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Techno-Economic Design and Implementation of Vehicular Access Control

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Abstract: Traffic management and control is pivotal to maintaining orderliness in corporate organizations. The effective management and control of traffic will lead to improved security. As a result, investments in security take a good percentage of their expenses, which necessitates improved security solutions at reduced costs. Most corporate organizations adopt the use of a boom barrier, which is an improved version of the traditional or manual barrier system (MBS). However, the boom barrier uses a remote controller with limited capability in terms of operating range and security level. The running cost is also key in choosing the system to be adopted for security purposes. This study developed a techno-economic design and implementation of a vehicular access control system using the Bells University of Technology, Ota, Nigeria, as a case study. The study first designed a control system module by exploring the capabilities of the loop detector, Arduino, Raspberry pi, four-channel relay, radio frequency identification (RFID) card and scanner, and a camera. The control system module was then integrated into the boom barrier for seamless control to realize the boom barrier access control system (BACS). The paper developed economic models for the MBS and the BACS, which were simulated using MATLAB to justify the need for the adoption of the developed BACS. A sensitivity analysis was performed to demonstrate the robustness of the developed cost models. The functionality tests on the developed BACS showed that the system is characterized by an average response time, opening time, delay time, and closing time of 5.06 seconds, 6.12 seconds, 30.02 seconds, and 6.02 seconds, respectively. Results on costs showed that the BACS is cost-effective with an initial cost of $7,650 compared to $15,223 for the MBS. The BACS is also more resilient to annual increments than the MBS. A cost-benefit analysis revealed an annual increase in the cost-benefit over the entire system lifespan. The study has demonstrated the viability of BACS in vehicular access control considering both the ease of operation and systems costs.

Keywords: Access control, vehicle identification, RFID, loop detector, boom barrier.

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1. Introduction

Traffic management is an important aspect of security that must be properly managed for an environment or organization to be secured (De Souza et al., 2017). The inability to properly manage traffic might result in degraded security. Security in Nigeria is fast becoming a source of concern as it has been confronted by an array of challenges (Duerksen et al., 2021, Nwagboso, 2018). The security of lives and properties is pivotal to the existence of organizations and governments (Achumba and Ighomereho, 2013). Consequently, continuous investments in security have become a culture that contributes to a significant percentage of organizations' and governments' spending. With the development of smart technologies, quite a number of systems can be seamlessly controlled and manipulated (Das et al., 2020). Most organizations control their processes to achieve orderliness and security, which in turn leads to improved productivity at a reduced cost, (Cascio and Montealegre, 2016). This is achieved through access control technology which is the process of authorizing people or objects to available resources within a particular environment or location (Liu et al., 2020).

Access control is essentially a process that stops unauthorized users from accessing reserved resources or permits authorized users to access reserved resources and prevents genuine users from illegal access to reserved resources. In the field of information management, various methods like role-based access control (RBAC) (Rana and Sportiello, 2014), break-the-glass role-based access control (BTG RBAC) (Ferreira et al., 2009), emergency role-based access control (E-RBAC) (Nazerian et al., 2019), have been employed to grant access to predetermined tasks in information management and security. However, these methods do not consider physical infrastructures such as schools, large-scale companies, and banks, for example. It is necessary in this current dispensation to recognize the importance of security in the physical structures, especially in a country like Nigeria where insecurity is becoming the order of the day (Aleyomi and Nwagwu, 2020).

Traditionally, the use of manual gating and barrier arm systems have been used to restrict and/or permit access into the infrastructures. Gates, on the one hand, for instance, provide entry and exit to infrastructures enclosed by a fence, (Siembieda, 1996). The boom barrier, on the other hand, has both manual and automatic types. A manual boom barrier is simply made up of a first-class lever, fulcrum, and counterweight, whose movement is controlled by a certain mechanism enabling the boom to lift on its own whenever the center of gravity is passed. Most corporate organizations adopt the boom barrier, which is an improved version of the traditional manual barrier. The manual systems are highly laborious, cost-intensive, and highly subjective. These shortcomings motivate the quest for alternative solutions such as the application of automation that serve as a paradigm shift in gating (Amusa et al., 2012). This is essentially the art of enabling a device, machine, process, or procedure to be self-controlling (Ciubotaru-Petrescu et al., 2006). Therefore, the automatic boom barrier type is an example of an alternative solution to the manual boom barrier. It is an electro-mechanical device that consists of a pole pivoted on a base housing an integrated circuit and a microcontroller that controls the movement of the arm thereby enabling its seamless operation.

In recent times, many gates are opened by automated gate operator which is endowed with many special features (Dandang et al., 2015). For instance, while Abu and Obomeghie (2017) reported a scholarly work on the design and development of automatic gate openers, Kasym et al. (2018), presented a parking gate control system based on a mobile application.

The study on wireless solutions for telemetry in civil equipment and infrastructure monitoring was presented by (Ciubotaru-Petrescu et al., 2006). Aliyu et al. (2016), employed wireless sensor networks to develop smart car parking systems. Gunda (2012), reported a radio frequency identification (RFID) based automatic tollgate system, which comprises tags, readers, a network, and a database.

The capability of microcontrollers in developing intelligent systems has been demonstrated by various researchers by employing microcontroller like programmed PIC16F84A, ATMEGA 8, and AT89C2051 that links the software and the hardware components together (Adewuyi et al., 2013, Oluwole et al. Amole et al., 2020). Similarly, the capabilities of discrete components like LED, a decoder integrated circuit (IC), NPN transistor, counter CD401, RFID, IR sensors, RFID, liquid crystal display (LCD), buzzers, light led, and motor driver (Enokela and Tyowuah, 2014, Rohini et al., 2017, Abu and Obomeghie, 2017, Balamurugan et al., 2018). A study was conducted on the utilization of an optoelectronic device to design a low-cost security alarm system (Barkat et al., 2015).

The mentioned studies have made useful contributions in the aspect of gate control, which form a relevant technical background to this paper. The reviewed works focused on the technical part and did not consider the economic aspect of the design. Technologies come with cost implications, and it is crucial to ascertain this at the design stage, as it can determine the acceptability of the technology by the users (Serrado et al., 2019). Besides, the system cost may be used as a benchmark for the competitiveness of improved system designs. Affordability is also key in systems design because not all innovative designs are affordable and not affordable designs are innovative. Hence, there must be a connection between acceptability, affordability, and system designs.

Traffic is one of the key features of cities and organizations which must be properly managed to avoid a breakdown of law and order. It has been reported that factors such as inadequate parking spaces, erratic public transport, and motorists indiscipline (Asiyanbola et al., 2012). Loss of human lives and money can be attributed to traffic in most cases. To effectively manage traffic, Nigerian states create traffic management agencies like Lagos State Traffic Management Authority (Belloa and Usifob, 2009). However, these agencies have been found culpable with implications for safety and security in some instances (Olojede et al., 2017). Advances in dynamic adaptive technologies and communication can be deployed to efficiently develop traffic management systems (Djahel et al., 2013).

Considering the higher number of vehicular movements at the entrance of the Bells University of Technology, Ota daily, the manual checks of cars in and out of the University are quite laborious, highly subjective, and unnecessarily time-consuming. Hence, there is a need for an efficient and cost-friendly traffic management system; this serves as a motivation for this paper. Therefore, the following research question suffices:

i. Is it possible to design and integrate a control system module into an automatic boom barrier to allow for seamless control?
ii. Are boom barrier access control system (BACS) and manual boom barrier system (MBS) economically viable?
iii. How robust are MBS and BACS cost models to change in prices?

