Simulation Study on an ICT-Based Maritime Management and Safety Framework for Movable Bridges

Md Mostafizur Rahman Komol 1, Md Samiul Islam Sagar 2, Naeem Mohammad 2, Jack Pinnow 1, Mohammed Elhenawy 1, Mahmoud Masoud 1, Sebastien Glaser 1 and Shi Qiang Liu 3,*

1 Center for Accident Research and Road-Safety—Queensland (CARRS-Q), Queensland University of Technology, Brisbane, QLD 4059, Australia; mdmostafizurrahman.komol@hdr.qut.edu.au (M.M.R.K.); j.pinnow@qut.edu.au (J.P.); mohammed.elhenawy@qut.edu.au (M.E.);
2 Department of Electrical and Electronic Engineering, Khulna University of Engineering Technology, Khulna 9203, Bangladesh; samiul.kuet.2k14@gmail.com (M.S.I.S.); nmsamit36@gmail.com (N.M.)
3 School of Economics and Management, Fuzhou University, Fuzhou 350108, China
* Correspondence: samsqliu@fzu.edu.cn

Abstract: Maritime management is a crucial concern for movable bridge safety. Irregular management of water vehicles near movable bridges may lead to collision among ships and bridge infrastructures, causing massive losses of life and property. The paper presents a theoretical framework and simulation of an intelligent water vehicle management system for movable bridges corresponding to vehicle traffic responses. The water regime around the bridge is considered in virtually separated domains to estimate the desired safety actions based on the position of the approaching ships. An emergency clash avoidance control system is represented to prevent ship-infrastructure collision and ensure transportation safety. In addition, a simulation platform is developed specifically adaptable for movable bridge maritime and dynamic traffic management. The proposed theory is experimented using the simulation platform for different ship speeds and bridge-vehicle traffic volumes. Based on analyzing the velocity profile of approaching ships at different incidents, the bridge is found incapable of evacuating vehicles and unable to open promptly in case of speeding ships and high traffic density of vehicles on the bridge. Computational results show that the emergency control system is effective in reducing ship speed and prevent certain collisions. Lastly, the transportation policy for the newly proposed maritime management system is validated by real-world implementation in movable bridges across the world.

Keywords: movable bridge; maritime management; emergency control; simulation; information communication

1. Introduction

Movable bridges represent an alternative navigation route to cross an active waterway where the construction of fixed bridges with a desired vertical profile is beyond our reach. With economic globalization, the complexity of waterways is increasing to maintain vessel navigation in inevitable routes for faster shipping and supply. Especially for human-made waterways like the Suez Canal is an exemplary route where gigantic vessels transport through a very complex waterway. Such transportation policy requires precise monitoring and management of a navigation system. Movable bridges are an effective solution to many complex waterways of inevitable routes facilitating transportation management for both vehicles and ships. It also has the potential to enhance security by restricting unauthorized access. In 1666, the movable bridge was used to prevent riots during the Great Fire in London [1].

At present, a remarkable number of movable bridges reside all over the world. These bridges are familiarized with their unique motions to calibrate flexibly with internal
structures and give navigation path-away and vehicle passage. Most commonly, bascule bridges rotate transversely with the horizontal axis and permit vessel transit regardless of the vessel height [2]. Tower Bridge in London and Woodrow Wilson Bridge at Washington resemble a bascule bridge [1]. Among other movable bridges, swing bridges circulate horizontally, and vertical lift bridges translate the entire moving part to an upward limit. The Sale Swing Bridge at Victoria and The Paringa Bridge over river Murray in South Australia are two renowned heritages in Australia. Lastly, foldable bridges, such as those in Kiel, Germany, present folding movable bridges which rotate about multiple transverse horizontal axes. Retractile bridges are capable of translating the moving span horizontally, and gyratory bridges rotate about the longitudinal axis [2]. In New South Wales, different movable bridges are subdivided based on generation and ages [3]. In the modern age, war support bridge-launching vehicles (e.g., M60 AVLB) can launch a movable bridge with folding capabilities which enables movement over craters, moats, damaged bridges, railroad rails, water canals, and other untraversable zones [4].

Nonetheless, there exist many movable bridges of colossal embodiment over the world; they are manually operated. Due to high expense and complex structure, few are bestowed with modern technologies. With the advancement of information communication technology (ICT), automation of movable bridges is desired that aspire the requirement for maritime management and safety as well. Manual inspection of movable bridges by human operators does not achieve the same advanced level of safety and reliability as an automated bridge. The sheer automation of a movable bridge requires control of internal mechanical structures, maritime management, and bridge traffic management. It is evident that movable bridge automation refers to the automated operation of bridge leaf structures and subsequent gears. However, to set the condition of automated bridge-leaf rotation, the controller system must identify the approaching ships leading to the bridge leaf opening command. Furthermore, bridge-leaf opening requires fulfilling pre-condition on evacuating bridge of any vehicles followed by sensing approaching ship. Therefore, a movable bridge automation system incorporates ship sensing, navigation control, collision avoidance for maritime management, and signalization of bridge traffic and other advanced technologies to ensure the bridge can be evacuated successfully out of any bridge vehicles when any water traffic comes closer to the bridge. Movable bridge automation requires imposing concern over these phenomena when considering observation and security. For example, failure in the automation of internal mechanical control may cause the bridge to move inappropriately or get jammed in the middle of the operation. Failure of maritime automation may result in a collision between bridge moving parts and water vessels. Accurate detection of approaching ships and their disciplined navigation towards the bridge opening gate is a prominent concern. A movable bridge may not always be capable of opening bridge leaf in a timely manner due to the high volume of bridge traffic or speedy approaching ships. Moreover, improper signalization or control of bridge vehicles may cause the bridge to move before the clearance of bridge vehicles that will cause damage to bridge traffic. If the bridge stays stationary to give extended time for bridge vehicle clearance, the ship may come closer and collide with the bridge structure. This is considered a maritime management failure for the movable bridge. Therefore, security is considered a major challenge for the automation of movable bridges. Automation protocol of movable bridge must identify ships that are approaching the bridge too quickly and maintain emergency safety approach to prevent potential collisions. Maritime management of a movable bridge also includes safe transit of multiple ships without bottle-necking near the bridge opening gate. If many ships rush together toward the movable bridge opening gate, a potential collision may arise among ships. Furthermore, opening or closing of movable bridge leaves is time-consuming due to mechanical constraints and power management limitations. Ideally, there should be a time gap between closing and reopening, as continuous gate operation may not be favorable for high structural durability. Therefore, after opening, it has to ensure that all ships intend to pass have crossed the bridge for a specific broad area around the bridge. In this way, if a new ship is detected entering this
area that intends to pass the bridge, the bridge will have enough time to evacuate the bridge vehicle and re-open. This area can be measured based on the maximum allowed ship speed and bridge opening time. Thus, a movable bridge maritime management system requires special concern on when to close the bridge.

