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RAPIDBRIDGEBUILDER - SIMULATION TOOL FOR ACCELERATED BRIDGE DESIGN AND CONSTRUCTION

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ABSTRACT

This paper presents RapidBridgeBuilder, a discrete-event special-purpose simulation modeling tool for accelerated bridge design and construction geared towards practitioners. The paper explores the capabilities of the system by modeling a bridge operation as a case study. The design and operation of bridge construction are initially modeled with input parameters and are successively improved based on insights obtained from the static and dynamic outputs of the previous model. The paper also describes the tools and techniques that were used to develop the simulator.

1 INTRODUCTION

In Australia, during the years 2003 to 2011, an average of 69 collisions involving trains and pedestrians or road vehicles occurred each year at level crossings (Australia Transport Safety Bureau 2011). According to the Federal Railroad Administration (2014), more than 2000 accidents were observed at railway crossings in the United States each year from 2006 to 2013. Moreover, the statistics show that there were 230 and 239 fatalities reported in 2012 and 2013 respectively. These deaths at crossings were on a pace to reach the highest level since 2010. Each year hundreds of people across Europe die in accidents at level crossings, which accounts for one third of all rail fatalities (European Commission 2010). These statistics have led to calls to increase the safety at level crossings to mitigate the risk of fatal incidents. The simplest approach to the problem is to build an overpass bridge. The literature (Silla and Kallberg 2012) shows that the number of road users killed at level crossings has fallen since the mid-1990s due to the construction of overpasses at crossings in Finland. However, as it presently stands, the process of constructing a grade-separated crossing is majorly disruptive, time consuming and costly—costs range into the hundreds of millions of dollars for a single upgrade (Queensland Department of Transport and Main Roads 2014).

To address this issue, the authors explore a bridge superstructure concept that employs advanced composite members, which has been conceived with the express intent of reducing design and site construction time. However, this method could result in an increase in construction cost due to the reduced duration, which can cause project owners to hesitate in applying it to their construction projects. Furthermore, innovative concepts and projects, particularly in the realm of structural engineering, take a while to become accepted as standard practice. Therefore, it is necessary to develop tools to identify as many scheduling conflicts as possible in the design stage and allow practitioners to find the best way to reduce construction time while minimizing cost.

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This paper thus presents a special-purpose modeling tool that allows a person to choose the location of a potential bridge and, based on a few simple inputs, design 3D bridge members, simulate and visualize the construction process. Firstly, the program requests a few simple inputs related to the geometric, speed and comfort requirements of the bridge. Following this, a subroutine is executed which designs the bridge structurally, breaking down and sizing the core components. The results are then passed on to a Stroboscope (Martinez 1996) based discrete-event simulation (DES) routine to ascertain the scope and duration of the required works. DES system that uses forms of activity cycle diagrams (ACDs) and the activity scanning (AS) modeling paradigm has been recognized as a useful technique for the quantitative analysis of operations and processes of a constructed facility (Martinez and Ioannou 1999; Martinez 2010). The system presented in this paper thus uses Stroboscope as a simulation engine.

Concurrently, the information from the structural design subroutine is used to generate 3D models of the bridge componentry. Upon completion of both the Stroboscope based simulation and the generation of 3D component models, the program creates a Vitascope++ (Kamat 2003; Rekapalli 2009) 3D animation to visualize the construction process for verification and presents the user with summary and key statistics.

It is this output that can help to convince stakeholders that the Rapid Bridge concept is worthy of attention. The costs, timeframes and resource consumption can be estimated and validated by way of 3D simulation. This achieves the objective of the tool: to fill the gap between the design/construction team and stakeholders. Lee at el. (2013) identifies that applicability of simulation models to the industry is one of the main three challenging areas in computer simulation. The Coupling of functionality that RapidBridgeBuilder provides can greatly increase the power of DES in the industry. Therefore, the practitioner can have the ability to evaluate a much wider scope of possibilities for bridge design than previously available.

2 RAPID BRIDGE CONCEPT

The Rapid Bridge concept design makes use of lightweight, high-strength composite-materials which reduce the weight of large spanning members, allowing for the bridge to be assembled from fewer, larger components. The design has a strong focus on minimizing construction time by avoiding large earthworks, reducing the number of crane lifts and prefabricating as many structural elements as possible. The structure has been designed as a symmetric 2D row of arches and trusses, as shown in Figure 1 below, which is repeated identically along the width of the road.

Figure 1: A 2D representational showing one row of the Rapid Bridge concept design spanning over three train lines. This structural configuration was designed to fit the vertical alignment curve of a 60 km/h road.