Consequently, the goal of this study is to design and implement a vehicular access control system which is an improved version of the existing solution to ensure efficient traffic management. Also, cost models were subsequently developed for these systems to demonstrate their viability. Bells University of Technology is used as a case study and the remaining part of this work is organized as follows; theoretical backgrounds on cost, materials, and methods, results and discussions, and conclusion.

2. Theoretical Backgrounds on Cost

Cost is simply the required payment for goods or services and can be estimated using different methods that might cause cost overrun (Barakchi et al., 2017; Ekung et al., 2021). The cost concept has extended to the droop scheme as cost-based adaptive (CBA) control to reduce the total generation cost (Song et al., 2020). Generally, the total cost of a product or good depends on a number of factors that can be summarily expressed as Eq. (1):

$$T = f(Q, Tech, Pf, K) \tag{1}$$

Where T is the sum of the costs, Q is the quantity, $Tech$ is technology, Pf is the price factor, and K is the capital.

Cost is of different categories depending on the context where it is incurred. Cost can be direct or indirect; while the former is easily traceable and identifiable to a particular product or good the later not easily traceable to a particular product or good. A typical example of direct cost is the manufacturing costs in a production line, while that of indirect costs include the salary of security men, electricity bills, and maintenance costs (Jiang and Marggraf, 2021). Another category of cost is fixed and variable costs. Technically, for fixed costs a constant expenditure is required regardless of the output level, for example interest on a loan, whereas for variable costs, the level of output strongly depends on the expenditure example, including raw materials for production and wages (Zhao and Yang, 2022). Simply put, while variable cost varies with output level, it remains constant for fixed costs. Total Cost relates to the total actual costs required to produce a given amount of goods and services. Total cost is given rise to by the summation of total variable costs and total fixed costs as shown in Eq. (2):

$$TC = TFC + TVC \tag{2}$$

The average value of these costs (Kara et al., 2019) that is; TC, TFC, and TVC can be obtained by normalizing them with the Q of the goods or services as follows:

$$AFC = \frac{TFC}{Q} \tag{3}$$

$$AVC = \frac{TVC}{Q} \tag{4}$$

$$ATC = AFC + AVC = \frac{TFC+TVC}{Q} \tag{5}$$

Where ATC is the average total cost, AFC is the average fixed cost, and $AVC$is the average variable cost. It follows from Eq. (5) that the dynamics of ATC depend on the dynamics of AFC and AVC where a rise in both AFC and AVC leads to a rise in ATC and vice visa.

Marginal cost is a common term in production economics as it implies the addition made to the total cost by the production of an additional unit of output (Gao *et al.*, 2019). It should be noted that marginal cost is independent of fixed cost and can be mathematically expressed as Eq. (6):

$$MC = TC_N - TC_{N-1} \tag{6}$$

Where TC_N is the total cost of producing *N* units of goods and services while TC_{N-1} is the total cost of producing *N-1* units of goods and services.

3. Materials and Methods

The materials and methods used for the development of the two-stage boom barrier access control for the entrance of Bells University of Technology, Ota, include an RFID card, Loop detector, Arduino, Microsoft Life Cam-3000, four-channel relay, Raspberry pi, and traffic light.

The study first designs a control system module by exploring the capabilities of the loop detector, Arduino, Raspberry pi, four-channel relay, RFID card and scanner, and a camera. It then integrates the designed control module into the boom barrier for seamless control to realize the boom barrier access control system in the MATLAB environment. The paper introduces economic models for the manual barrier system and the boom barrier access control system, which are to be simulated using MATLAB. It also presents a sensitivity analysis to demonstrate the robustness of the developed cost models.

3.1. Description of the Case Study

The case study in this work is the entrance of the Bells University of Technology, Ota, Ogun State, Nigeria. Fig. 1 shows the entrance of the University with two gate compartments separated by the security house in the middle. The gate compartment by the right serves as the entry, while the one by the left serves as the exit. Each of the compartments is made up of the traditional gate that is closed at night, to prevent entry and exit from the university during the night, and a manual boom barrier that is used during the day to stop cars for security checks. The manual barrier is made up of a barrier arm and a counterweight placed on a pivot, and the barrier is operated with the aid of a rope. An automatic boom barrier is, therefore, deployed to ease the stress of the manually-operated boom barrier that is currently used.

Fig. 1. The case study: Bells University entrance

3.2. Manual Barrier System

The MBS currently in operation at the University entrance is simply a crossbar pivoted on a pole with a counterweight. The effort end has a rope with which the barrier is opened and closed. Fig. 2 shows the MBS at the University entrance with the specifications presented in Table1.

Fig. 2. The manual boom barrier

Table 1. Specification of the MBS

Parameters	Value
Barrier Arm Length	6m
Fulcrum height	1m
Rope length	9m
Counter Weight	40kg
Operators	10

3.3. Barrier Access Control System

The BACS comprises of two parts, namely the automatic boom barrier and the control system module. The automatic boom barrier used is a readily available one while the control system module was locally designed. The control system module is integrated into the automatic boom barrier to achieve a seamless operation.

3.3.1. Automatic boom barrier

The automatic boom barrier used in this work is shown in Fig. 3 while its parameters are presented in Table 2. The barrier is of dimension 1m in height and 0.33m in width. The casing of the barrier is made of iron to give it the needed stability while in operation; the barrier arm is made of aluminum to ensure that the system poses little torque on the barrier motor. The selection of the boom barrier motor is based on the subsequent calculations using the parameters in Table 2. The current flow is obtained using Eq. (7):

$$I = \frac{P}{V} = \frac{80}{220} = 0.364A \tag{7}$$

Where P is the power in watts and V is the voltage in Volts. The required mechanical power (P) of an electric motor is obtained using Eq. (8) as follows;

$$P = \frac{2\pi NT}{60} \text{watts} \tag{8}$$

Here N denotes the speed of the motor. From Eq. (8), the load torque (T) is given by using Eq. (9):

$$\mathrm{T} = \frac{60\mathrm{P}}{2\pi\mathrm{N}} \tag{9}$$

$$\mathrm{T}_{\text{at load}} = \frac{60 \times 80}{2 \times 3.142 \times 1350} = 0.566\text{Nm}$$

$$\mathrm{T}_{\text{no load}} = \frac{60 \times 80}{2 \times 3.142 \times 1480} = 0.516\text{Nm}$$

The barrier is mounted on a concrete base of 0.6m by 0.6m by 0.6m and installed with an iron rod basket that has a threaded end, which allows the barrier to be fastened to the concrete base.

Fig. 3. The automatic boom barrier

Table 2. Automatic boom barrier parameters s at normal condition

Design Parameters	Design Specifications
Voltage (V)	220 ± 10%
Power (P)	80 W
Operation time	6 seconds
Remote distance	≤ 30 meters
Working temperature	-35^0C to 80^0C
Relative humidity	< 90% RH
On-load speed (N)	1350 rev/min
No-load speed (N)	1480 rev/min
Barrier arm length	4.5m
Boom height	1m

3.3.2. Control system module

The boom barrier naturally works with remote control for the control of the barrier arm. This type of control has some limitations, such as cases where the remote control gets damaged, and the control of the barrier constituting a challenge. Also, the use of remote control might fail the holder if the controller is out of the range of controllers' range. Consequently, a two-stage control scheme is designed and integrated into the boom barrier considered for this work to allow for seamless control of the barrier. This is done to achieve an increase in the efficiency of the barrier system. The various components used to develop the control system module are subsequently discussed in subsections 2.3.2.1 through 2.3.2.7 while subsection 2.32.8 briefly presents the schematic of the control system module.

