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d'Enginyeria de Vilanova i la Geltrú
UNIVERSITAT POLITÈCNICA DE CATALUNYA

EPS - PROJECT

TITLE:

SMARTENING THE BRIDGE

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I. Abstract

This report explains the process the team went through when designing and developing a smart bridge that integrates into a smart city. It was proposed by the CRAAX lab which is a research group based in UPC Vilanova. It consists of both students and researchers studying computer science and telecommunications. In the CRAAX lab, there is a smart city testbed, which is a miniature model of a smart city. A smart city uses a framework of information and communication technologies to create, deploy and promote development practices to address urban challenges and create a joined-up technologically enabled, and sustainable infrastructure. Our goal is to create a smart bridge concept and show its integration into the smart city and the benefits it has towards improving traffic flow. Simulations will be conducted using an online program called Flexsim to compare traffic flow in different street layouts; an intersection, a four-lane bridge, and a two-lane bridge. From these calculations, we can decide which bridge will be most suited for the smart city. In the smart bridge, there will be many smart features incorporated to enhance the bridge further. These include smart sensors, big data, VMS, and other smart features. The bridge's concept will be communicated through the simulation programs and with detailed design sketches describing each smart feature's layout and function.

Keywords: smart city, smart bridge, testbed, simulation, traffic congestion, sensor

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VMS - Variable-message sign

DES - Discrete Event Simulation

QoE - Quality of Experience

QoS - Quality of Service

1. Introduction

1.1 About the company

Smarting The Bridge project was proposed by CRAAX, which possesses the smart city testbed. CRAAX is a lab based at Universitat Politècnica de Catalunya (UPC). The lab is in the Neapolis building on the UPC campus in Vilanova i la Geltrú. It was founded in 2008 supported by both the Generalitat de Catalunya (Catalan Government) and the City Council. In 2009 CRAAX was awarded an official research group by the Generalitat de Catalunya. CRAAX sets a multidisciplinary team bringing together researchers from the Computer Architecture Department (DAC) and the Hospital Clinic of Barcelona. These disciplines are connected by undergraduate students that study Computer Science and graduate students running distinct Master degrees. The lab also takes part in integration industrial research projects to create high-quality research, student training, and technology transfer [1].

CRAAX Lab
UPC - BARCELONA**TECH**
Advanced Network Architectures Lab

Figure 1 CRAAX Lab logo[2]

1.2 History of the project

A testbed is a platform for experimentation with large development projects. Testbeds allow for rigorous, transparent, and replicable testing of scientific theories, computational tools, and new technologies. CRAAX's smart city is 15 m2 and it is a miniature version of a city with several roads and smart buildings such as a hospital, a fire station, and an automatic car park [3, Fig. 2]. It was designed and implemented by a research team for their final degree project which was called "Design and implementation of a Testbed for a Smart City". The following table [4,Tab. 1] briefly explains which elements are inside the testbed; what they are used for, what they represent in a real city, their status of change, and if they are active or passive. Active refers to their connection with other elements in the smart city.

ELEMENT	USE	WHAT REPRESENTS	STATUS CHANGE	ACTIVE/PASSIVE
Roads	Car traffic	Streets	NO	P
RFID	Technology to the location of cars within the cars inside the testbed at all times at any time	Sensors or GPS	YES. TAGs lecture	P
Cars	It moves around the testbed and interacts with the other elements	Vehicles	YES. Tracked movement	A
Arduino	Connection and programming of all passive and state-changeable components	IoT element on mf2c	NO	A
Raspberry Pi	Arduinos connexion and control	Mf2c agent	NO	A
Traffic light	Traffic control using everyday colours and an emergency light	Traffic lights	YES. Switching each LED on and off	P
Sidewalk	Structure for cabling and incorporation of street lamps and traffic lights	Sidewalk	NO	P

Containers	Box to place Arduinos and Raspberries	Rubbish containers	NO	P
Bridge drawbridge	Up and down to allow or block the passage of cars	Bridge drawbridge	YES. Up, down or in movement	P
Streetlights	Lighting control of the runways	Streetlights	YES. Off, medium brightness y 100%	P
Buildings	Structures to represent emergency cases	Neàpolis, fire station, hospital, automatic parking	YES. Opened or closed.	P
Cables, transformers, and WiFi	All elements connections	Cables, power supply, and IoT	NO	P
PC	Raspberrys Pi connexion and control	Mf2c master	NO	A