The integration of smart sensors will enable continuous monitoring even without human supervision. Internet of Things technology is recommended as an efficient bridge monitoring and control system due to the availability of Internet-based data for real-time comparison and remote data transfer facilities [5]. The incorporation of advanced predictive technologies with smart sensors and devices will conduct case analyses to forecast risks and issues not readily comprehended by humans. The data from these sensors are able to be applied for equilibrium analysis in traffic systems [6], especially for on-road vehicles, which are being gradually extended in marine transportations as well [7]. Such predictions of critical cases will help to point out existing flaws in the bridge and marine technologies and will aid to work on possible solutions, preferably through automation, to avert further challenges, ensuring reliability and efficiency. For the automated control of the navigation system, a ship-to-ship communication system is demonstrated as human-computer interaction. Here, the warning signal system is implemented for collision prevention among ships, and an automated adoption of collision prevention is installed in case of reluctance over warning signals. This procedure is maintained by utilizing the ship domain system [8]. Automatic Identification System (AIS) based vessel tracking systems are garnering popularity, as they are incorporated with state-of-the-art Internet of Things and automation technologies [9–11]. Maritime road networks are growing resilient with the aid of a large AIS dataset for precise control [12]. Besides, maritime automation [13], maritime surveillance, and ship classification are a few soaring applications of AIS where intelligent adaptive algorithms such as Douglas–Peuker are being embedded [14–16]. Recently in Australia, smart camera technology and data science methods have been implemented as a preliminary trial for water vehicle navigation control and security [17]. These studies motivate the implementation of advanced technologies for movable bridge navigation and security system.

The current study proposes an ideal maritime management and safety protocol for movable bridges using the ship-to-bridge infrastructure communication system. In order to locate approaching ships and take corresponding decision measurements, the navigation zone of the movable bridge is defined into specific belts based on calculating the maximum ship speed limit and minimum bridge vehicle speed. An emergency clash avoiding control system is integrated with the proposed protocol that will prevent any probable collision between the bridge and ships. To evaluate the proposed protocol, a simulation system is developed specifically for maritime management of movable a bridge. Moreover, ships’ transit behavior under adaptive cruise control (ACC) is demonstrated using the simulation system to ensure additional safety among ships. Furthermore, the transportation and litigation policy for this newly proposed maritime management and safety system is discussed with future improvement and potential implications.

The subsequent sections in the paper elaborate on the proposed methods in detail and correlate each technology for ensuring spontaneous operation. The sections in this paper are organized as follows. Section 2 discusses the system components. Sections 3 and 4 specify the system considerations and principles of the study respectively. Section 5 explains the development of the simulation environment and the proposed methodology. Section 6 presents the results and discussion. The last section summarizes the outcomes with concluding remarks.

2. System Components

Every automated system relies on the smart use of alarms, cameras, and sensors that are systematically embedded to enable continuous monitoring, anomaly detection, and autonomous recovery in most cases. Similar automatic detection, warning scheme, and automated recovery are indispensable for the proposed system as well to ensure a flawless
operation both on the river and roadside with proper safety protocol for avoiding danger. In this system, two hypothetical boundaries, called Alert Belt and Emergency Belt are introduced in this paper. The Alert Belt is the zone of interest situated at both ends of the bridge where the ship will be continuously monitored from start to end. There will also be a Dedicated Short-Range Communication (DSRC) range at both ends for transmitting important communication data during ship location, on-bridge traffic control, and bridge movement. These belts and ranges are marked through sensor- and camera-based self-powered buoys, which consists of a camera for detecting and identifying ships within the route, tracing data, and feeding it back to the bridge control system for determining whether the ship height qualifies to move the bridge. The buoys will also include solar panels with energy storage to obtain power from the sunlight and keep it charged even during the night. Figure 1 shows a generalized layout of how the system components are assumed in the setup. For the system to work in different movable bridges all over the world, two lanes for ships and two lanes for on-bridge vehicles have been considered so that these can be narrowed down to one for single-lane movable bridges by minimizing the components. Ships moving from Point A to Point B or Point C to Point D faces Alert Belt, DSRC range, and Emergency Belt in this particular order. The specialized buoy in each belt establishes communication to three control systems; the ship control systems on the ship, traffic bollard unit at two ends of the bridge, and the bridge control system on the bridge through DSRC radio communication consisting of DSRC wave boxes, global positioning system (GPS) server, and a communication node connected through cellular networks.