3.3.2.1. RFID technology

RFID is based on the concept of electromagnetic waves for capturing and transmitting data interpretation. The RFID is structurally made up of a tag's chip which is activated when it is near a reader thereby sharing the information that is electronically stored on the tag. Active RFID with a high range has its own power source whereas passive RFID that works at a shorter range is powered by a reader. In this work, the RDM6300 RFID reader shown in Fig. 4 is used while the tag and card in Fig. 5 used for this work is a 125 kHz RFID card.

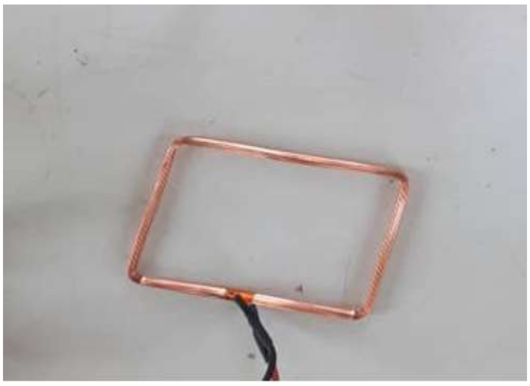


Fig. 4. RDM6300 RFID reader

Fig. 5. 125kHz RFID Card.

3.3.2.2. Camera

In this work, the Microsoft Life Cam-3000 camera shown in Fig. 6 is used to capture the image of the incoming vehicle. The camera is triggered when the system receives a command from the vehicle loop detector which is buried at the entrance and exit. The camera is positioned such that when triggered, the vehicle is within its region of coverage, and the vehicle image is stored in the system database.

3.3.2.3. Arduino

The Arduino UNO shown in Fig. 7 is employed in this work to serve as the microcontroller which serves as the activities coordination center for the boom barrier. The codes were simply loaded into the Arduino with a USB cable while powering the RDM6300 card reader.

Fig. 6. Microsoft Life Cam-3000

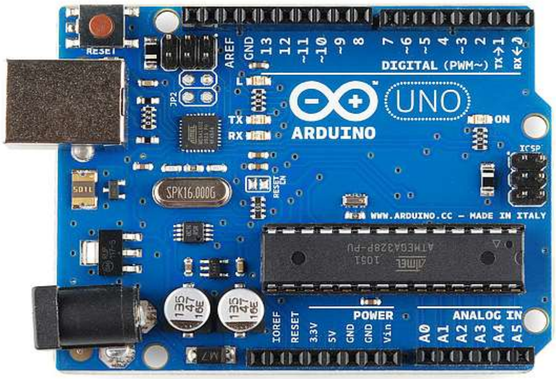


Fig. 7. Arduino

3.3.2.4. Four channel relay

A four channel relay designed to interface with a microcontroller such as Arduino and PIC is a suitable board, which is capable of controlling motors, solenoid valves, and lamps. The relay status is indicated with a LED and the one used in this work is shown in Fig. 8. Two of the four channels were used to simulate the press of a button; the first is used to simulate ‘boom barrier open’ while the second is used to simulate ‘boom barrier close’. The third channel turns on and off the red lamp while the fourth turns on and off the green lamp. This is achieved by making and breaking contact with just a 500ms (millisecond) delay.

3.3.2.5. Traffic light

The traffic light is generally used for communicating with road users. It is a set light of different colours namely; red, amber, and green which is automatically operated, for controlling traffic at road junctions and pedestrian crossings. Different colour of lights implies different actions to be taken by the road user. Fig. 9 showed the traffic light used in this work where “Red” indicates “Stop”, “Amber” indicate “Ready”, and “Green” indicate “Go.”

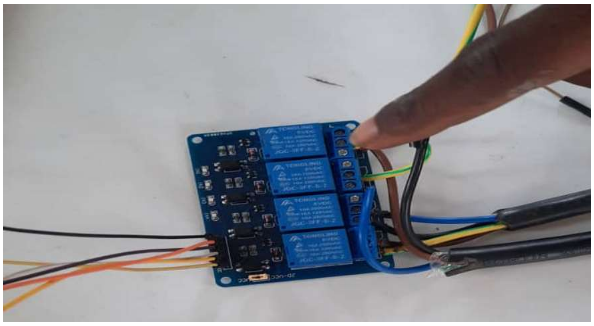


Fig. 8. Four channel relay

Fig. 9. Traffic light

3.3.2.6. Vehicle detection loop

The vehicle detection loop is an inductive-loop traffic detector capable of detecting vehicles within the loop. An alternating current is applied onto the wire loops at frequencies between 10 kHz to 200 kHz thereby making the inductive-loop behaves as a tuned electrical circuit in which the loop wire and lead-in cable are the inductive elements. The passage of a vehicle over the loop or within the loop increases the loop's inductance. However, the metal of the vehicle produced an opposite effect on the inductance due to eddy currents which decreased the inductance more than the offsets. The net inductance results in a decrease in the inductance of the wire loop which in turn leads to a decrease in the electrical impedance of the wire to alternating current. The decrease in impedance actuates the electronics unit output relay which triggers the traffic signal controller thereby showing the presence of a vehicle.

In this work, a 6mm cable flex is used to make the loop which is buried beneath the ground 3 meters away from the traffic light pole. Fig. 10 shows the connection of the vehicle loop to the Centurion loop detector which has 8 ports 2 of which are used to connect the loop.

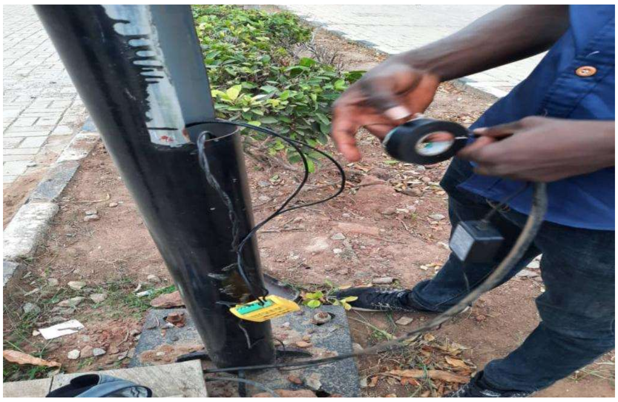


Fig. 10. Connection of the vehicle loop and centurion loop detector

3.3.2.7. Raspberry pi

The Raspberry pi used in this work is shown in Fig. 11, which is Raspberry pi 3 model B VI. 2. It is characterized by audio and video ports, HDMI, Micro USB power, Network port, USB ports, CPU, Memory, Micro SD, Bluetooth 4.1, and General-Purpose Input Output (GPIO) pins. The GPIO pins are forty pins in two rows of twenty on each side. While the pins on the left have their pin numbered as odd numbers, those on the right were numbered as even numbers. The pins are configured to a defined set where some pins are allocated for ground, open and close. The communication setup between the Raspberry Pi and the BACS control circuit requires the use of ground pins and GPIO pins to send control signals to the control unit of the BACS.

3.3.2.8. Control system module schematic diagram

The schematic diagram of the control system module is shown in Fig. 12 which shows the connection of the components earlier discussed in the previous subsections to function as a unit. The figure shows the interconnection of the loop detector, camera, Raspberry Pi, Arduino, four-channel relay, traffic light, and boom control. The RFID connection is not shown in the diagram due to the unavailability of the RFID devices in the drawing software. The relay on receiving a command from Raspberry Pi sends signals to the actuator for the control of the boom barrier automatically. The red traffic light is pre-enabled with the barrier arm at the horizontal position to help alert the oncoming vehicle to stop at the appropriately marked region of the loop. With the coil loop connected to the detector and the vehicle detected, a signal is simultaneously sent to the detect pin of the Arduino microcontroller and Raspberry Pi. This enables the microcontroller to generate another signal and make the card reader ready for scanning. The Raspberry Pi on receiving a command as it detects pin renames the image captured by the camera with the card number, the time and date stamp data produced by the card reader on scanning the RFID card. After scanning, the barrier arm starts rising with the yellow light on and the green light when the arm is fully raised. The control system module was built according to the schematic diagram in Fig. 12 and interfaced with the boom barrier to form the BACS.

