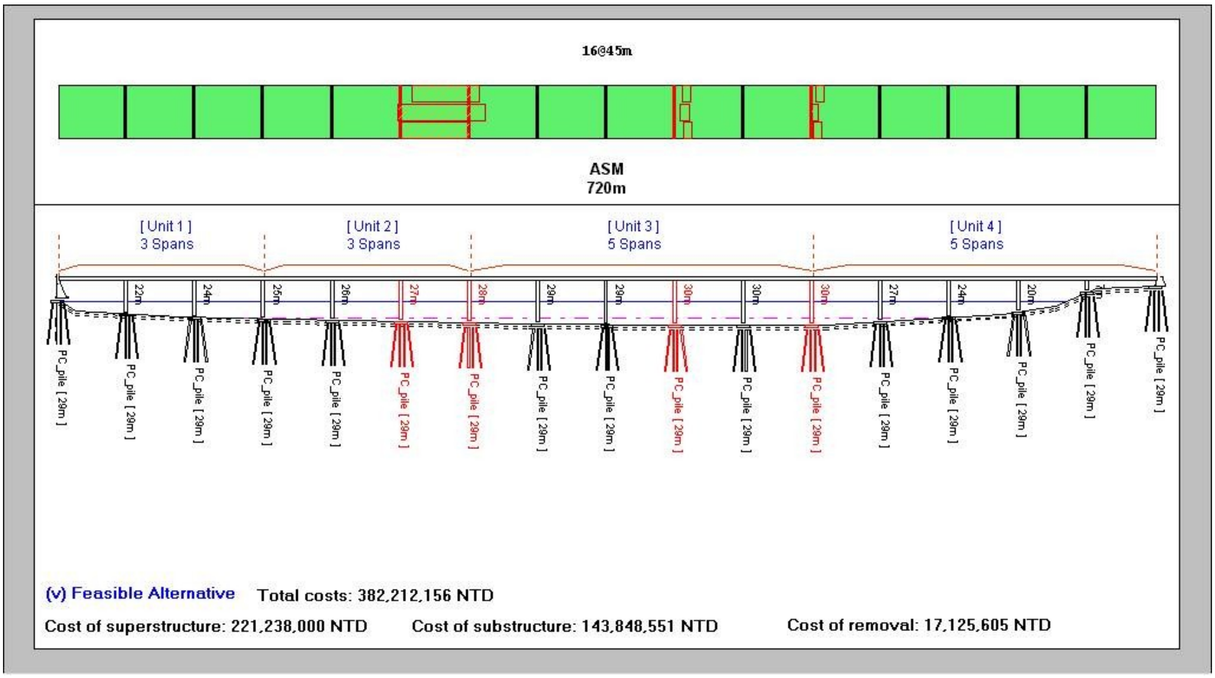

Figure 3. Display of structural units and spans for the demonstration example

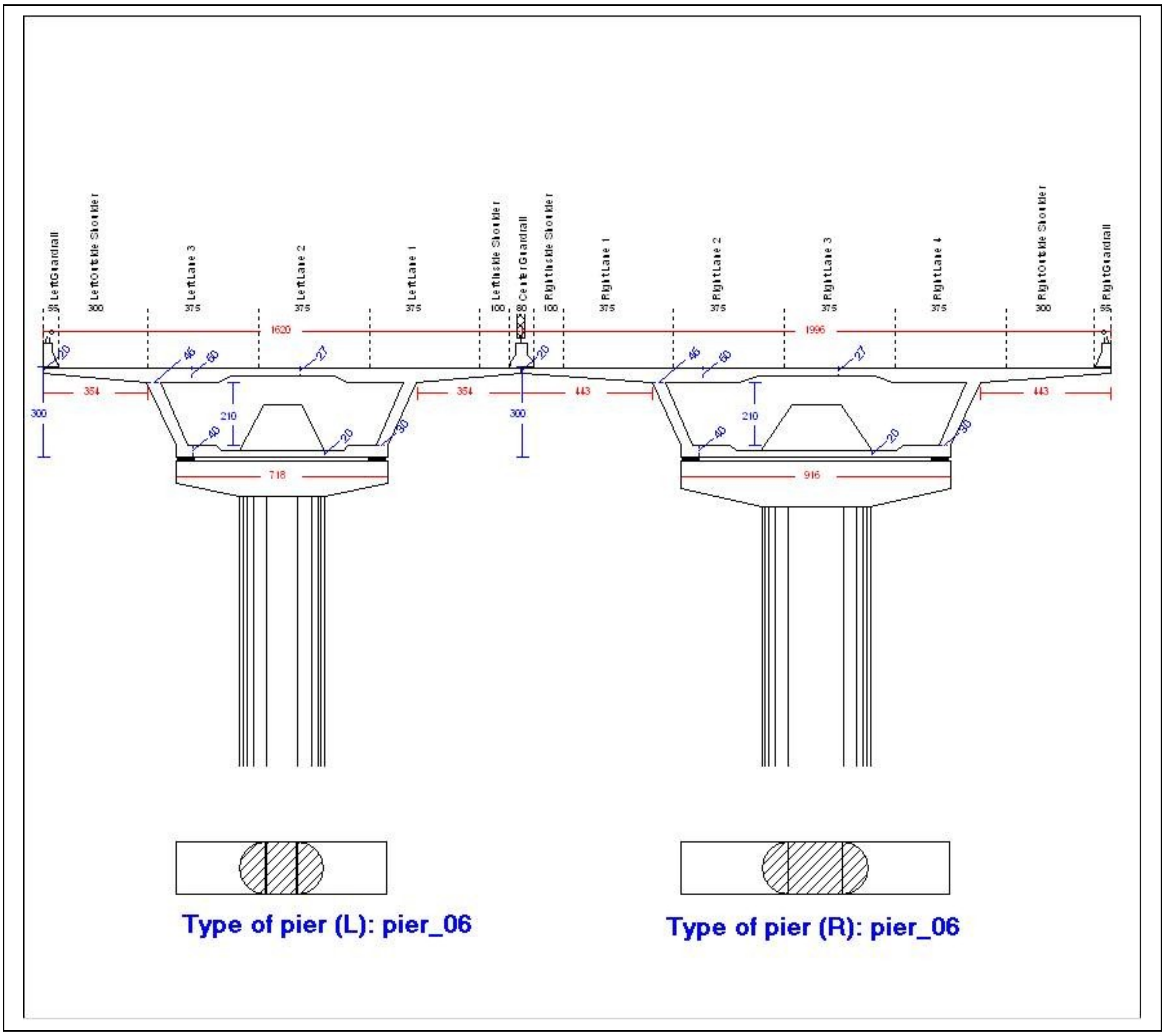


Figure 4. Geometrical details of proposed piers and box girders

Table 4. Span arrangements of the top 10 alternatives

| No. | Bridge Sections | Total Costs | Span Arrangement |
|---|---|---|---|
| 1 | AXX | 382,212,156 NTD | [16@45m] |
| 2 | AXX | 392,800,266 NTD | [18@40m] |
| 3 | AIX | 393,019,406 NTD | [9@50m]+[6@40m+1@30m] |
| 4 | AIX | 401,084,193 NTD | [9@50m]+[7@35m+1@25m] |
| 5 | IAX | 402,109,501 NTD | [1@40m+4@50m]+[12@40m] |
| 6 | IAX | 402,125,379 NTD | [1@30m+6@40m]+[9@50m] |
| 7 | AIX | 402,143,859 NTD | [12@40m]+[4@50m+1@40m] |
| 8 | SAS | 407,016,987 NTD | [4@30m]+[12@40m]+[4@30m] |
| 9 | AIX | 407,673,858 NTD | [10@45m]+[6@40m+1@30m] |
| 10 | IAX | 410,363,666 NTD | [1@25m+7@35m]+[9@50m] |

## 6. Conclusions

This paper presents ABPS, an integrated, automatic system for bridge design at the preliminary design phase. ABPS is capable of generating a set of alternatives for which code requirements, site conditions, bridge aesthetics, feasible construction methods, and construction costs are all considered. For each alternative, ABPS determines the arrangements of spans, piers, beams, and foundations with minimum interaction on the part of the user.

ABPS is a robust system for preliminary bridge design in that it is able to perform quick, comprehensive search for feasible solutions. However, ABPS has not yet been verified by practical bridge projects that are under planning. If ABPS is acceptable by bridge design professionals, its functions are likely to be integrated with existing bridge detail design software, so as to fully automate bridge design.

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