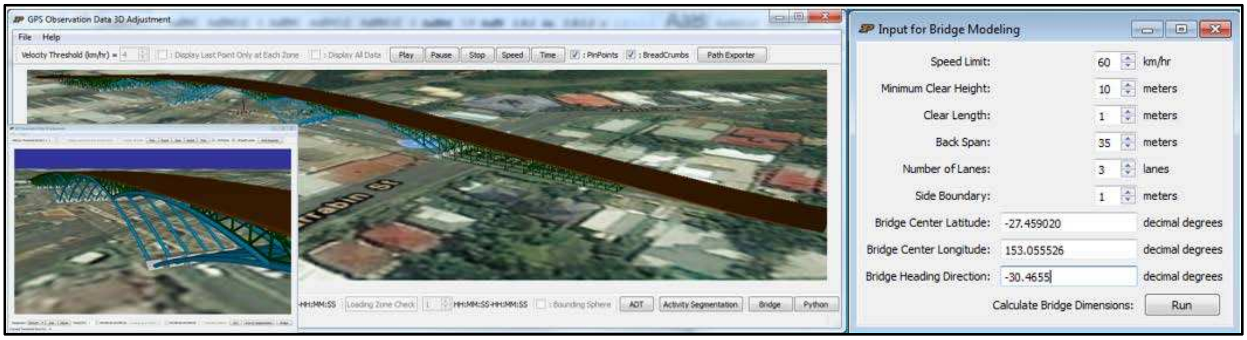
Repeating identical rows of the same superstructure simplifies the construction process, reducing the number of unique tasks required. The primary spanning members are arches, shown in light blue in Figure 1. Each arch is installed in a single lift. Truss segments, shown in green in Figure 1, serve a number of purposes by (1) filling out the road surface alignment curve which reduces the spanning distance of deck panels, (2) extending beyond the outer arches which reduces the earthworks required and (3) taking large point loads applied to the deck, transferring them to the arches in a more distributed and uniform way. Lateral restraint is provided by diagonal bracing between trusses in each adjacent row.

3 RAPID BRIDGE SIMULATOR

3.1 User Input Parameters

To ensure that the tool is intuitive to all users, a simple Graphical User Interface (GUI) as shown in Figure 2 has been implemented with a limited number of key inputs. To begin with, the user locates a potential site from an ESRI ArcGIS server derived satellite imagery. The program then requests simple geometric conditions including: road speed, bridge center location, available bridge deck span, required clear height/clear length relative to the chosen center and finally the available carriageway width as number of lanes. For the geometric and structural design aspect of the bridge, no other information is required from the user and the design subroutine will then execute.

While the design subroutine determines the geometry of the bridge, the user is requested to choose storage areas, crane locations and paths leading from the storage areas to the construction site. Transit durations are largely affected by the proximity of the storage areas to the construction site and in many cases more than one storage area would be required.



Speed Limit:	60	km/hr
Minimum Clear Height:	10	meters
Clear Length:	1	meters
Back Span:	35	meters
Number of Lanes:	3	lanes
Side Boundary:	1	meters
Bridge Center Latitude:	-27.459020	decimal degrees
Bridge Center Longitude:	153.055526	decimal degrees
Bridge Heading Direction:	-30.4655	decimal degrees

Calculate Bridge Dimensions: Run

Figure 2: Graphical User Interface (GUI) for bridge modeling input parameters.

3.2 Design Subroutine

After the GUI has passed on the initial geometric data, the design subroutine can execute. A series of spatial algorithms are first carried out to determine basic structural features. These algorithms will determine the rough height, span and quantity of required arches. A structural and section capacity analysis will then be run to find the size and mass of the arches. Finally, given a fixed deck structure system, the vertical alignment and road surface will be determined. The subroutine consists of the following components:

1. Spatial algorithms to determine basic structural features;
2. Determination of load patterns in accordance with design standards;
3. Initial member cross-section geometry selection;
4. Action analysis;
5. Iteration to find a suitable cross-section; and
6. An output consisting vertical and horizontal alignment information, and superstructure components as shown in Figure 3.

3.3 Discrete-Event Simulation Modeling Subroutine

The construction process can be broken into two distinct parts: the preparation phase and the installation phase. The installation phase is further divided into two time periods: (1) one that requires only road closure; and (2) the other that involves both road and rail closures. In order to minimize the disruption to both road and rail traffic, any work which can be completed without total road closures is done in the preparation phase. This includes delivery of components and equipment, assembly of arches and trusses from delivered components, and substructure work which can be completed with partial road closures.

To minimize road and rail closures, the activity network in Figure 4 was developed to aid scheduling. This allows the user to choose a scheduled road and rail closure time which controls the start of the installation phase. The model will not close the road unless all tasks in the preparation phase are completed and the scheduled closure time has passed. The rail closure has been split into two periods which correspond to work being conducted above the rail corridor. Both rail closure periods can have a scheduled start time set by the user.