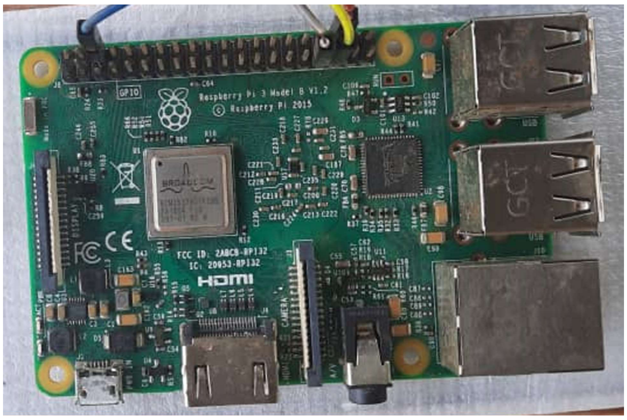


Fig. 11. Raspberry Pi

3.4. Working Principle of BACS

The operation of the barrier access control system can be described in the four subsections namely; the registration stage, the verification stage, and the system operation subsequently discussed.

3.4.1. Registration stage

A registration firmware is uploaded to Arduino. The firmware is used to save RFID card numbers on the SD card for the first authentication by placing the new card to be registered near the RFID module scanner. The card numbers are read and sent to the Arduino which saves the card number on the SD card.

3.4.2. Verification stage

The verification is performed while Arduino is running the main firmware. At the entry point, firmware crosschecks the card number of the scanned card with the pre-registered card numbers saved on the SD card in the Arduino. At the exit point, the firmware checks for the vehicle image tagged with the scanned card number.

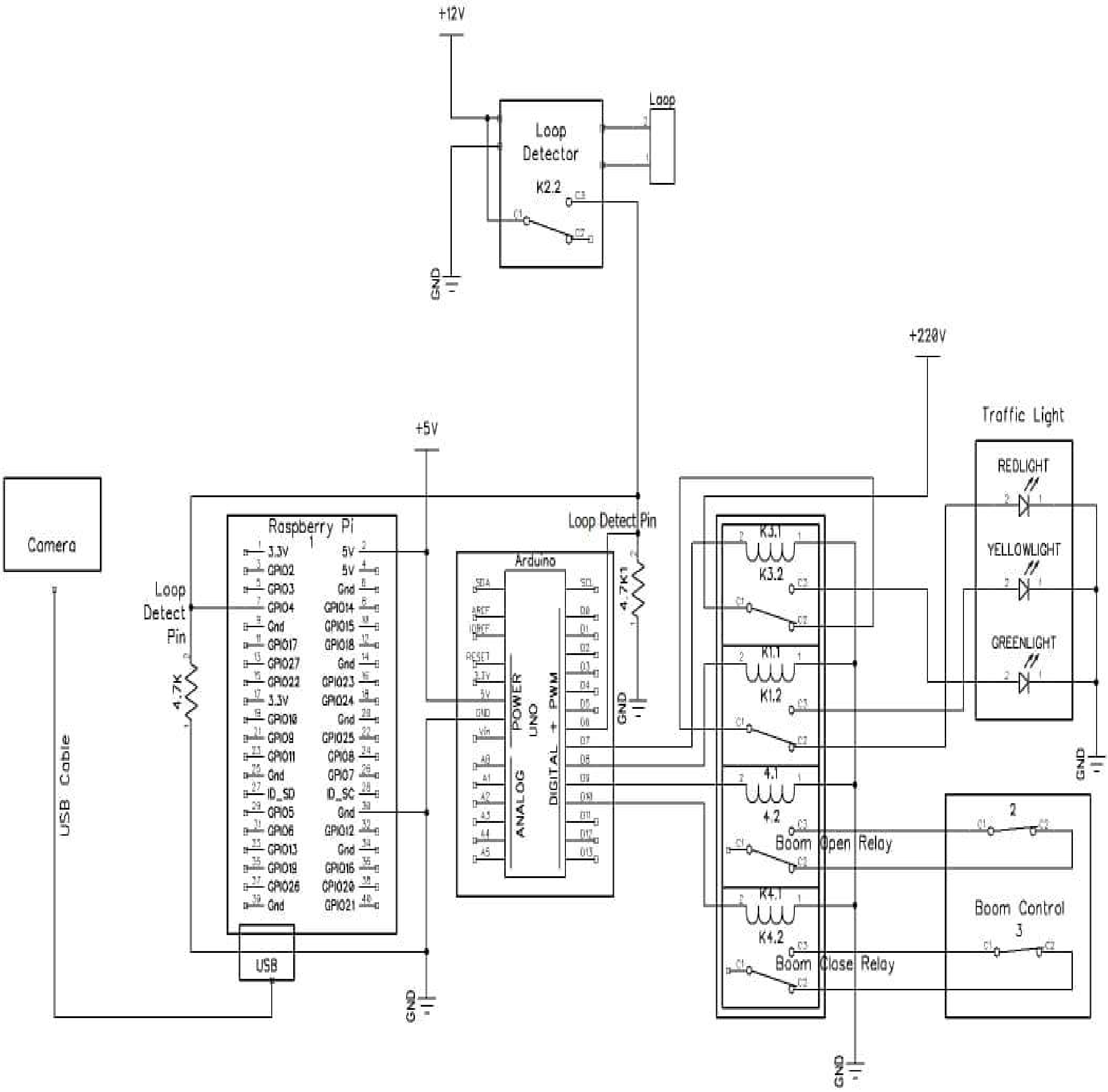


Fig. 12. Schematic Diagram of the Control System Module

3.4.3. System operation

The operation of the two-stage access control system developed in this work is as presented in the flow chart shown in Fig. 13. At the entry point, the loop detector detects the vehicle a few meters before the entrance gate and sends a control signal to the four-channel relay to switch on the Amber light in the traffic lights. The loop detector also sends a signal to the buck converter which powers both the Arduino and the Raspberry pi. The Raspberry pi triggered the camera to capture the image of the incoming vehicle while the security guard performed security checks and then issued a scanned RFID card to the vehicle. The card number is read and sent to the Arduino to check if the card number is pre-registered on the SD card, if “Yes” the vehicle image is tagged with the scanned card number, and saves the tagged image in the SD card. Consequently, a control signal is sent to the four-channel relay that triggers the barrier to open, thereby turning off the red traffic light while the green light is turned on to grant access to the vehicle. A delay period of approximately 30 seconds is observed and the barrier is closed and the traffic lights’ green light is turned off while the red light is turned on. However, if the loop detector does not detect the vehicle or the scanner is unable to scan the card number, or the scanned card number does not exist on the SD card, access is denied to the vehicle.

At the exit, again the loop detector detects the vehicle a few meters before the exit gate, the control signal is triggered and sent to the four-channel relay and the buck converter thereby switching on the Amber traffic light and powering both the Arduino and the Raspberry pi, respectively. The Raspberry pi triggered the camera to capture the image of the outgoing vehicle while the security guard performs security checks and then retrieves the previously scanned RFID card from the vehicle. Again, the card number is read and sent to the Arduino to check if the card number and the tagged vehicle image are saved on the SD card, if “Yes” a control signal is sent to the four-channel relay to open the barrier with a delay period of approximately 30seconds and turn off the red traffic light while the green light is turned on to grant exit to the vehicle. Finally, if the loop detector fails to the vehicle or the scanner is unable to scan the card number or the scanned card number does not match the one on the tagged vehicle image on the SD card, access is denied to the vehicle.