![Generalized layout of the system components used in the proposed scheme.](image)

The proposed buoys that will be placed in the mentioned locations will consist of antennas for communication purposes, sensor boxes to collect and analyze data, and a mechanical gimbal lock-based camera to capture ship images and compare with the database for the ship details. These buoys are an integration of autonomous weather buoys for an automatic identification system (AIS) [18] and GPS-based calamity detectors [19], with mounted camera systems [20]. The camera is an optional component in the buoy, as
the antenna is sufficient for obtaining ship data from the database from the ship itself, but is considered in this proposed setup for the purpose of generalization. The buoy will obtain power from sunlight using photovoltaic solar panels and battery-based energy systems. Spring-mounted buoys are considered in this context for less movement and turbulence. The sensor box will include a microcontroller unit, GPS module, weather sensors, and a data transmission unit for performing monitoring, calculations, and communication at the same time. Components of the typical camera-based sensor integrated self-powered buoy for the proposed system are illustrated in Figure 2.

![Components of the typical camera-based sensor integrated self-powered buoy for the proposed system.](image)

For each lane in the river, three buoys will be used in the Alert Belt, DSRC range, and Emergency Belt. During daylight, the solar panel will store energy and charge the battery storage system for using the power at night. In case of bad weather conditions, the buoys will proceed with data transmission at least, which requires very little battery power to operate. Therefore, even during the case of bad weather, the proposed system is capable of transmitting important data through GPS and cellular services, which can work while offline as well. The system is generalized for different movable bridges in various parts of the world, where it can be installed with minimum changes to the existing components for the varying range of movable bridges.

3. System Considerations

The entire maritime automation and security system is pivoted on the basis of an imaginary belt division system. The Alert belt and the Emergency Belt are two virtual belts that are considered on both sides of the bridge at a specified distance. Based on the origin and destination movement of the ship, the Alert Belt and Emergency Belt are named sequentially entry Alert Belt, entry Emergency Belt, exit Emergency Belt and exit Alert Belt. Another distance based on the DSRC range is also considered for the buoy placement,
from which data will be connected for further investigation. The direction of two different routes is shown in Figure 3 using arrow indications.

![Figure 3. Illustration of the complete system and installments with specific legends.](image)

For design consideration, four fixed buoys are installed at each of the two ship routes. The purpose of these being to detecting ships’ positions. The buoy has been named according to the following considerations.

For direction A to B,
- The buoy at entry Alert Belt = \(Baa\)
- The buoy at DSRC range = \(Ba\)
- The buoy at entry Emergency Belt = \(Bae\)
- The buoy at exit Emergency Belt = \(Bbe\)

For direction C to D,
- The buoy at entry Alert Belt = \(Bca\)
- The buoy at DSRC range = \(Bc\)
- The buoy at entry Emergency Belt = \(Bce\)
- The buoy at exit Emergency Belt = \(Bde\)

The distance of the Alert Belt from each side of the bridge has been determined by the bridge length and how much time is needed for evacuating the bridge off of the on-bridge traffic. When ships enter the Alert Belt from any route, the traffic signal turns yellow, followed by red light in a safe interval. The bridge evacuation system is maintained by a counting algorithm and a camera-detection system. The time for bridge evacuation, \(T_{\text{bv}}\), has been calculated by considering the average speed of the on-bridge traffic, \(V_{\text{bva}}\), and the length of the movable part of the bridge, \(D_{\text{fl}}\), using Equations (1) and (2).

\[
T_{\text{bv}} = \frac{D_{\text{fl}}}{V_{\text{bva}}} \tag{1}
\]

\[
V_{\text{bva}} = \frac{\text{Sum of the velocities of the vehicles inside the movable part of the bridge}}{\text{Total number of the vehicles inside the movable part of the bridge}} \tag{2}
\]

A setup of four speed cameras is considered separately on both entry and exit lanes of the bridge to ensure the counting and velocity detection of each vehicle in entry and pass. The installment of the speed camera system is illustrated in Figure 4.
Figure 4. The camera setups for bridge traffic control system.

For bridge vehicle traffic route AB,
Assigned camera for entry lanes = Ca
Assigned camera for exit lanes = Cb

For bridge vehicle traffic route CD,
Assigned camera for entry lanes = Cc
Assigned camera for exit lanes = Cd

When vehicles enter through bridge entry lanes, they are counted, and their velocities are being recorded. At the same time, each vehicle that passes through the exit lanes of the bridge is classified by cameras at the exit lanes. The number of vehicles on the bridge is then the difference of the aggregated count between entry and exit lane cameras. If the number of vehicles is found to be 0, the bridge is empty and is ready to be opened. This procedure has been coined as bridge evacuation. Consequently, the algorithm used to achieve this has been named the counting algorithm for bridge evacuation. When ships are detected by buoys Baa or Bca, the evacuation is initiated to make the bridge clear out the vehicles and open to allow the passing of the ships.