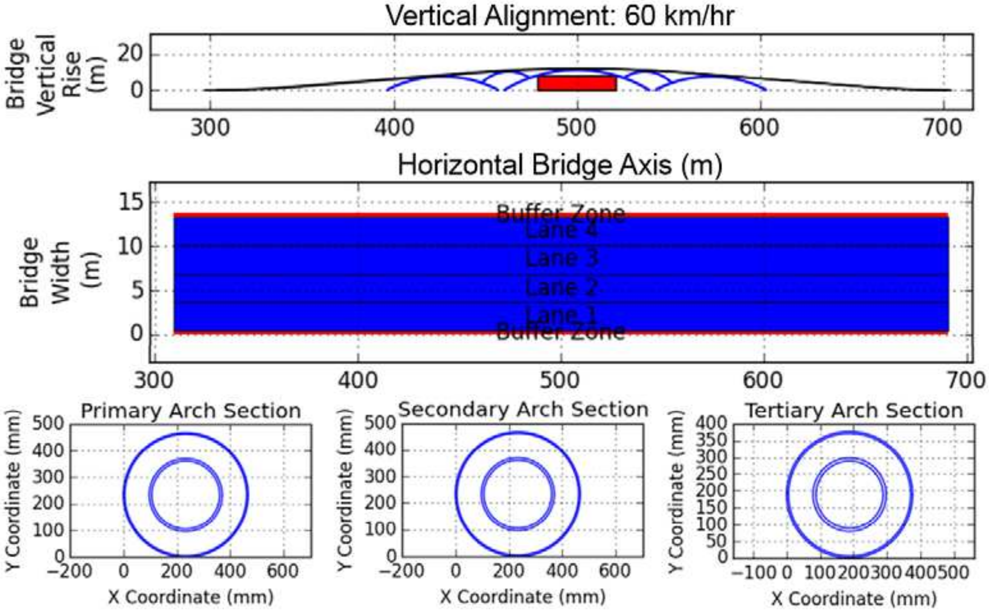


Figure 3: A 2D representative of a bridge designed for a speed of 60km/h. The red area represents the railway passage or clear-zone, arches are represented in blue and vertical alignment is displayed in black.

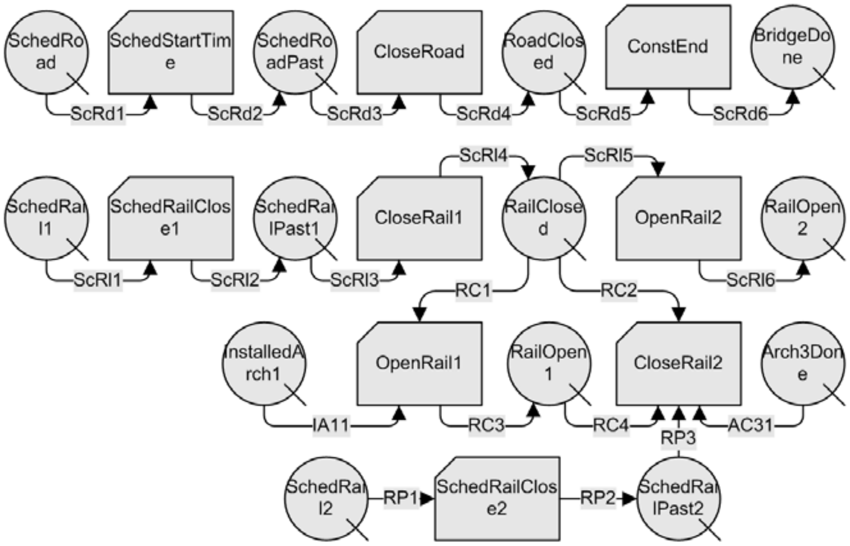


Figure 4: Stroboscope network fragment to represent road and rail closures.

Delivery tasks make up a large part of the preparation phase. Currently the delivery task network only models the action of unloading and storage of resources which have been delivered to the site. While modeling the transport of resources from the location of manufacture to the site is important, it is deemed outside the scope of the current model.

Delivery task networks for all bridge components follow the same form shown in Figure 5, using a communal resource *Crews* and a location specific resource *Lifter* to move the bridge component from the delivery queue *Footing* to the storage queue *StoredFooting*. The delivery task network of each component has an activity cycle for each crane used in the construction process. Each cycle is labeled with the corresponding suffix of the crane which will eventually install that resource.

Installation task networks model the installation of bridge components that require a crane. Each installation task uses the activity cycle shown in Figure 6 to model the process of rigging, lifting, positioning and connecting the component then detaching crane and clearing the area. *Rig* activities are dependent on queues for the stored resource as well as any prerequisite tasks in the construction process. This may include road closure, rail closure or a prerequisite component being installed. Currently all bridge components are lifted into place using a crane and connected by a crew. As the concept design is further refined, the installation process for each component will be adjusted to reflect the more detailed information available.

In order to model the construction of bridge configurations for a range of design speed limits, a naming convention has been used to identify each resource, queue or activity. Figure 7 shows the naming convention for truss segments, Truss1 being the outermost truss.