Table 1 Testbed elements from "Design and implementation of a Testbed for a Smart City" research project[4]

All the passive and state-changing devices such as streetlights, traffic lights, and bridges are connected via digital and analogue pins to different Arduinos distributed around the testbed. There are 6 in total, and these are connected via the serial port to two Raspberries located inside the test bench. Each car has a Raspberry Pi connected via Wi-Fi to each other and a leader, a CRAAX computer. The car's Raspberry Pi in turns communicates via the serial port to an Arduino that is incorporated inside the car. Each one has an RFID reader connected to it that can read the tags placed on the tracks. At the same time, all the data that represents a change of state is sent to a Frontend to reflect the situation of the testbed on a screen.

Figure 2 Testbed of the smart city at CRAAX lab[3]

1.3 Problem statement

With the world's modern infrastructure, people should be able to travel around their city without the concern for traffic congestion. However, due to economic expansion, increased urbanisation, the rise of ride-hailing services and e-commerce, underinvestment in infrastructure, and mixed results from various policies and programs are seen as the primary trends that have exacerbated urban congestion in recent years [5]. As smart cities worldwide develop, it is important to incorporate a method to combat the increased traffic flow and congestion that comes with it.

There are many ways to improve traffic flow. Real-time traffic data can power algorithms used by municipalities to manage traffic congestion by optimizing road logistics and routes. According to a McKinsey Study, this can cut commuting time in cities by 15-20%. Data can be used to prevent congestion through intelligent syncing of traffic signals, prompting variable speed limits, and providing drivers with real-time alerts advising the fastest routes [6].

1.4 Project goals and objectives

With the smart bridge project, the goal is to use the bridge as a tool to improve the traffic flow. To be integrated into a smart city the bridge will have smart features to improve the quality of experience (QoE) and the quality of service (QoS). Simulations will be conducted to compare traffic flow in different street layouts: an intersection, a bridge with two lanes, and a bridge with four lanes. From these calculations, the best layout can be implemented in the design of the bridge, together with the smart features to create an efficient smart bridge. The bridge's concept will be communicated through the simulation programs and with detailed design sketches describing each smart feature's layout and function.

1.5 Group introduction

This project is a part of the European Project Semester (EPS). EPS is a one-semester program designed to train engineering and technology students to carry out project work in international teams [7]. Our team consists of the following members:

- Gema Sánchez Lang (Spain) – Electronical Engineering & Mechanical Engineering
- George Clarke (Ireland) – Product Design
- Natalia Przedborska (Poland) – Electronic and Telecommunication Engineering
- Roos Bökkerink (Netherlands) – Industrial Product Design
- Thiago Andrade Villarino Rana (Brazil) – Industrial Engineering

2. Research

2.1 The smart concept

2.1.1 Smart cities

The word smart is difficult to define. It is often understood that the word means intelligence, quick-witted, and the ability to adapt to your surroundings. However, the word can be perceived in many ways.

The concept of smart cities is gaining popularity due to rapid urbanization and favourable government initiatives worldwide [8]. According to 'A literature survey on smart cities' [9], the term smart city first appeared in the 1990s, and since then the definition has been constantly changing. From the research conducted in this project, we can conclude that a smart city uses a framework of information and communication technologies to create, deploy and promote development practices to address urban challenges and create a joined-up technologically enabled, and sustainable infrastructure [10]. As the world is constantly innovating for greatness the study and implementation of smart cities are essential for human life. Dr. Mark Deakin and Dr. Husam Al Waer, experts on smart cities listed four factors that contribute to a city being smart:

1. The application of a wide range of electronic and digital technologies to communities and cities.
2. The use of ICT to transform life and working environments within the region.
3. The embedding of such Information and Communications Technologies in government systems.
4. The territorialization of practices brings ICT and people together to enhance their innovation and knowledge [11].