The total time required for preparing ship route through the bridge is given as

\[ T_i = T_b + T_{pv}, \]  

(3)
where $T_b$ refers to the time required for bridge opening or, closing. Similarly, the minimum required distance between the Alert belt and DSRC range is expressed as

$$D_{abr} = V_{bsh} * T_b,$$

(4)

where $V_{bsh}$ is the assigned highest speed limit for ships at the bridge maritime zone. Therefore, the assigned distance of the Alert Belt from each side of the bridge can be expressed as

$$D_{abr} = D_{abc} + D_{dscr},$$

(5)

where $D_{dscr}$ is the DSRC range of the bridge on both sides. The Emergency Belt distance from the bridge, $D_{abr}$ in both sides of the bridge has been determined by adding half of the length of the movable part of the bridge, $D_{hl}$ the distance, $D_{zov}$ covered by a ship before achieving the zero operational velocity from $V_{bsh}$ by applying a standard deceleration, $A_{sd}$, and an allowance, $D_{ea}$, which has been shown by Equations (6) and (7).

$$D_{zov} = \frac{V_{bsh}^2}{2 * A_{sd}},$$

(6)

$$D_{abr} = D_{hl} + D_{zov} + D_{ea}.$$  

(7)

4. Principle of the Study

Two separate counting algorithms are implemented in parallel of which one ensures bridge evacuation and another confirms whether the ship has passed through the bridge. When bridge traffic enters the bridge through the entry lane, each traffic is detected with an object number. The number of vehicles entering through the bridge is counted by entry cameras $Ca$ and $Cc$ at both sides of the bridge. When one vehicle enters the entry lanes, it gives a value of one which is subsequently added to the aggregation of the total vehicle entered. When this vehicle passes the bridge through any of the exit lanes, the previously added value is subtracted from the total aggregation. The passing vehicles through exit lanes are detected through exit cameras $Cb$ and $Cd$. Thus, for the continuous transport of vehicles on the bridge, there is a continuous cycle of counting by adding value per vehicle’s entrance and subtracting value from the total aggregation per vehicle’s exits.

In this paper, the case considered is continuous traffic flow through a movable bridge. The notation for this case is described below.

Number of vehicles detected through the camera, $Ca$ for different entry lanes = $k$
Number of vehicles detected through the camera, $Cb$ for different exit lanes = $l$
Number of vehicles detected through the camera, $Cc$ for different entry lanes = $m$
Number of vehicles detected through the camera, $Cd$ for different exit lanes = $n$
Number of vehicles remaining between $Ca$ and $Cb$ = $k - l$
Number of vehicles remaining between $Cc$ and $Cd$ = $m - n$

Therefore, the total number of vehicles remaining in the movable part of the bridge = $(k - l) + (m - n)$

When the ship is identified by the prime buoy, the bridge control system automatically activates the road barrier of entry lanes. This prohibits further vehicle entrance to the bridge. When vehicles get through the exit lanes of both sides of the bridge, this total aggregation keeps reducing, and this turns to zero at the point when all the vehicles leave the bridge through exit lanes. This zero-count condition is considered an evacuated bridge.

For the bridge traffic evacuated condition:

Number of vehicles remaining between $Ca$ and $Cb$ = $k - l = 0$
Number of vehicles remaining between $Cc$ and $Cd$ = $m - n = 0$

The total number of vehicles remaining in the movable part of the bridge = $(k - l) + (m - n) = 0$
For ease of understanding, the control system is divided into three domains: the ship control system, the bridge control system, and the vehicle control system. The systems are shown as large circles in a relation diagram in Figure 5. The figure provides an overview of the data flow and transmission of warning signals depending on the velocity and time of the ships, on-bridge vehicles, and the bridge movement. It is seen from the figure that when the ship crosses its first (incoming) alert belt, it sends its data through the buoy to the bridge control system to assess whether its specification calls for the bridge to open. If it does, the bridge sends the on-bridge vehicle control system to activate the traffic bollard unit, start the counting algorithm, and calculate the time required for the bridge evacuation. If the ship reaches the Emergency Belt before bridge nullification, the bridge is commanded to be opened. However, if there is a chance of collision, the ship is given a distress signal to either control its speed to decrease until nullification. The bridge control system can also force stop the ship through the DSRC radio communication. A complete flowchart of the control system of movable bridge maritime management is illustrated in Figure 6.

Figure 5. Relationship diagram for the three control systems in ships, vehicles, and bridge.
Figure 6. Flowchart for the control system of movable bridge maritime management and collision prevention.
A simulation environment has been designed using Python programming language to demonstrate different conditions of the movable bridge automation process. The core modules that are incorporated to construct the simulation are the random and matplotlib packages. The simulation environment consists of two major segments: class creation and controlling the simulation. The graphical contents of the simulation have been designed using the AutoCAD designing tool. For a successful demonstration of the complete automation, a total of six classes has been introduced. The background is the class that creates the background of the GUI (Generic User Interface), including the buoy illustration, camera for detecting the traffic for counting purposes, the river, and label registry for each of the components in a complete scene. The cameras are considered as reference points in our simulation system to count the entry and exit number of passing vehicles. The Bridge class is the main component of the simulation environment which illustrated a swing bridge for the proposed simulation purpose. For a certain placement of the ship and the on-bridge road traffic, the bridge moves automatically. The Ship class illustrates a manually controllable ship and an ACC-enabled ship. This ship can sense other ships inside its shape domain and can control its velocity as per the requirements to avoid any type of collision. The manually controllable ship is the illustration of a ship that can be controlled via user input through the directional keypress and can be moved independently, although it will maintain all the rules of movable bridge automation to avoid clashes with the bridge. The controlling parameter is the velocity which can be controlled with a predefined interval. The Car class refers to the road traffics, which is automated and automatically generated at a regular interval from both routes. There are three colors: Red, Green, and Blue. While the bridge opens or closes, the cars standstill at a predefined distance from the bridge until the complete reformation of the bridge happens. The density and speed of the cars can be controlled via programming to perform different modes of automation. The Graph class is responsible for showing the graphs in the simulation GUI to indicate the timely changes in the velocity, the distance covered, and the distance from the bridge of the ship. The maximum data at any time in the plotted graph is equivalent to 100 samples. There are three graphical representations indicating the velocity of the ship, the distance covered by the ship, and the distance from ship to bridge. In all three graphs, the independent axis represents the time in hours which is synchronized evenly according to the real-life scenario. Figure 7 refers to the graphical representation used in the designed simulation.