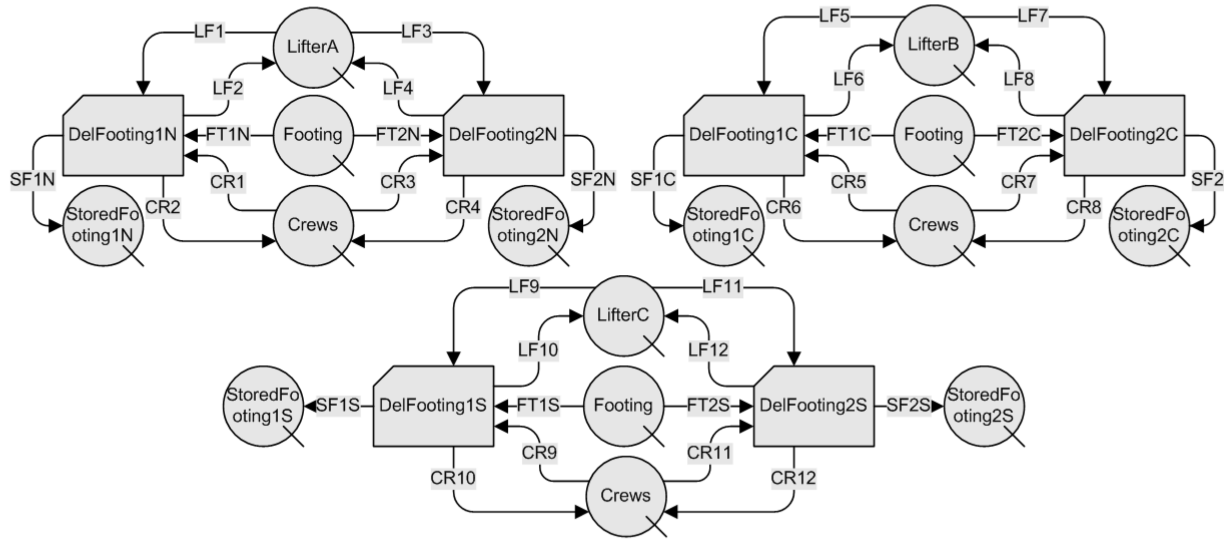


Figure 5: Stroboscope network fragment to represent footing delivery for footing types 1 and 2, and three cranes at different locations of center (Cb), north (N1b) and south (S1a).

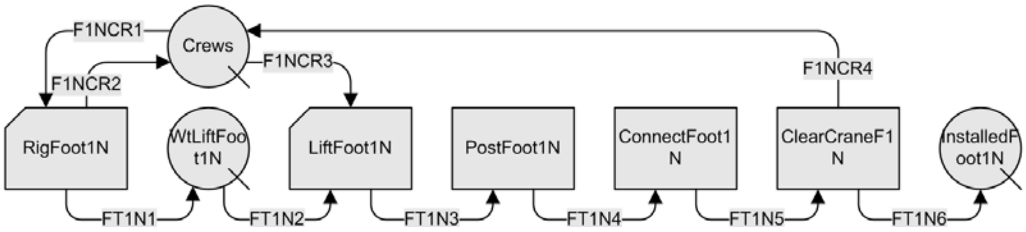


Figure 6: Stroboscope network fragment to represent lifting operation for Footing type 1 using Crane N1b.

Figure 7: Truss naming convention diagram, showing three truss segments.

The naming convention used to label arches (black) and footings (red) can be seen in Figure 8. The primary arch is Arch1, secondary arches take even numbers and tertiary arches take odd numbers, both increasing moving away from the center. Footings are labeled in the same direction with the innermost footing supporting an arch being Footing1. Footings a, b, and c are footings that support parts of Truss1.

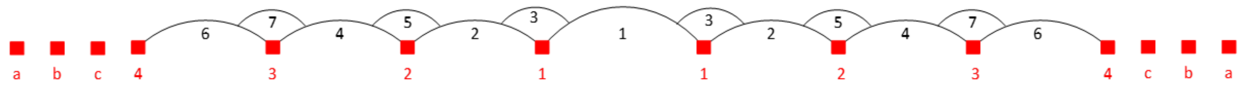


Figure 8: Arch and footing naming convention diagram showing seven arch types and seven footing types.

The model is able to represent a number of cranes being used at once. The model network is built to allow the possibility of all cranes being used. The construction process is modeled in a way that could be completed by a single crane, assuming that the crane could either reach the entire construction area or relocate. This construction process model is repeated identically for all cranes. A crane and the corresponding assembly and storage sites can be used for all, part, or none of the construction process by controlling the resources allocated to the queues corresponding to that crane.