To fully understand what it takes to build a smart city it is important to understand the community it is based on. It is important to research and understand the community's unique attributes, such as citizens' age, education, hobbies, and attractions of the city. Then, it is possible to create and adopt strategies on how to adapt the city to best serve the citizens.

There are three principles of the success of a smart city initiative – people, processes, and technology (PPT) [12]. Once we understand these principles we can design and implement the correct technology that can fit into the city. It is important to understand that the citizens' needs come first as the aim is to improve their quality of life and create economic opportunities.

Barcelona is a great example of a large smart city. It is one of the 'smartest' cities next to London and Singapore, according to the report Understanding the Challenges and Opportunities of Smart Cities carried out by Philips Lighting and SmartCitesWorld [13]. The city started creating the strategy and focusing on becoming a smart city in 2010. The Smart City Expo and World Congress held for the first time in 2011, helped to launch and promote this idea. In 2013 Barcelona City Council began to aim to make Barcelona one of the first smart cities in Spain. New technologies and infrastructure implemented in Barcelona were supposed to boost economic growth and guarantee a greater quality of life for its citizens.

Examples of smart cities innovations by the City Council:

- Smart streetlights

The LED-based lighting system solution is more energy sufficient and reduces the heat produced by the old city lamps.

- City bike system

Barcelona was one of the first largest cities to implement the system on a such large scale.

- Waste disposal

The use of smart bins, that use a vacuum to suck the waste into underground storage. It helps by reducing the smell of the trash and makes the city more sanitary.

- Noise sensors

Noise sensors were implemented around the city to combat noise pollution.

- Irrigation systems

Various sensors on the ground offer live data on humidity, temperature, wind velocity, sunlight, and atmospheric pressure.

Figure 3 Barcelona smart city[14]

2.1.2 Smart bridges

The term smart bridge is not recognised as much as the term smart city. Bridges have been essential to the infrastructure of a developing city. Bridges were built to connect different places to allow for further trade and travel.

The goal of the project is to redesign a bridge so that it would fit into the smart city testbed. In other words, make the current bridge a smart bridge. The main characteristic of smart bridges is that they have many sensors which monitor the performance of the bridge to make sure the bridge is performing optimally. Below there are the five core components of a smart bridge [15]:

1. Data acquisition
2. Data transmission
3. Control Centers
4. Data instructions
5. Action devices

Seen below is The Rio- Antirro Bridge located in Greece. This is a prime example of a smart bridge as it has 24/7 surveillance on the structural integrity of the bridge.

Figure 4 The Rio- Antirro Bridge[16]

Similar examples are Kap Shui Mun Bridge from Hong Kong and GI-LU Cable Stay Bridge from Taiwan, both are equipped with a very modern network of smart bridge sensors providing continuous monitoring of the weather, traffic, and air quality.

Lastly, is the I-35W Saint Anthony Falls Bridge (seen below in Figure 5) from Minnesota in the United States. This bridge is a replacement for the I-35W Mississippi River bridge that collapsed during rush hour traffic in 2007. To prevent another disaster, the engineers equipped this bridge with 323 sensors that regularly measure bridge conditions such as deck movement, stress, and temperature.