![Figure 7](image-url)

**Figure 7.** Graphical representation of different parameters in the designed simulation.

All the classes are stored in a module, which is then called the main simulation program. The program is a continuous one that generates a 1280 p × 720 p display where all the other class components are positioned. The calling procedure of the classes is maintained by a layer-wise system, where the background will be the bottom-most layer, then the ship, the bridge, and the road traffic sequentially. The simulation is controlled accordingly to the mentioned methodology of automation, which will be elaborately discussed later in the article.
5. Methodology

Although the proposed system is designed for different movable bridges all over the world, a case study analysis for Fort Madison Swing Bridge is demonstrated in this section. The software application is also developed for the case study, which can later be modified for any other bridges. Redundant components have also been considered for a more generalized analysis of movable bridges, which can be narrowed down to singular components for simpler bridges. The step-by-step analysis for the chosen case study is demonstrated in the following subsections.

5.1. Alert Belt Ship Sensing

The maritime automation of the proposed system is initiated from the Alert Belts of the bridge. When a ship crosses the Alert Belt, the prime buoy that is directly positioned on the entry Alert Belt senses the position of the ship. For the route directions AB and CD, the buoys *Baa* and *Bca* respectively identify incoming ships at Alert Belt. This gives a signal to the bridge control system about the incoming ship to the bridge. At this time, the bridge traffic signal at the entry control system turns yellow for a few seconds to provide drivers ample time to decelerate and stop. Later, the signal turns red to stop the vehicles before the bridge entry. After the vehicles stop, the traffic bollard units pull up automatically to prevent further vehicle entrance to the bridge. A simulated environment of detecting approaching ships at the Alert Belt is shown in Figure 8.

![Figure 8. Ship sensing at the Alert Belt.](image_url)

The figure illustrates the regular passage of bridge vehicles at fixed bridge conditions when an approaching ship is detected at Alert Belt. The simulation GUI explains the ship speed condition, distance from the bridge, and traffic volume through graphical representation. Distance between the ship and the bridge reduces with time as the ship approaches and the distance covered by the ship increases.
5.2. Bridge Evacuation

As per the information of the approaching ship detected by the prime buoy at the Alert Belt, the bridge initiates the evacuation process. The bridge evacuation comprises several automated steps to ensure safe traffic flow on the bridge. The bridge is kept stationary until complete clearance of the bridge traffic. The bridge has to be opened before any ship approaches the bridge. For traffic control during bridge evacuation, two separated traffic bollard units are placed as a traffic barrier at the bridge entry and exit lanes of both sides. Furthermore, four independent cameras are suggested for entry and exit lanes at both sides of the bridge. This connection is maintained to detect and count the bridge traffic. For our simulation, these camera points are considered reference points $Ca, Cb, Cc,$ and $Cd$. The bridge is considered completely evacuated when the total number of vehicles remaining on the bridge, $(k - l) + (m - n)$ is zero.

After evacuation, the bridge launches its moving operation to open and give access for water vehicles to pass safely. Ships and other water transport vehicles pass through these two routes at movable bridge open positions. Different movable bridges such as the Swing and the Bascule bridges have distinct mechanisms to operate. In our simulation environment, a potential maritime management and ship navigation scenario through the Swing Bridge is depicted in Figure 9.

Figure 9. Automated bridge system and ship navigation at Fort Madison Swing Bridge.

The figure shows the ship crossing the bridge when the bridge is opened. Here, the bridge vehicles are stopped at the roadway before the bridge, and therefore, the number of on-bridge traffic is measured to zero. The distance between ship and bridge reduces to the lowest and the ship is approaching at a constant velocity with time.
5.3. Measures for Collision Prevention

One of the primary purposes of this research is the prevention of collisions or casualties resulting from the collision between any combination of ships, bridges, and bridge vehicles. Some conditions may arise when the ship comes too close to the bridge while vehicles are still traversing it, and the ship may collide with the bridge in this situation. Therefore, the proposed algorithm for maritime management and control is incorporated with multiple security parameters. Three collision detection techniques are maintained for safe navigation regarding the bridge. To prevent collision among bridge and ship, a dual security system is maintained using the DSRC control system: DSRC safety message system before an Emergency Belt and Emergency Belt DSRC control. The ship driver may ignore or delay reacting to the DSRC safety message. In such cases, DSRC takes over the ship’s speed control at the Emergency Belt and will stop the ship. This can also be considered as an act of aggressive behavior by ship driver, and they can be fined if DSRC finds any existing operating velocity of the ship higher than the speed limit at the Emergency Belt. Moreover, as an additional security measurement, adaptive cruise control is used and demonstrated in our simulation study for ship-to-ship collision avoidance.

5.3.1. Adaptive Cruise Control for Inter-Ship Collision Prevention

ACC technology is simulated as an additional safety system to prevent the ship from shipping collision for multiple ship crossing. It also creates a distance gap among ships when they are detected by buoys to prevent any possible conflict or miscalculation in sensing ships. In our simulation environment, a ship is manually controlled, and a secondary ship is automated to maintain the ACC without crashing with the primary ship. The velocity, acceleration, and distance between two ships are continuously monitored and recorded in the simulation environment and visualized in real-time by the graphs of time vs. distance, speed, and acceleration. The change in these aforementioned parameters is demonstrated in Figures 10 and 11.