3.4.4. System testing

Testing of the BACS was carried out during the day by making cars pass through the system for five trials while functional parameters like response time, opening time, delay, and closing time defined as follows were evaluated to determine the performance of the system.

1. **Response Time:** is simply defined as the time interval between the time the loop sensor detects the car and the time the barrier arm starts to open. It is measured in seconds.
2. **Opening Time:** is the time interval between the time the barrier arm starts to open and the barrier arm is in a vertical position, i.e., the time it takes the barrier arm to make 90^0 in a counter-clockwise direction from its horizontal position. It is also measured in seconds.
3. **Delay:** is the period during which the barrier arm is in a vertical position before it starts to move back to the horizontal position. It is also measured in seconds.
4. **Closing Time:** is the time it takes the barrier arm to move from the vertical position to the horizontal position, i.e., the time it takes the barrier arm to make 90^0 in a clockwise direction from its vertical position. It is also measured in seconds.

3.5. System Cost Models

Cost is an important factor that must be given adequate attention in the product development process as it determines the consumer's willing to buy. Consequently, cost models for manual barrier systems (MBS) and barrier access control systems (BACS) are developed and simulated to determine the cost-friendliness of the systems under the following assumptions:

i. The number of system operators for MBS and BACS over the system lifespan remains constant.

ii. The maintenance cost, powering cost, and operational cost, are dynamic over the system lifespan. β, γ, and α are constants that account for variation in maintenance cost, powering cost, and operational cost, respectively, over the system lifespan.

iii. The cost of system purchase and installation costs for both MBS and BACS are fixed over the system lifespan.

iv. System depreciation remains constant and is zero over the system lifespan.

The cost model of the MBS includes the cost of purchase, installation cost, and operational cost which are mathematically modeled as Eq. (10):

$$C_{MBS} = C_p + C_i + \alpha C_o \tag{10}$$

Where C_{MBS} is the cost of the MBS, C_p is the cost of purchasing MBS, C_i is the installation cost of the MBS, C_o is the operational cost of the MBS, and α accounts for variation in operational cost over the system lifespan. The C_p and C_i are fixed over the system lifespan. In this model, C_o accounts for the salary of the operators and can further be defined in Eq. (11):

$$\alpha C_o = \sum_{i=0}^{p} \sum_{n=1}^{N} \alpha_n C_n \tag{11}$$

Where $n = 1, 2, 3, \ldots\ldots N$ and denotes the number of operators. C_n is the salary of operator n, α_n is the salary annual increment of operator n and p is the system lifespan in years. Substituting Eq. (11) into (10), Eq. (12) is arrived at as follows:

$$C_{MBS} = C_p + C_i + \sum_{j=0}^{p} \sum_{n=1}^{N} (1 + \alpha_{n,j}) C_{n,j} \tag{11}$$

Eq. (6) gives a complete representation of the MB cost model over the system lifespan p in years.

Again, the cost model of the BACS designed for the gate is considered as the system cost throughout a lifetime of usage. It includes the cost of purchase, installation cost, operational cost, powering cost, and maintenance cost. The cost model for the BACS can be expressed as

$$C_{BACS} = C_{ps} + C_{is} + \sum_{j=0}^{p} \beta C_{mj} + \sum_{j=0}^{p} \gamma C_{poj} + \sum_{j=0}^{p} \sum_{n=1}^{N} (1 + \alpha_{n,j}) C_{n,j} \tag{13}$$

Concisely, Eq. (13) can be re-written as in Eq. (14)

$$C_{BACS} = C_{ps} + C_{is} + \sum_{j=0}^{p} \left(\left(\beta C_{mj} + \gamma C_{poj} \right) + \sum_{n=1}^{N} (1 + \alpha_{n,j}) C_{n,j} \right) \tag{14}$$

Where C_{BACS} is the cost of the BACS, C_{ps} is the cost of purchasing BACS, C_{is} is the installation cost of the BACS, C_m is the maintenance cost of the BACS, C_{po} powering cost of BACS, C_n is the operational cost of the BACS while β, γ, and α account for variation in maintenance cost, powering cost, and operational cost, respectively over the system lifespan p. The C_{ps} and C_{is} are fixed over the system lifespan. Eq. (12) and (14) represent the cost models for MBS and BACS under the assumption that the operational cost is the same for operators $n = 1, 2, 3, \ldots\ldots N$.

3.5.1. System cost-benefit analysis

The cost models developed in the previous section were simulated to determine the cost incurred by each model to determine the cost implication of each model over the system lifespan. The data presented in Table 3 obtained from the case study and authors' bill of engineering measurement and evaluation (BEME) were used to simulate the cost models in the MATLAB environment. The cost-benefit analysis was performed to determine the savings in monetary terms derived from owning the BACS over the MBS and this can be expressed as Eq. (15):

$$CB = C_{MBS} - C_{BACS} \tag{15}$$

Where CB is the cost-benefit derived by the client for the adoption of BACS over the MBS for the system lifespan. Eq. (9) is simulated using the cost model parameters presented in Table 3.

3.5.2. System cost sensitivity analysis

To further demonstrate the robustness of these cost models, cost sensitivity analysis was performed by varying β, γ, and α at an annual increment of 2.5%, 5%, 7.5%, and 10% of the previous year over the system lifespan as presented in Tables 4, 5, 6, and 7, respectively. These tables were also used to simulate the MBS and BACS cost models in the MATLAB environment and the results were analyzed.

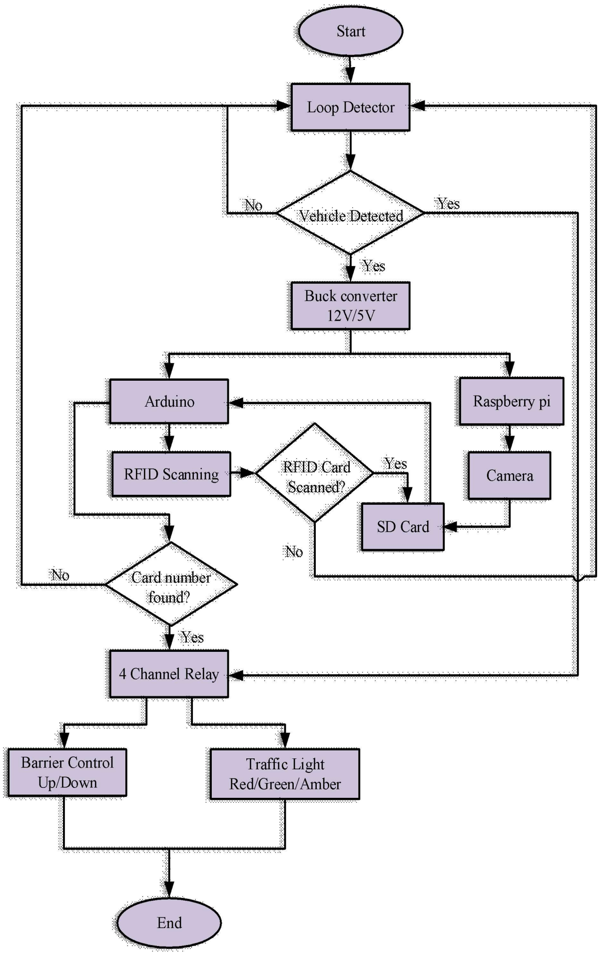


Fig. 13. Flow chart of the two-stage access control system

Table 3. Cost models parameters

Parameters	MBS cost model	BACS cost model
C	1	1
N	10	2
j	0	0
p	12	12
β	0	0.1
γ	0	0.1
α	0.05	0.05
C_n	1200($)	1200($)
C_p	450($)	0
C_i	45($)	0
C_{ps}	0	2180($)
C_{is}	0	260($)
C_m	0	20($)
C_{po}	0	5($)