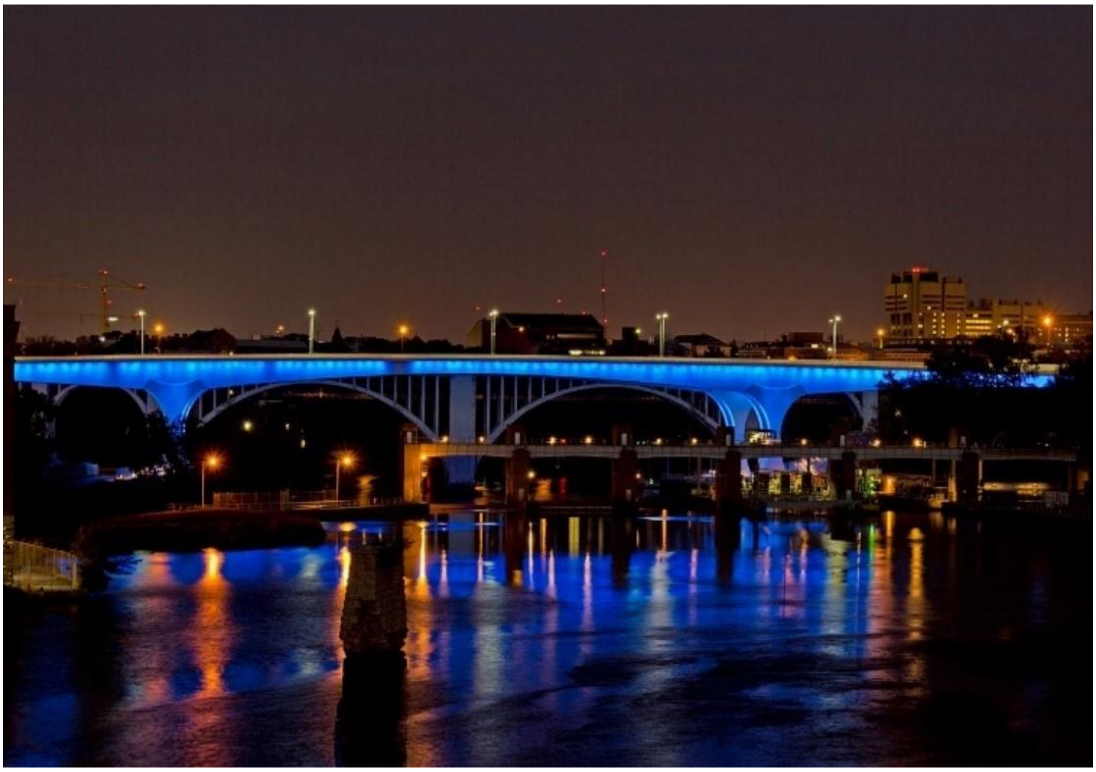


Figure 5 I-35W Saint Anthony Falls Bridge[17]

To conclude, as the world is innovating the cities must develop along with it as well. The most important reason for the innovation of cities is to improve and protect the lives of the citizens that live within them. Bridges that can monitor their structural health and the environment around them, which is essential to prevent disaster and can be used to improve the quality of life of the citizens.

2.1.3 Comparison of different smart bridges

Using the newly-acquired information on smart bridges, we can compare two similar bridges to analyse their strengths, weaknesses, and qualities. When comparing the Rio - Antirro Bridge located in Greece (Figure 4) and Kap Shui Mun Bridge in Hong Kong (Figure 6), it is seen that both bridges are cabled stayed - suspension bridges. They are also similar in width at around 30m. However, Rio - Antirro Bridge is much longer than Kap Shui Mun Bridge, its total length is 2880 meters while the Kap Shui Mun Bridge is only 750 meters.

Figure 6 Kap Shui Mun Bridge[18]

Table 2 Comparison of The Rio- Antirro Bridge and Kap Shui Mun Bridge

Bridge	**The Rio- Antirro Bridge[19]**	**Kap Shui Mun Bridge[20]**
Anemometers	yes	yes
Temperature and Humidity sensor	yes	yes
Accelerometers	yes	yes
Weigh-in-motion station	no	yes
Displacement transducer	no	yes
level sensor	no	yes
Monostrand load of cables	yes	no
Magnetic distance meter	yes	no
Strain gauges	yes	yes

From Table 2, both bridges are equipped with similar technologies. The main difference is the Antirro bridge opened 7 years after the Kap Shui Mun Bridge. In those 7 years, different technologies and approaches to bridge design have been developed. Both bridges have sensors that help them adapt to the environment, climate, and traffic prediction. This comparison allowed us to see which sensors were most important when designing a smart bridge. Both bridges are equipped with anemometers, accelerometers, weather sensors, and strain gauges.

2.2 The problem of traffic congestion in big cities

As it was said at the beginning of this report the goal of the project is to use the newly redesigned bridge as a tool to improve the traffic flow over bridges. To do that, it is important to research the topic of traffic congestion and traffic management in big cities.

As a definition, congestion refers to the obstruction or hindering of traffic flow. In terms of traffic congestion, this can be seen by the build-up of vehicles moving slowly and irregularly. Transport can be divided into two parts: privately owned vehicles and public transport systems. The use of the modern car has transformed the way people move around. As urbanisation and population increase, road traffic congestion has increased with it. The core of the problem is the use of private cars. However, both private cars and public transport systems suffer the consequences.