![Figure 10. Adaptive Cruise Control among ships at phase one.](image-url)
Figure 10 demonstrates two ships starting from the left portion of the GUI, going towards the right. The simulation environment resembles the real-world scenario and the change in speed among ships. Two ships are also depicted at a specific distance using a GUI. For maintaining ACC, a radar system and a camera are required to be installed in ships. Any obstacle or moving object in front is comprehensively detected by the radar using frequency modulated continuous wave (FMCW). Camera detection eventually helps in path prediction [21]. For phase one, the curves for velocity, acceleration, and distance between ships are found consistent with the principle of ACC. Initially, the rear ship was approaching from afar at a slow speed. The ship then begins to decelerate and reduces its velocity. After some time, both ships start maintaining reasonable speed, acceleration, and a level of distance.

Figure 11 illustrates two ships in a more forward position than those in Figure 10. The GUI shows the rear ship attempting to maintain a safe distance from the forward ship; however, the forward ship accelerates greatly, and the rear ship attempts to match this. Lastly, ships maintain ACC in movable bridge zone successfully, follow a specific distance among them, and help buoys preventing any conflict in sensing or miscalculation. As depicted, ACC acts as a collision prevention technology among ships in the bridge zone when any sudden speed variation occurs in a leading ship.
5.3.2. DSRC Safety Command

DSRC is a short-range communication system between vehicle to vehicle and vehicle to infrastructure. For the default DSRC system, the maximum range is 300 m [22] which has been improved up to 11 miles by the Utah Transportation Department. In this research, DSRC is maintained for communication between ships to bridge the control system. Using the DSRC system, a safety message warning system is maintained when ships move within a short distance of a movable bridge that is currently maintaining traffic flow. During this condition, the bridge will prioritize the safety of vehicles on the bridge and disregard the moving command. At the same time, the bridge control system will give a safety message using the DSRC system to stop any ships from moving too close. The message acts as a direct command to the ship operator before passing the Emergency Belt. The ship detection scenario at DSRC range and bridge impromptu condition is simulated and shown in Figure 12.

A buoy is placed exactly $D_{dsrc}$ apart from the bridge Emergency Belt. In the figure, it is denoted as $Ba$ for route AB and $Bc$ for route CD. When a ship is about to pass the buoy, $Ba$, its position is detected, and a signal is transferred to the bridge control system. Subsequently, the bridge control system checks the evacuation condition. If the count at bridge evacuation is nonzero, there must be a vehicle remaining on the bridge, and the bridge considers itself unprepared to move for the safety of bridge traffic. Thus, the bridge control system of the bridge directly gives the safety command using the DSRC system to stop the ship before an Emergency Belt.

![Figure 12. Ship detection scenario at DSRC range and impromptu bridge condition.](image-url)
5.3.3. DSRC Control Establishment

At the Emergency Belt, the DSRC control system is given authoritative power over the ship control system. It can directly stop the ship’s operating speed to zero to prevent the probable collision between ship and bridge. This system is generally deactivated for the regular ships incoming and outgoing of the bridge. When a ship comes too close to the movable bridge when the bridge is still not prepared for evacuation, safety command is transferred to ships by DSRC. At the same time, Emergency Belt DSRC control is activated. Two buoys $B_{EA}$ and $B_{EC}$ are placed within the Emergency Belt to detect the position of any ship that is about to enter an Emergency Belt. If a ship enters the Emergency Belt ignoring the DSRC safety command, its position is detected by the buoy at the Emergency Belt and forwards a signal to the bridge control system. At this point, the bridge control system takes over the ship’s operating speed control system. The system determines what the operating speed of the ship is. If the ship is not moving, it is evident that it is waiting for bridge evacuation to end. This security technique diminishes any remaining probability of collision between a ship and a movable bridge. Algorithm 1 shows the algorithm for the DSRC based collision prevention system using safety messages and emergency control.

Algorithm 1 Algorithm for DSRC Clash Avoiding Control System

```
for Baa = Activated do
    Checking value for $(k - l) + (m - n)$
    if $(k - l) + (m - n) = 0$ then
        Turn Bridge Open
    else
        for Ba = Activated do
            Checking value for $(k - l) + (m - n)$
            if $(k - l) + (m - n)0$ then
                DSRC = Activated
                Command = "Stop the ship before Emergency Belt"
                Send Command to ships via DSRC
            end
        end
        for Bae = Activated do
            if Ship velocity 0 then
                DSRC = Activated
                DSRC takes over the control of ships
                Operating ship speed = 0
            else
                No action. No fine.
            end
        end
    end
end
```

Operating at greater than the suggested speed at the Emergency Belt is considered a dangerous act. If a collision occurs, it can result in major structural damage and causalities. Excess speeding after the Emergency Belt is considered as a ship operator acting aggressively. As a result of such a dangerous act, financial penalties through the form of a fine are recommended to dissuade ship operators from performing such aggressive acts.

In another case, the ship that was stopped before the Emergency Belt, according to the DSRC safety message, may still pass the Emergency Belt and get detected by the Emergency Belt buoy. This can occur due to the inertial speed of the ship being too high at the time of receiving the DSRC message. Even after a ship’s operating speed begins to reduce, it often takes time to completely stop and will still move due to the previous speed range factor and the loads carrying the ship. As the ship’s operating speed is zero, the DSRC control will not detect any operating speed, and DSRC will not interrupt in that case. This
is considered safe in this system, and ships will get sufficient distance of Emergency Belt as breaking distance. Ships will neither be considered aggressive nor be fined in such circumstances. For the ships needing higher braking distance, a larger Emergency Belt distance needs to be implemented according to this research.