Table 4. Sensitivity variables at an annual increment of 2.5%

Year	β	γ	α
0	0.0000	0.0000	0.0000
1	0.1000	0.1000	0.0500
2	0.1025	0.1025	0.0513
3	0.1050	0.1050	0.0525
4	0.1077	0.1077	0.0538
5	0.1104	0.1104	0.0551
6	0.1131	0.1131	0.0566
7	0.1160	0.1160	0.0580
8	0.1189	0.1189	0.0594
9	0.1218	0.1218	0.0609
10	0.1249	0.1249	0.0624
11	0.1280	0.1280	0.0640
12	0.1312	0.1312	0.0656

Table 5. Sensitivity variables at annual increment of 5%

Year	β	γ	α
0	0.0000	0.0000	0.0000
1	0.1000	0.1000	0.0500
2	0.1050	0.1050	0.0525
3	0.1103	0.1103	0.0551
4	0.1158	0.1158	0.0579
5	0.1216	0.1216	0.0608
6	0.1276	0.1276	0.0638
7	0.1340	0.1340	0.0670
8	0.1407	0.1407	0.0704
9	0.1477	0.1477	0.0739
10	0.1551	0.1551	0.0776
11	0.1629	0.1629	0.0814
12	0.1710	0.1710	0.0855

Table 6. Sensitivity variables at annual increment of 7.5%

Year	β	γ	α
0	0.0000	0.0000	0.0000
1	0.1000	0.1000	0.0500
2	0.1075	0.1075	0.0538
3	0.1156	0.1156	0.0578
4	0.1242	0.1242	0.0621
5	0.1335	0.1335	0.0668
6	0.1436	0.1436	0.0718
7	0.1543	0.1543	0.0772
8	0.1659	0.1659	0.0830
9	0.1783	0.1783	0.0892
10	0.1917	0.1917	0.0959
11	0.2061	0.2061	0.1031
12	0.2216	0.2216	0.1108

Table 7. Sensitivity variables at annual increment of 10.0%

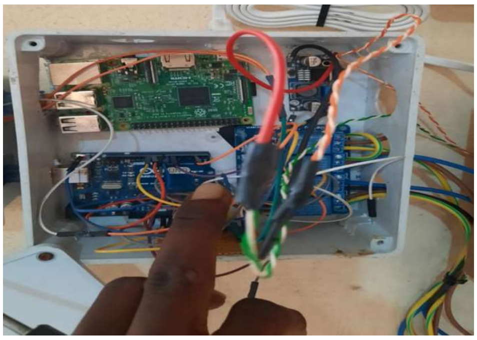
Year	β	γ	α
1	0.1000	0.1000	0.0500
2	0.1100	0.1100	0.0550
3	0.1210	0.1210	0.0605
4	0.1331	0.1331	0.0666
5	0.14641	0.1464	0.0732
6	0.1611	0.1611	0.0805
7	0.1772	0.1772	0.0886
8	0.1949	0.1949	0.0974
9	0.2144	0.2144	0.1072
10	0.2358	0.2358	0.1179
11	0.2594	0.2594	0.1297
12	0.2853	0.2853	0.1427

4. Result and Discussions

The results obtained from both the implementation of the technical design of the two-stage access control system and the cost models to justify the necessity for the design are presented and discussed in this section. The internal structure of the control system module during construction is as presented in Fig. 14 (a) and (b) where components like the four-channel relay, Raspberry pi, and Arduino were been connected. In Fig. 15, the assemblage of the RFID scanner is presented while Fig. 16 presented the control system module mounted on the wall of the security post at the university gate. The green and red buttons on the mounted control system module provide a manual override for opening and closing the BACS.

The system functionality tests are presented in Tabs. 8, 9, and 10 for loop detectors, traffic lights, and boom barriers, respectively. The loop detector test result revealed that the presence of a vehicle within the loop results in a relay signal of 12VDC that triggers the Amber light of the traffic light on whereas in the absence of a vehicle within the loop, the relay signal of 0VDC is observed, therefore, the Amber light remains off. The functionality test result on the traffic light revealed that the red light is on when the barrier arm is in the horizontal position with a relay signal of 220VAC when relay 2 is at the normally closed position, the yellow light is on when the barrier arm is in about to leave the horizontal position with a relay signal of 220VAC with relay 2 at the normally open position. The green light is on when the barrier arm is in the vertical position with a relay signal of 220VAC when relay 1 is at the normally open position. The boom barrier test result showed that relay 3 is responsible for opening the barrier with a 12VDC relay signal while relay 4 closes the boom barrier with a 12VDC relay signal. The BACS response test is presented in Table 11 for five trials. The table shows that the BACS is characterized by an average response time of 5.06 seconds, the average opening time of the BACS is found to be 6.12 seconds, the average delay time of the BACS stands at 30.02 seconds, and the average closing time of the BACS is 6.02 seconds. It is observed that the opening time is more than the closing time by 0.1 seconds which might be a result of the barrier arm moving against the force of gravity while opening.

(a)



(b)

Fig. 14. Assembling of the control system module

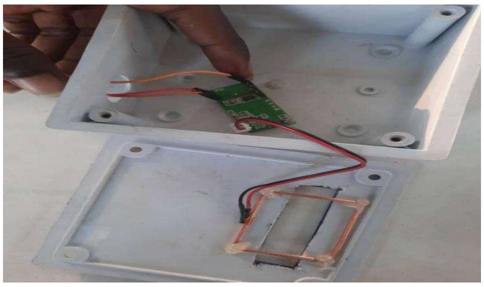


Fig. 15. Assembling of the RFID scanner

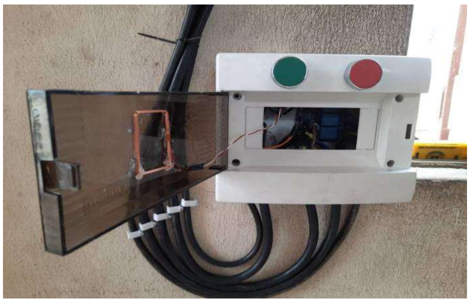


Fig. 16. The control system module

Table 8: Loop detector test result

Cases	Vehicle Position	Traffic Light	Relay signal
Case 1	Inside loop	Amber on	12VDC
Case 2	Outside loop	No	0VDC

Table 9. Traffic light test result

Traffic light	Barrier arm position	Relay signal
Red	Horizontal position	220VAC N/C Relay 2
Yellow	Horizontal position	220VAC N/O Relay 2
Green	Vertical position	220VAC N/O Relay 1

Table 10. Boom barrier test result

Boom barrier status	Relay	Relay signal
Boom barrier arm opens	Relay 3	12VDC
Boom barrier arm closes	Relay 4	12VDC

Table 11. BACS response test

Trials	Response time (sec)	Opening time (sec)	Delay (sec)	Closing time (sec)
1	5.10	6.10	30.20	6.05
2	5.20	6.10	29.60	5.90
3	4.80	6.16	29.80	6.10
4	5.10	6.12	30.10	6.00
5	5.10	6.13	30.40	6.05