One of the major drivers of congestion and delays is the concentration of economic activity in and around major cities. Economic growth and social development increase mobility in cities and promote the use of private cars. Growth in the size of the city also generates a greater amount of traffic [21].

Although population growth and urbanization have been mentioned as the main cause, there are several reasons why congestion occurs on the roads:

- The increase in population and the reduction in the number of persons per household have led to a higher number of private vehicles per family.

- The increasing number of distractions and external inputs when behind the wheel. For example, smartphones and navigation systems.

- Outdated road designs, which aren't suited for high volume traffic as they were built hundreds of years ago.

For this reason, it is important to consider the factor of vehicle traffic and traffic jams when designing and implementing a road.

2.2.1 How traffic is handled in smart cities?

A smart city should focus on enhancing its energy efficiency and sustainability. We can take advantage of public transport to remove cars from the streets, reorganise the design of cities to make them more assessable to pedestrians, and create green areas for leisure. With this objective in mind, in recent years, different solutions based on new technologies have been implemented:

- Smart car parks allow us to locate free parking spaces thanks to the use of sensors and real-time connectivity.

- Smart traffic lights allow us to organise traffic in smart cities in the most optimal way regardless of the day and time.

- Digital twin is a solution that uses a realistic simulation of what would happen in a city under certain circumstances such as accidents or catastrophes.

- Smart lighting or smart bins are a solution to create an effective and efficient city.

- Sensors that measure air quality or weather to alert road users.
- A city design that promotes improved mobility for citizens, such as bike lanes, superblocks, and pedestrian spaces help helps organise and optimise the flow of people and light vehicles.
- City designs that create a city-centred vision to enjoy the city and not suffer from it.

Keeping up with the example of Barcelona, the team has researched how this smart city deals with traffic problems. Cities like Barcelona suffer the consequences of these traffic jams daily. The Catalan newspaper 324 reports: "The costs of the congestion to the enter Barcelona: 63,000 hours and 650,000 euros per day"[22]. According to this newspaper, the RACC (Royal Automobile Club of Catalonia) estimates that daily Barcelona traffic jams affect up to 320,000 people. The association also calls for an increase in the capacity of interurban public transport, intelligent management of road infrastructures, and efficiency in the use of private vehicles. The daily El Pais reports: "There's not enough room for so many cars in Barcelona. The diagnosis made years ago by the city council is increasingly shared by the Catalan government, which on Wednesday put figures on its plan to reduce private car journeys in the metropolitan area by 25 percent"[23]. They plan to do that by implementing different strategies in the city. The main goal is to encourage citizens to use public transport and or bikes instead of cars. In 2017, Low Emissions Zone (LEZ) Rondas BCN introduced a program, in which the citizens would receive a T-verda ("T-green") ticket, free of charge if they decide to give up their vehicle. Since its creation in 2017, Barcelona has awarded more than 12,000 T-green tickets, precipitating a reduction of 10,613 cars and 1,735 motorcycles across the metropolitan area[24].

2.2.2 Greenhouse gas emissions from transport in Europe

An important point to be considered in this report are the laws regarding the 2030 Climate Target Plan set in place by the European Union. A plan that proposes to cut greenhouse gas emissions by at least 55% by 2030 to set Europe on a responsible path to becoming climate neutral by 2050. This Climate Target Plan is part of the 2030 Agenda for Sustainable Development adopted by all UN Member States in 2015, an action plan to end poverty, protect the planet, and improve the lives and prospects of everyone, everywhere, which also intends to strengthen universal peace and access to justice[25].

Greenhouse gases, caused by the transport sector, noticed a large increase between 2013 and 2019. A decrease is seen in 2020 due to the decrease in activity due to Covid-19. Even so, it is predicted that after this global pandemic, emissions levels will rise again. And that even if the Member States' planned strategies are followed, transport emissions will return to 1990 levels by 2029.