5.4. Bridge Reformation

Bridge reformation is the process of retracting the bridge to previous fixed conditions to let the bridge vehicle pass through it. The bridge reformation process depends on ensuring zero ships between two Alert Belts, and it is confirmed through another counting algorithm. As mentioned in the section, belt division, two routes are maintained for a ship passing through the movable bridge, and the direction of the ship passing through these routes is transverse. For each route, the buoy at the entry Alert Belt counts the number of ships entered and aggregated it. The buoy at the exit Emergency Belt detects the outgoing ships and counts the number of ships. The subtracted value of exit buoy modifies count from entered buoy; therefore, the aggregated count defines the number of ships remaining in each route. When the number of the remaining ships is zero at both routes based on the final value determined by the buoys, then the bridge proceeds to reform and close again for the passage of bridge vehicles.

Considering continuous ship transportation through the movable bridge navigation system.

Number of ships detected by buoy, $B_{ab}$ at entry Alert Belt of route AB = \(w\)
Number of ships detected by buoy, $B_{be}$ at exit Emergency Belt of route AB = \(x\)
Number of ships detected by buoy, $B_{ca}$ at entry Alert Belt of route CD = \(y\)
Number of ships detected by buoy, $B_{de}$ at exit Emergency Belt of route CD = \(z\)
Number of ships remaining at route AB = \(w - x\)
Number of ships remaining at route CD = \(y - z\)

Therefore, the total number of ships remaining in the bridge navigation system = number of ships remaining at route AB + Number of ships remaining at route CD = \((w - x) + (y - z)\).

The bridge control system proceeds the reformation process when it confirms that the total number of ships remaining in both routes AB and CD = \((w - x) + (y - z)\) = 0. The bridge reformation process after the ship crossing is shown in Figure 13.

In Figure 13, the ship has already crossed the bridge, and the bridge initiates the reformation process. It starts moving back to turn back to the fixed bridge condition for bridge vehicle transportation. The graph shows the distance between ship and bridge starts increasing with time.
6. Results and Discussion

The proposed navigation management scheme for the movable bridge is evaluated in the simulation environment by simulating the methodology for 20 trials at both routes and tracking the outcome of the detection system as well as bridge status. The performance result is shown in following Table 1.
| Trial | Alert Belt Status, Baa | Bridge Evacuation Status | DSRC Range Status, Bb | Emergency Belt Status, Bae | Emergency Control System | Ship Crossing Status, Bbe | Bridge Reformation | Comment |
|-------|-----------------------|---------------------------|-----------------------|---------------------------|----------------------------|--------------------------|-------------------|---------|
| 1     | Activated, Traffic: 0 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 2     | Activated, Traffic: 4 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 3     | Activated, Traffic: 1 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 4     | Activated, Traffic: 13 | Initiating, Road barrier: Closed | Activated, Traffic: 4, Bridge Status: Closed | Activated | Activated, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | High Traffic Volume |
| 5     | Activated, Traffic: 4 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 6     | Activated, Traffic: 8 | Initiating, Road barrier: Closed | Activated, Traffic: 1, Bridge Status: Closed | Null | Null, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | High Traffic Volume |
| 7     | Activated, Traffic: 4 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 8     | Activated, Traffic: 11 | Initiating, Road barrier: Closed | Activated, Traffic: 3, Bridge Status: Closed | Null | Null, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | High Traffic Volume |
| 9     | Activated, Traffic: 3 | Initiating, Road barrier: Closed | Activated, Traffic: 3, Bridge Status: Closed | Activated | Activated, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | Speedy Ship |
| 10    | Activated, Traffic: 5 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
|       |                       |                           |                       |                           |                            |                          |                   |         |
|       |                       |                           |                       |                           |                            |                          |                   |         |
| Trial | Alert Belt Status, Bca | Bridge Evacuation Status | DSRC range status, Bc | Emergency Belt Status, Bce | Emergency Control System | Ship Crossing Status, Bbe | Bridge Reformation | Comment |
|-------|-----------------------|--------------------------|-----------------------|---------------------------|----------------------------|--------------------------|-------------------|---------|
| 11    | Activated, Traffic: 6 | Initiating, Road barrier: Closed | Activated, Traffic: 5 | Null | Null, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | Speedy Ship |
| 12    | Activated, Traffic: 0 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 13    | Activated, Traffic: 0 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 14    | Activated, Traffic: 13 | Initiating, Road barrier: Closed | Activated, Traffic: 7 | Null | Null, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | High Traffic Volume |
| 15    | Activated, Traffic: 1 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| Trial | Alert Belt Status, Bca | Bridge Evacuation Status | DSRC range status, Bc | Emergency Belt Status, Bce | Emergency Control System | Ship Crossing Status, Bde | Bridge Reformation | Comment |
|-------|-----------------------|--------------------------|-----------------------|---------------------------|--------------------------|--------------------------|-------------------|---------|
| 16    | Activated, Traffic: 0 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 17    | Activated, Traffic: 5 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 18    | Activated, Traffic: 2 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 19    | Activated, Traffic: 4 | Initiating, Road barrier: Closed | Null, Traffic: 0, Bridge Status: Open | Null | Null | Activated | Successful, Road barrier: open | Regular |
| 20    | Activated, Traffic: 14 | Initiating, Road barrier: Closed | Activated, Traffic: 6 | Activated | Activated, Bridge open at traffic 0 | Activated | Successful, Road barrier: open | High Traffic Volume |
The performance results of the study show that 65% of regular ship transportation through the movable bridge occurs without any requirement of safety warning message or emergency control. Some incidents are found with bridge opening delay due to high traffic volume or an excessively fast ship where DSRC safety warning is required, followed by the further imposition of the emergency clash avoiding control system. Around 35% of events show the usage of DSRC safety warning and 15% of events required prevention of ship’s approach using emergency clash avoiding control system. For high traffic volume, the movable bridge must delay evacuating bridge vehicles, leading to opening delay as well. Ships approaching the bridge at excessive speeds also cause a threat to the bridge structure and the ship. Therefore, the ship is given a DSRC safety warning to stop before the Emergency Belt. For any disorderly ship that is violating safety warning and approaching the Emergency Belt, the emergency clash avoiding control system takes over the speed control to stop before reaching the bridge structure. In regular cases, bridge evacuation, opening, reformation, and road barrier operations are maintained successfully in a proper manner.