The theoretical site layout which the model is based on can be seen in Figure 9. Cranes are represented by circles labeled with the suffix of the corresponding location. Storage yards and assembly sites are represented by rectangles and labeled with the corresponding suffix. All activities, queues and resources are labeled with the suffix of their corresponding crane location.

The process of assembling bridge components in the assembly sites varies for each component. Lateral truss bracing, footings and deck panels require no assembly prior to installation. Truss components are delivered to site in parts, aligned in the assembly site and connected before being installed. Arches are delivered to site in quarters (or halves for tertiary arches) which must be aligned, welded and inspected. Once inspected the arches are lifted onto a transporter shown in Figure 10 which holds them upright and allows them to be rolled to the storage yard. The arches can either be filled with concrete and left to cure in these transporters or they can be installed and cast in-situ. The assembly task network diagrams are not presented here due to the space limit.

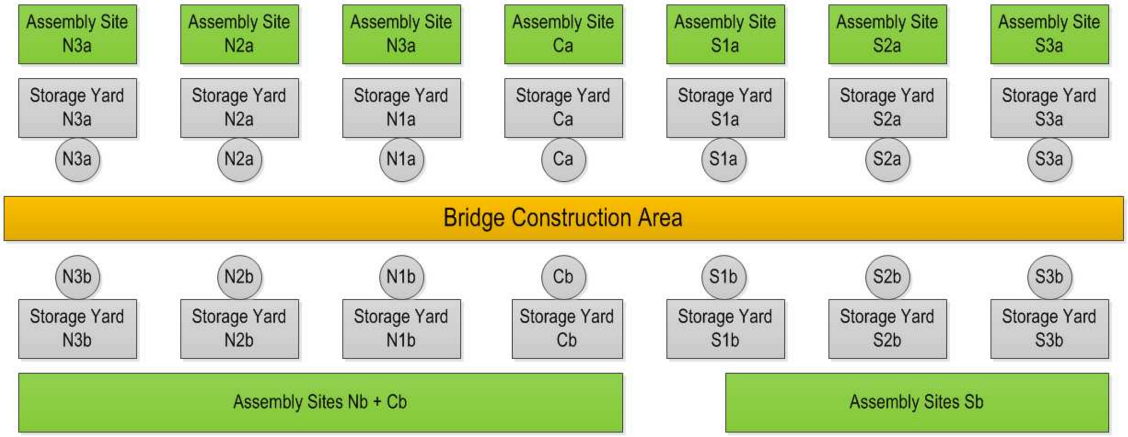


Figure 9: Site layout for the Rapid Bridge construction operations.

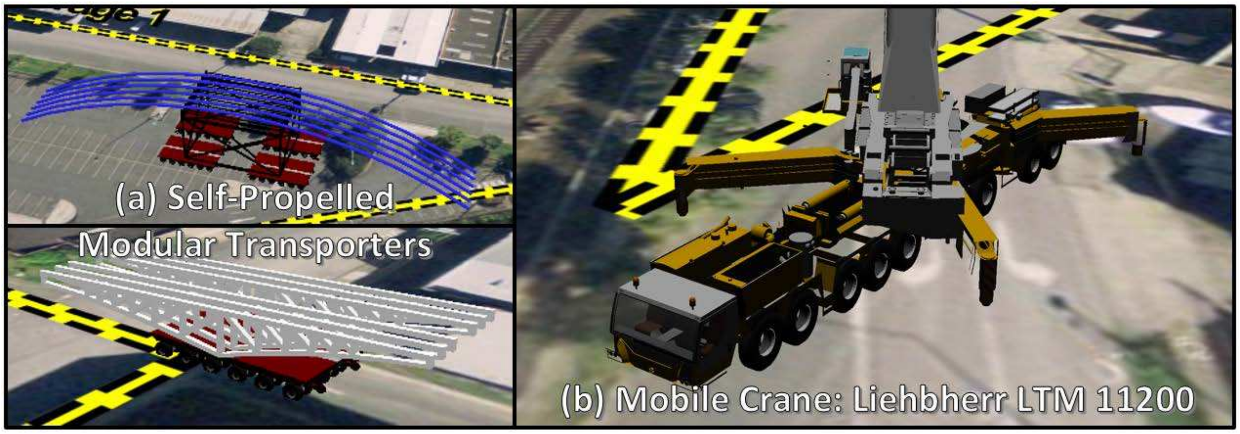


Figure 10: 3D models of construction equipment in Vitascope++.

3.4 Visualization and Data Presentation

A set of visualization instructions is assembled as the discrete-event simulation subroutine models the construction process of the bridge. Upon completion of the event modeling, the user will have the option of viewing the entire construction process as a 3D animated scene. The Vitascope++ (Kamat 2003; Rekapalli 2009) engine powers the visualization facet of the program which allows the user to manipulate the display of the scenario as shown in Figure 11. By animating the scene, the construction process can be verified by people with intimate knowledge of fabrication and erection procedures, but who lack experience in discrete event modeling. Furthermore, a fully animated scene will help explain the concept to the stakeholders more clearly.