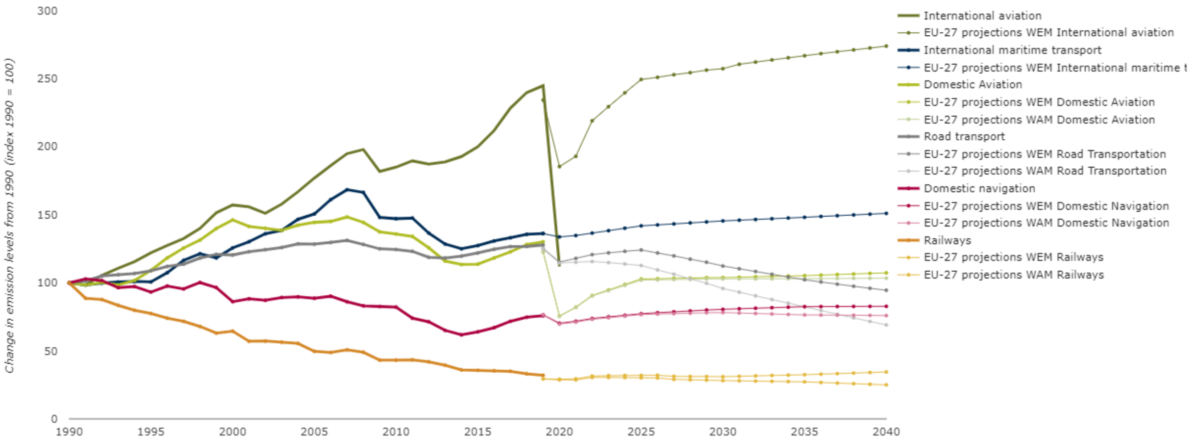


Figure 7 Greenhouse gas emissions from transport in the EU, by transport mode and scenario[26]

The main objective of this Climate Agenda for 2030 is to keep the global temperature rise well below 2°C and to continue to strive to keep it to 1.5°C [27].

This increased climate ambition, in addition to requiring a transformation of EU industry, will:

- Boost sustainable economic growth
- Create jobs
- Deliver health and environmental benefits for EU citizens; - contribute to long-term global competitiveness;
- Contribute to the long-term global competitiveness of the EU economy by promoting innovation in green technologies.

2.2.3 Human factor

From a podcast with traffic psychologist Gerard Tertoolen on BNR radio [28] where they talk about traffic congestion, it can be concluded traffic congestion is caused by human behaviour. Traffic congestion is a condition in transport that is characterised by slower speeds, longer trip times, and increased vehicular queueing [29]. According to Gerard Tertoolen, traffic congestion can cause people to get quite frustrated which can lead to erratic and irrational behaviour behind the wheel.

Three things can influence the rise of traffic congestion:

1. Lower threshold of people driving on the streets
2. Optimising the best route for individuals
3. Influencing human behaviour to combat and reduce traffic congestion

With the use of smartphones, people can choose the most efficient route for their journey. With this people can choose the best time to leave and the most efficient route to avoid locations with high traffic congestion.

In the podcast, Gerard Tertoolen spoke about ways to influence the behaviour of traffic participants. To enforce certain behaviour, a penalty system can be used. For example, a toll could be introduced to high traffic areas during rush hour to reduce the overall traffic flow. This system has worked successfully in places like London and Singapore. It has significantly reduced emissions and traffic congestion and could work on the smart bridge. It incentives people to use more environmentally friendly methods of transportation like walking, cycling, or public transport.

As a conclusion of the human behaviour in traffic congestion here is an empathy map with all they see, hear, and feel of the users.