This research is accomplished by only considering the movable bridges which act as a gateway barrier to ships or any other water vehicles. Some bridges have height factors that only open for ships that exceed the specific height threshold. Such bridges and their height parameters are kept out of consideration for this research. However, further research can be conducted considering the height factors and the sensor technologies required to be installed to account for them.

Since the counting algorithm will be run continuously, a backup energy storage system using renewable energy sources, such as solar panels or turbines for wind or hydropower generation, will provide power to the major systems, especially the microcontroller-based systems only. Moreover, the data is continuously being stored in the GPS server; therefore, if any problem occurs, the system can recover the data instantly from the database upon power retrieval. Thus, there is very little risk in losing the data or in maintaining the communication during a power outage or network error.

At the initiation of the bridge evacuation process, a simple speed limit and a signalization scheme are maintained in the bridge area as a less expensive approach. However, in this modern era of rapidly evolving technology, the used technology examined in this paper can be improved by the use of GPS detection and hybrid sensors. Furthermore, devices such as RADAR, LIDAR, thermal camera, and Mobile Eye can provide a more fruitful result when producing solutions for maritime automation of movable bridges. The authors of this research will work to implement these advanced sensors and technologies as further research improvement on movable bridge maritime automation. Moreover, machine learning-based vehicle detection can be implemented for detecting vehicles through cameras and counting accordingly for bridge evacuation. Future research will focus on collecting experimental data of ship speed, acceleration, position, and other important features by running the models of hundreds of ships through movable bridge navigation system and predict the ship’s behavior to take more security measures or for better maritime management and control. Furthermore, using GPS tracking technology or connected vehicle technologies, further research on movable bridge traffic control may bring more precise and secure traffic control.

The fixed distance between the alert and Emergency Belt can be made dynamic by considering different vessels and their deceleration capacities. The range of this distance highly impacts the time bridges get for evacuation and opening. On the other hand, the amount of time a movable bridge needs to evacuate bridge vehicles and open depends on the bridge length, bridge positioning, and complexity of different transportation modes that link to the bridge. Therefore, the distance between Alert Belt to an Emergency Belt at each side of the bridge could also be calculated based on these parameters. Future research into determining the dynamic distance between the Alert Belt and Emergency Belt for different movable bridges and parameters would be highly useful. Furthermore, this approach should be validated and improved using more case studies, as Fort Madison
Swing Bridge was the only bridge used in this study. Other movable bridges apart from the swing bridges will also be considered in future studies to understand the feasibility of the system with more focused parameterization using the designed software system and practical implementation wherever possible.

The braking distance of the ship depends on the initial speed of the ship and the load of the ship. If the initial speed is higher, it takes more time to stop and tends to move further due to inertia even after stopping the ship. According to this paper, a ship speed limit of 11.5 km/h (around 6 knots) has been suggested to be maintained. High loading, tank ships and other water vessels may have a larger braking distance after the Emergency Belt. If the braking distance exceeds the distance limit, a collision may occur between ships and bridges even after the ship is stopped. Such cases may need a broader space to maintain an assured braking distance. In this research, the maximum default DSRC 300 m range has been suggested to be maintained affordable and handy with a conventional default sensor rather than high ranged and costly equipment. Further research can be performed considering the shipload factor to maintain safety assurance for braking distance. Lastly, it is also important to examine the impact of a longer-range DSRC on movable bridge emergency safety. Ideally, this examination would be in the form of a simulation-based scenario, which is intended to be described in a future research analysis on the concept.

7. Conclusions

Movable bridges in different countries are heritage structures known for their beautiful architectural design and unique operating technique. They also serve an important purpose within the transportation system ecosystem, and their positioning is often vital in conflicting traffic modes. A comprehensive theoretical framework and algorithm for movable bridge maritime automation have been proposed and simulated in this research. The virtual belt division, buoy setup, and geographical positioning have been considered for Fort Madison Swing Bridge, and the design automation installments with division ranges have been accomplished. Different scenarios and notations have been demonstrated through simulation, CAD design, and the algorithm have been discussed accordingly. A counting algorithm has also been implemented to ensure bridge traffic control and automated navigation maintenance. By implementing these algorithms, an error-free and safe bridge evacuation and bridge reformation have been maintained. The purpose of this research is to enhance the reliability of the maritime management and control system in the movable bridge. The variation of velocity, acceleration, and distance among ships have been shown in curves in GUI for different phases, and this variation has been found analogous to the principle of ACC. The algorithm of the DSRC system for safety message command and arbitrary emergency control has been described, and the possible scenarios have been analyzed using the simulation study. In summary, this research will open new avenues in movable bridge research, incorporating automation and optimization to make regional and route planning smart and flexible [23,24].

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