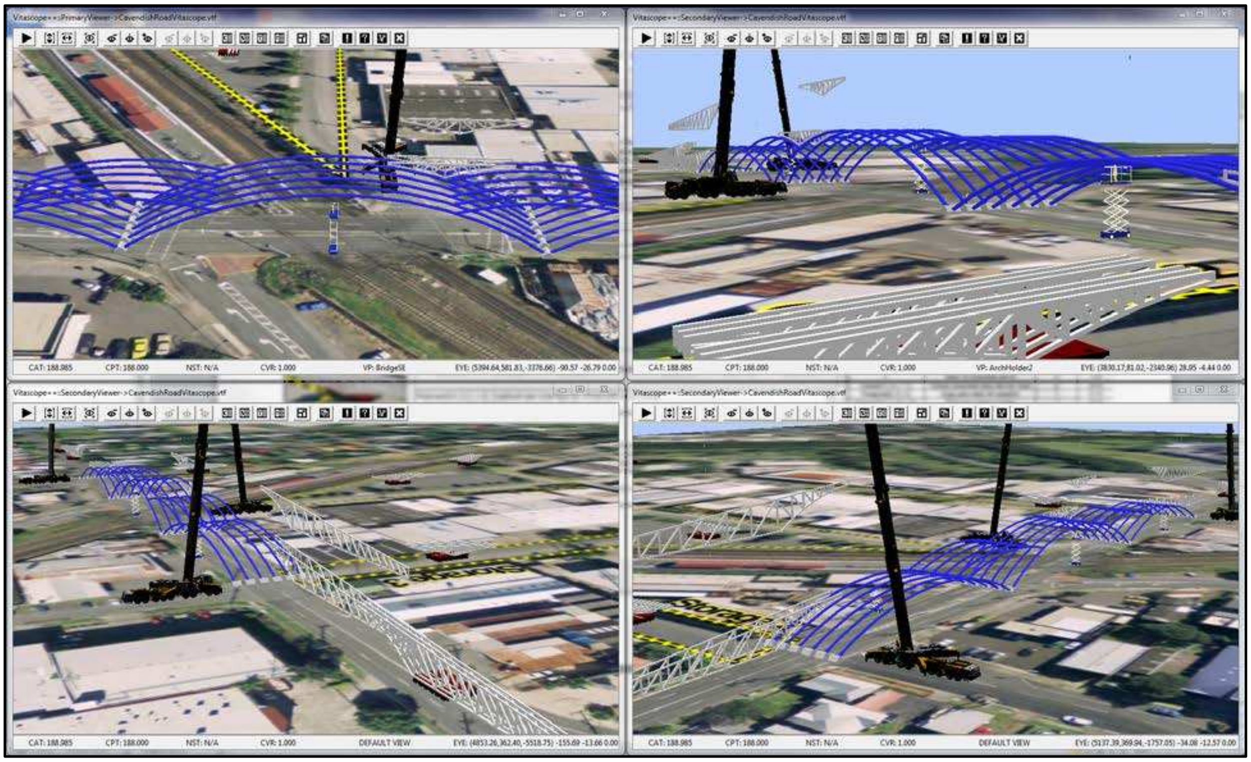


Figure 11: Vitascope++ 3D animations of manipulating trusses.

3.5 General Data

The activity durations used in the model are presented in Table 1. These durations will strongly depend on the individual site layout and the final design specifics of connections. However, in this study the values are used from similar operations data collected by Zhang et al. (2008) and Mawlana et al. (2012).

The costing of the project is also highly variable at this early concept stage. However, the current simulation model does not incorporate the cost of construction materials, labor and equipment.

Table 1: Activity durations used in the simulation model.

Activity Prefix	Example Name	Duration Function (min)	Description of Activity	Number of Activities	Stream Numbers
Arrival	ArrivalArch1Cq	0	Delay of component arrival	25	1-25
Unload	UnloadArch1Cq	Normal[15.03,1.71]	Unload component from delivery truck	25	26-50
Align	AlignArch1C	Triangular[8,10,12]	Align parts ready for assembly	5	51-55
Weld	WeldArch1C	Triangular[115,120,135]	Weld arch quarters together	3	56-58
Inspect	InspectArch1C	Triangular[10,15,20]	Inspect weld quality	3	59-61
Stand	StandArch1C	Normal[15.03,1.71]	Stand welded arches upright	3	62-64
Fill	FillArch1C	Triangular[50,60,65]	Fill arches with concrete	3	65-67
Cure	CureArch1C	4320	Concrete curing	3	68-70
Move	MoveArch1C	Triangular[8,10,12]	Move arches into lifting position	3	71-73
Assem	AssemTruss2	Triangular[5,10,15]	Assemble truss parts	2	74,75
Rig	RigArch1C	Triangular[5,10,15]	Rig components to crane cable	21	76-96
Lift	LiftArch1C	0.3×Normal[26.2,1.89]	Lift component to final location	21	97-117
Pos	PosArch1C	0.1×Normal[26.2,1.89]	Fine adjustments and positioning	21	118-138
Con	ConArch1C	0.5×Normal[26.2,1.89]	Fasten connections	21	139-159
Clear	ClearArch1C	0.1×Normal[26.2,1.89]	Clear crane from hook working area	21	160-180