The comparison of the annual system cost for MBS and BACS over the system lifespan is presented in Fig. 17 which reveals that the cost implication of the systems increases annually over the lifespan. However, it is observed that the annual growth in the cost of the BACS is reduced compared to that of the MBS. This is attributed to the fact that the number of operators whose take home increases annually involved in BACS (2 in this case) is small compared to that of MBS (10 in this case). The annual cost-benefit derivable from the adoption of BACS over MBS is presented in Fig. 18 which shows that the cost-benefit increases annually over the entire system lifespan from about $7650 at the beginning of the lifespan to $15223 at the end of the lifespan. This result implied that the total cost of MBS increases annually due to the higher number of personnel involved in running the system whose salary increases yearly dues to annual review and promotion. The results of cost sensitivity of both BACS and MBS at 2.5%, 5.0%, 7.5%, and 10.0% are presented in Figs. 19, 20, 21, and 22, respectively. The study of the figures revealed that both BACS and MBS behaved in a similar manner for all the sensitivity cases. It is observed from the figures that while BACS is resilient to annual increments, MBS is highly responsive to the same annual increment. It is observed that the more the percentage annual increment, the more the cost incurred by MBS therefore, MBS incurred less cost at 2.5% increment and highest at 10.0% increment. It is observed that the BACS incurred moderately low cost for all the sensitivity cases under consideration. The results obtained in this work implied that less would be paid by adopting BACS for maintaining vehicular movements. Consequently, the total running cost of the organization would be reduced leaving more funds for growth investment. Also, personnel's quality of life is improved since they are engaged in less laborious activities.