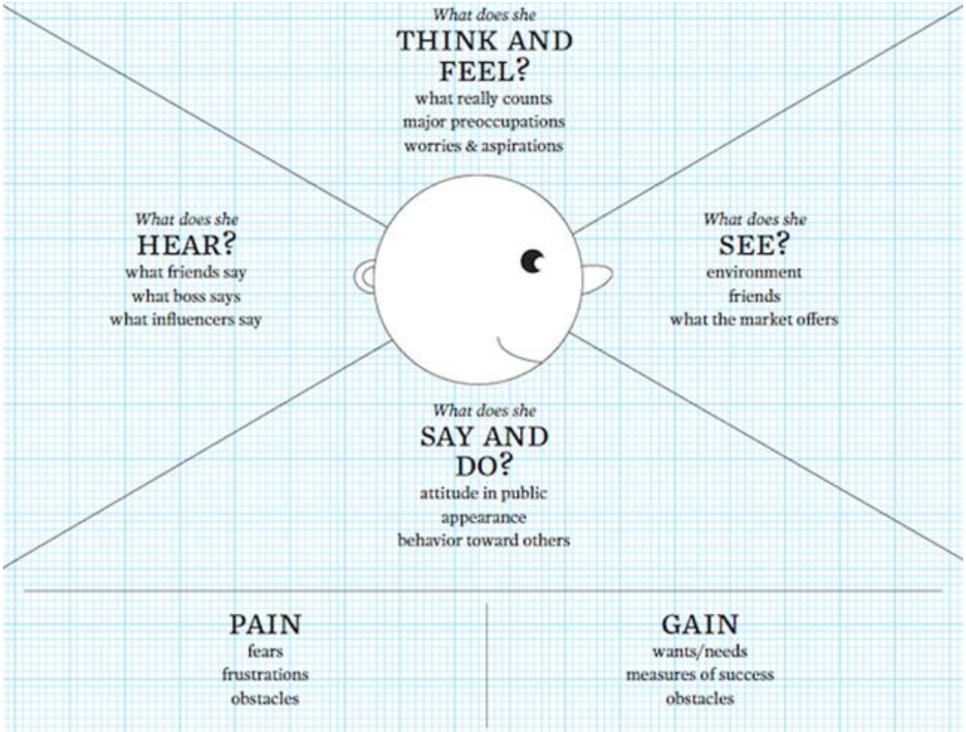


Figure 7 Think and feel[30]

Think and feel

When people are in a hurry, they may feel frustrated by the behaviour of others which may lead them to think irrationally.

See

The participants see the route they must use being blocked by all the other traffic participants.

Hear

They could hear honking or excessive accelerations.

Say and do

They could act unpredictably due to the frustration of the traffic congestion.

Pain

They may feel annoyed if they do not arrive at their destination in time due to the traffic.

Gain

They want to avoid the traffic congestion.

With this information, there is created a storyboard for the current situation of traffic congestion during rush hours on a bridge.

Figure 8 Storyboard[31]

3. Simulations

3.1 Simulation Definition

Simulation can be defined as the process of elaborating a model of a real or hypothetical system and conducting experiments in order to understand the behaviour of a system or evaluate its operation [32,33]. Simulations are not necessarily computational, although they have been linked to the term since the 1950s when the first use of computer simulation for military purposes was recorded. Its use has grown due to the large capacity and speed of computer calculations compared to the manual process. An example of non computational simulations would be the use of scale models or reduced aerodynamic models for testing.

Computational simulation can be divided into 3 categories according to its representation of time and state: Monte Carlo Simulation, Discrete Event Simulation (DES), and Continuous Simulation [34]. In this work, only the DES method will be addressed. According to Sasaki [35], a simple way to model a system is through input data and the model, producing outputs.

Carvalho [36] points out some advantages to the use of simulation, such as understanding the functioning of the system and identifying the main constraints to its performance, the possibility of visualisation, and the creation of other alternative experiments that could not be tested in the real system, and the creation of new insights for future projects.

According to Queiroz and Miranda [37] a simulation is an alternative to inference in the real system, avoiding experiment costs and interruptions in the production flow, and providing a complete view of the system in advance of implementation, allowing decision-makers to analyse and evaluate such results in advance.