4 EXAMPLE: CAVENDISH ROAD CASE STUDY

4.1 Cavendish Road Problem Statement

Cavendish Road, located in Brisbane, Queensland, Australia, shown in Figure 12 is a typical example of an Australian inner-suburban level rail-crossing. The railway line carries both passenger and freight trains at frequent intervals which bottlenecks the vehicular traffic stream. Properties and businesses surround the crossing with little-to-no vacant land in proximity and there is no room allocated for on-road parking. As it currently stands, there is no room to place construction equipment on the roadside without resuming and demolishing existing industrial buildings and houses. Any attempts to bridge over the road using conventional techniques would result in the long-term closure of the intersection and a large portion of the road. Combined, these problems make a traditional upgrade prohibitively expensive and inconvenient.

Further to the myriad problems that prohibit the construction of a conventional bridge, the railway line may not be closed for periods in excess of six hours. At this stage it is necessary to begin looking at solutions that deviate from the norm. It is the ultimate goal of this research to employ the Rapid Bridge concept to produce a solution to the Cavendish Road problem that can be erected in a 72 hour total road closure time frame.

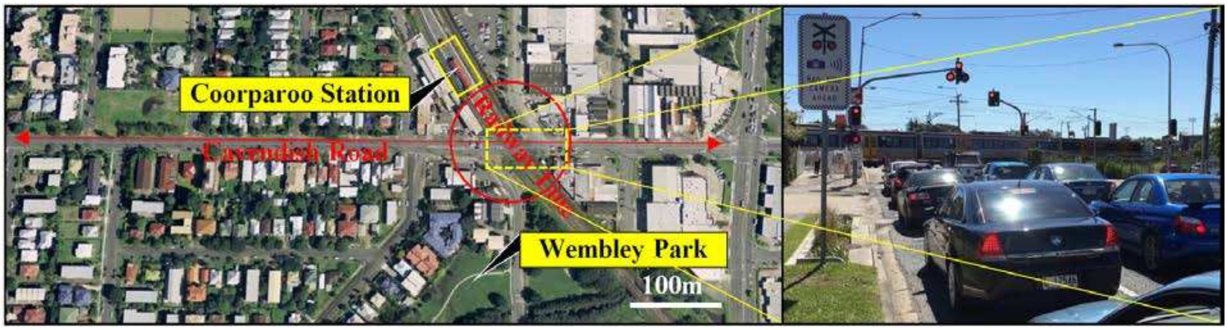


Figure 12: The Cavendish Road level rail-crossing satellite imagery (source: Google Earth).

The first and most significant issue is the closure of the road. Two road closures, one partial and the other complete, would be required if the Rapid Bridge concept were to be employed. Prior to the erection of the bridge superstructure, two of the four lanes would be closed to allow for piling and excavation operations. Once one set of footings had been completed, a temporary surface would be placed over the infrastructure which would allow traffic to use those lanes again. Following this, the other two lanes would be closed and the process repeated. The final road closure would commence just before the erection of the superstructure and would be reopened with the completion of the bridge. Rerouting of this traffic stream would be necessary during this phase. Partial closures may span into a fortnight, while the complete closure would span the 72 hour allotted time frame.

Such small bridge construction timeframes have never been attempted in Australia, which will inevitably lead to skepticism when the completed concept is pitched to stakeholders. Therefore, the capability to visualize modeled operations in 3D animations can be of substantial help in describing the intricacies of simulation models.

4.2 Geometric Bridging Requirements

In accordance with the local railway authority specifications, a minimum clear height must be maintained over the railway line (Queensland Department of Transport and Main Roads 2015). Furthermore, to accommodate the three rail lines, a certain clear length must also be provided. Available back span, road speed and the available carriageway width, or maximum bridge width, are required. These parameters given in Table 2 have been determined by the GUI (Figure 2).

Table 2: Bridge clearances.

Parameter Name	Parameter Value
Clear height (m)	7.9
Clear length (m)	30
Road speed (km/h)	60
Back span (m)	204
Carriageway maximum (m)	16.5

4.3 Operating Strategy

The construction process can be separated into a preparation phase and an installation phase. During the preparation phase, shown in blue in Figure 13, the roadway is partially closed as piles as constructed two lanes at a time. Bridge superstructure components are delivered, assembled and stored. Once both streams of preparation activities are finished, the installation phase can start. Bridge superstructure components are installed, shown in orange in Figure 13, and the road is reopened once construction is complete.