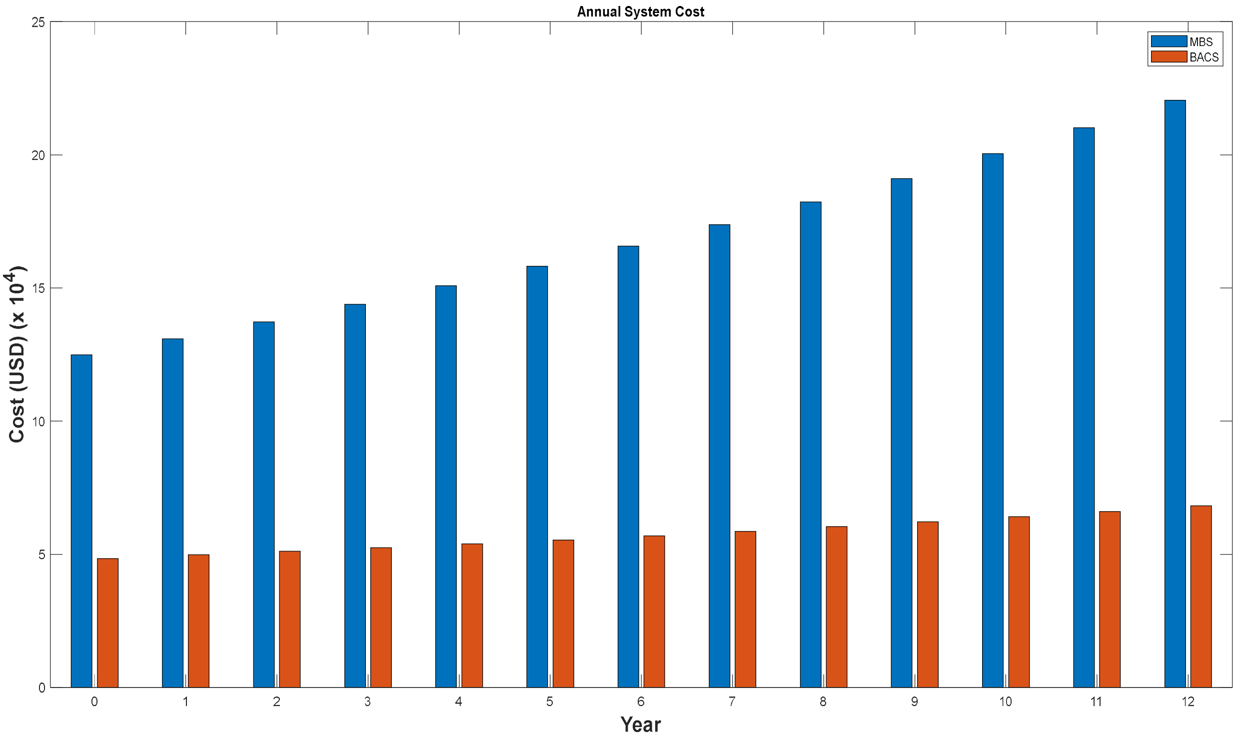


Fig. 17. Comparison of the annual system cost for MBS and BACS

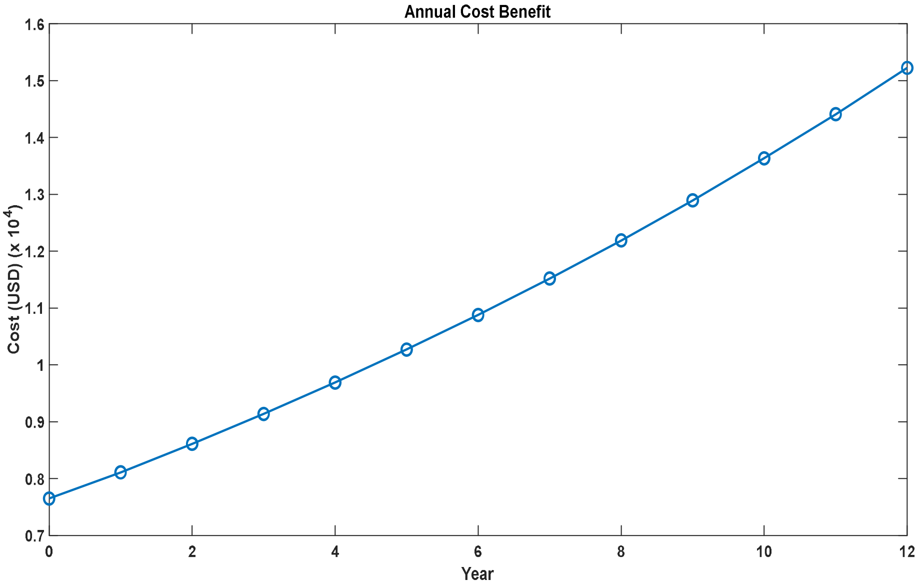


Fig. 18. Annual cost-benefit

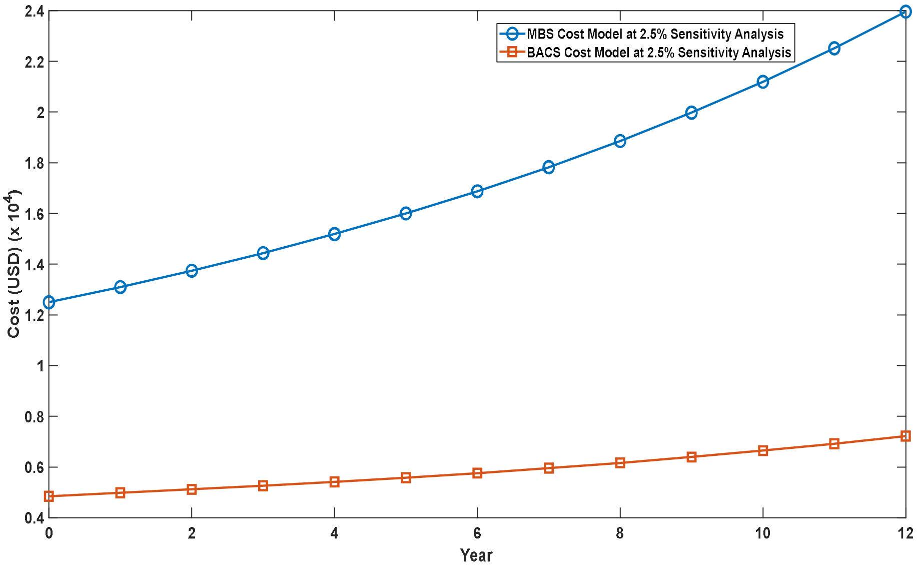


Fig. 19. Comparison of MBS and BACS cost models at 2.5% sensitivity

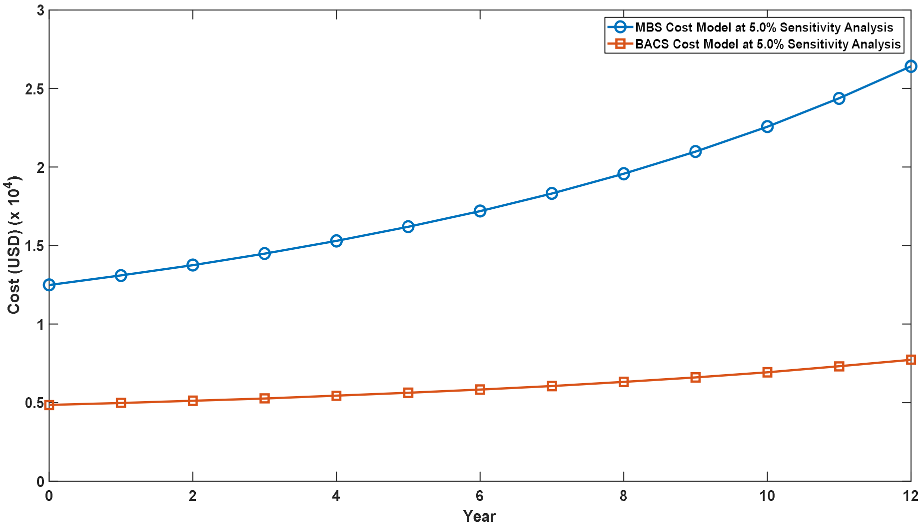


Fig. 20. Comparison of MBS and BACS cost models at 5.0% sensitivity

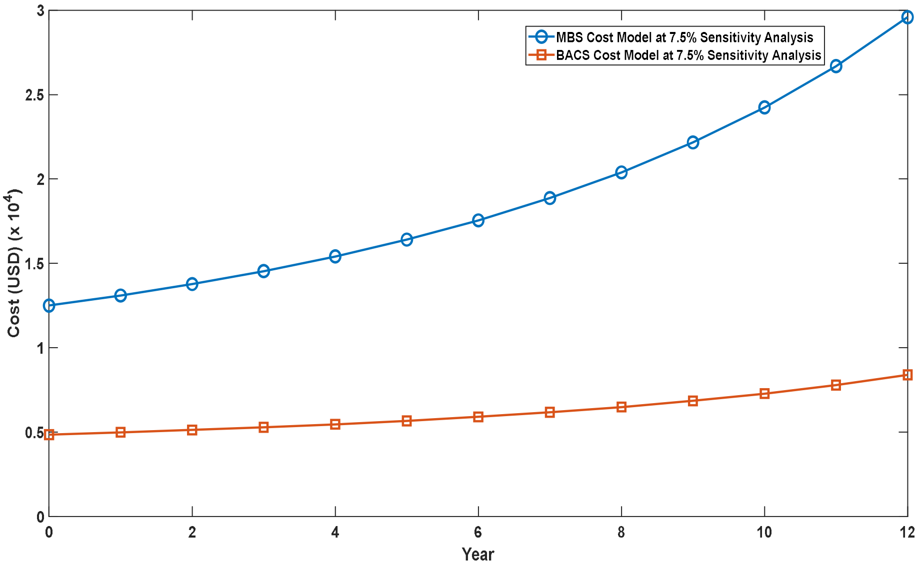


Fig. 21. Comparison of MBS and BACS cost models at 7.5% sensitivity

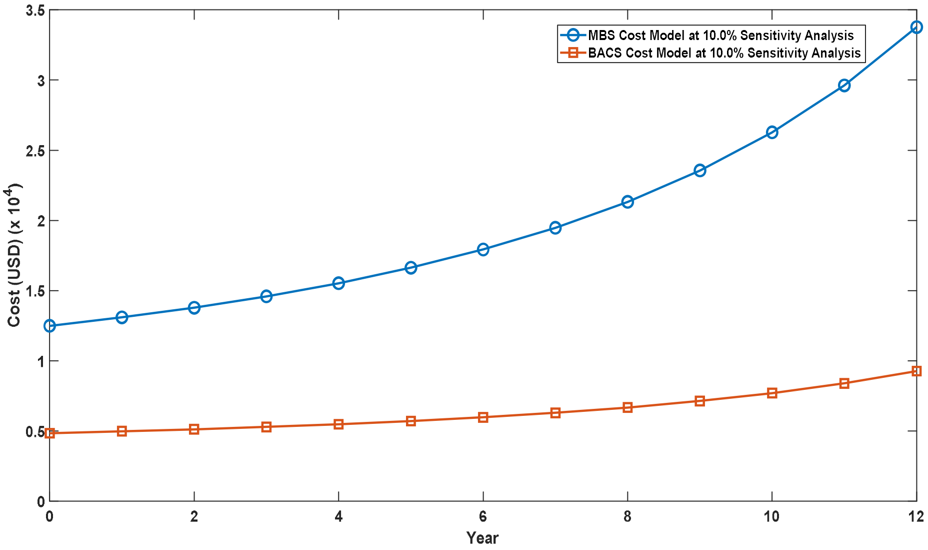


Fig. 22. Comparison of MBS and BACS cost models at 10.0% sensitivity

5. Conclusion

The need for a cost-effective and improved means of maintaining traffic orderliness necessitated this work due to the fact that the existing boom barrier is quite laborious, highly subjective, and unnecessarily time-consuming. A brief survey of the literature has revealed that most of the existing works are limited in terms of ease of control. However, it has been observed that most of the existing works do not factor in cost as part of design considerations. Consequently, this work explored the techno-economic design and analysis of the vehicular access control system at the Bells University of Technology entrance.

The possibility of designing and integrating a control system module into the boom barrier to realize the boom barrier access control system (BACS) for seamless control has been demonstrated in this work. The BACS was found to possess an average response time, opening time, delay time, and closing time of 5.06 seconds, 6.12 seconds, 30.02 seconds, and 6.02 seconds, respectively. Therefore, it can be concluded that the BACS can effectively replace the existing MBS and boom barrier.

The developed MBS and BACS cost models simulated in MATLAB environment showed that BACS is economically viable. The cost simulation results demonstrated that the BACS is better in terms of cost with an initial cost of $7650 when compared to $15223 for the MBS, this justifies the need for the adoption of BACS over MBS. It has been revealed through the cost-benefit analysis that the cost-benefit derived by the user of BACS increases annually over the entire system lifespan compared to the user of MBS.

Finally, cost sensitivity analysis was performed at 2.5%, 5.0%, 7.5%, and 10.0% annual increment of the maintenance cost, powering cost, and operational cost has demonstrated the robustness of the developed cost models. The result of the sensitivity analysis showed that the BACS is more resilient to annual increments when compared to the MBS. Based on the results presented in this work, the BACS is more viable both in ease of operation and cost for vehicular access control. Consequently, BACS is generally recommended for organizations to maintain traffic order at their entrances.

The BACS requires 12VDC and 230AC for its effective operation where the MBS works without electrical power hence, availability of power must be guaranteed prior to the adoption of BACS.

Authors Contributions

Abraham Amole contributed to conceptualization and methodology. Olakunle Olabode contributed to the writing of the original draft. Mobolaji Ariyo contributed to project implementation**.** Adeimpe Adeyeye contributed to software and validation.

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