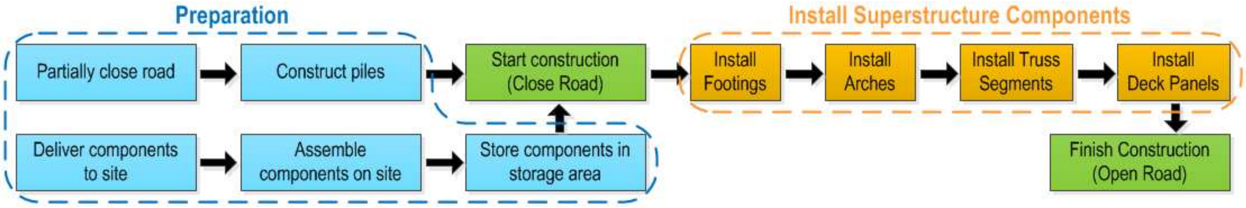


Figure 13: Construction process flow chart.

The Cavendish Road process will make use of 3 cranes positioned on side streets. These side streets will be used as storage yards, the Coorparoo Station carpark and Wembley Park will be used as assembly sites. The side roads will be closed for both the preparation and installation phases. Property access will be maintained for residents.

4.4 Design Subroutine Outputs

A first-run solution to the Cavendish Road problem was found with no reductions in speed or bridge comfort being required. Geometrically, the Rapid Bridge concept is an acceptable option for the site. From here, information critical to the construction of the bridge is passed along to the simulation subroutine for discrete event analysis. A summary of the bridge design is presented in Figure 3 as well as in Table 3.

Table 3: Summary of the Cavendish Road Bridge superstructure parameters.

Parameter Name	Parameter Value
Number of Lanes	4
Number of Arch Rows	6
Number of Tertiary Arches per Row	2
Number of Secondary Arches per Row	2
Primary Arch Total Length (m)	68.25
Secondary Arch Total Length (m)	60.00
Tertiary Arch Total Length (m)	25.80
Total Bridge Length (m)	382.22
Height of Crest at Apex (m)	11.09

4.5 Simulation Results

The Rapid Bridge concept is an attempt to construct a railway overpass bridge in 72 hours road closure time. The simulation has many degrees of flexibility, simple changes to the number of crews hired, the number of cranes used or the time taken to perform an activity have very large impacts on the construction time and therefore construction costs. The simulation results from three different scenarios below show the impact of altering how many deck panels the center crane installs and which cranes are used to install Arch3. Apart from the components listed, the simulation models are identical. Three different scenarios are prepared as follows. The basic results from implementing these strategies are shown in Table 4.

- Scenario A: 30-deck panels installed by crane C, 0-Arch3 installed by crane C.
- Scenario B: 20-deck panels installed by crane C, 12-Arch3 installed by crane C.
- Scenario C: 8-deck panels installed by crane C, 12-Arch3 installed by cranes N & S.

Table 4: Simulation results from three different strategies.

	Scenario A	Scenario B	Scenario C
Number of Lifts Performed by Crane C (Central)	66	68	44
Number of Lifts Performed by Crane N (North)	70	69	83
Number of Lifts Performed by Crane S (South)	70	69	83
Total Project Time [Days]	**7.11**	**7.62**	**7.83**
Time of Road Closure (Construction Start Time) [Days]	4.60	4.99	4.98
Road Closure [Hrs]	**60.17**	**63.13**	**68.33**
Time Reduction from 72 Hrs Road Closure Baseline [%]	**16.43**	**12.32**	**5.01**
Time of Rail Line Closure [Days]	5.03	5.42	5.42
Rail Closure [Hrs]	**31.2**	**22.53**	**12.13**
First Rail Closure Duration [Hrs]	5.20	5.20	5.20
Second Rail Closure Duration [Hrs]	26.00	17.33	6.93

The results above in Table 4 show that altering the allocation of resources can noticeably change the road closure and rail closure times of the same construction process. These results suggest it may be possible to complete the Rapid Bridge in under 72 hours road closure, however the activity durations are currently referring to the literature (Zhang et al. 2008; Mawlana et al. 2012) and further research must be conducted before this simulation can accurately represent the real construction process.

5 CONCLUSIONS AND FUTURE WORK

This paper presented a special-purpose simulator for accelerated bridge design and construction operations. The capabilities, simple input requirement, and effectiveness of the tool were demonstrated with an example. There are a number of improvements that could be made to make the model represent the real construction process more accurately and completely. The scope of the model could be extended to include the transport of components from their manufacture location. Earthworks, pile construction and concrete delivery could also be included. Additionally, unexpected events such as downtime of construction equipment could be added to the model. The authors will explore a systematic way to predict activity durations and incorporate the cost of construction materials, labor and equipment to perform cost analysis.

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