3.2 First Phase: Conception

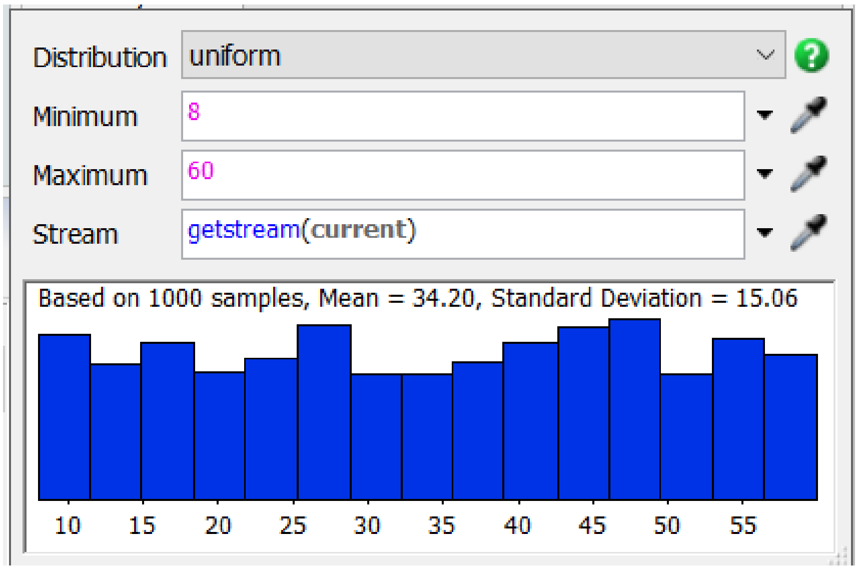
3.2.1 Objectives and system definition

The purpose of this study is to use the DES to evaluate the results in the traffic flow and average stay-time of vehicles in 3 different scenarios: an intersection, a two-lane bridge, and a four-lane bridge, to validate the design of the Smart Bridge in the testbed.

3.2.2 Input data modelling

Statistical distributions introduce randomness to a simulation model so that it is closer to a real-world simulation. Factors such as traffic, accidents, or even car problems can interfere with the time it takes the user to drive from point A to point B. Making considerations for this type of variation is important for a simulation, which is why Flexsim Software allows the use of statistical distributions to simulate real-life conditions.

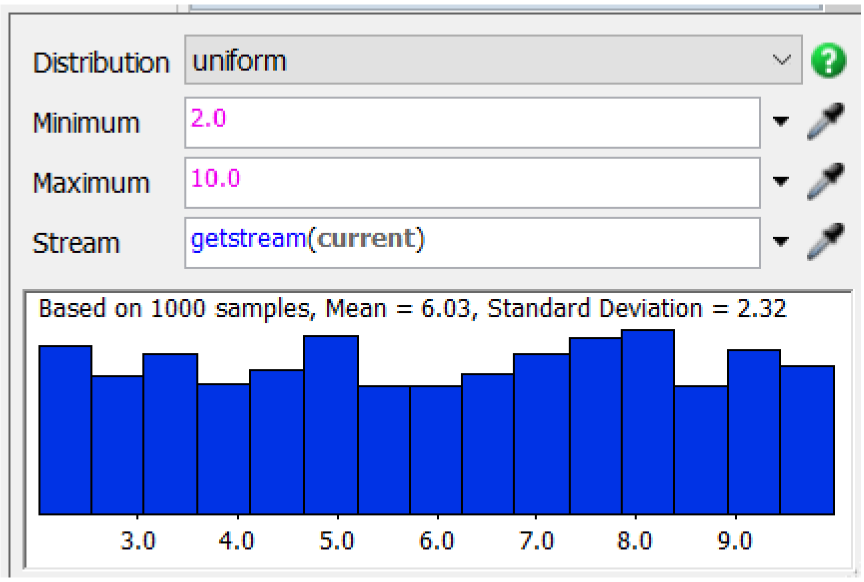
The Uniform distribution is widely used when little is known about the modelled phenomenon, except for its range of variation. In the experiment we will use two different distributions for the input of vehicles in the system, considering the car traffic ranging from a uniform distribution of a minimum of 8 to maximum of 60 seconds of inter-arrival time in the first part of the analysis and a uniform distribution of a minimum of 2 to a maximum of 10 seconds on the second part.



Distribution: uniform
Minimum: 8
Maximum: 60
Stream: getstream(current)

Based on 1000 samples, Mean = 34.20, Standard Deviation = 15.06

Figure 9 Flexsim print - Uniform distribution of vehicle inter-arrival time (8-60)[38]



Distribution: uniform
Minimum: 2.0
Maximum: 10.0
Stream: getstream(current)

Based on 1000 samples, Mean = 6.03, Standard Deviation = 2.32

Figure 10 Flexsim print. Uniform distribution of vehicle inter-arrival time (2-10)[39]

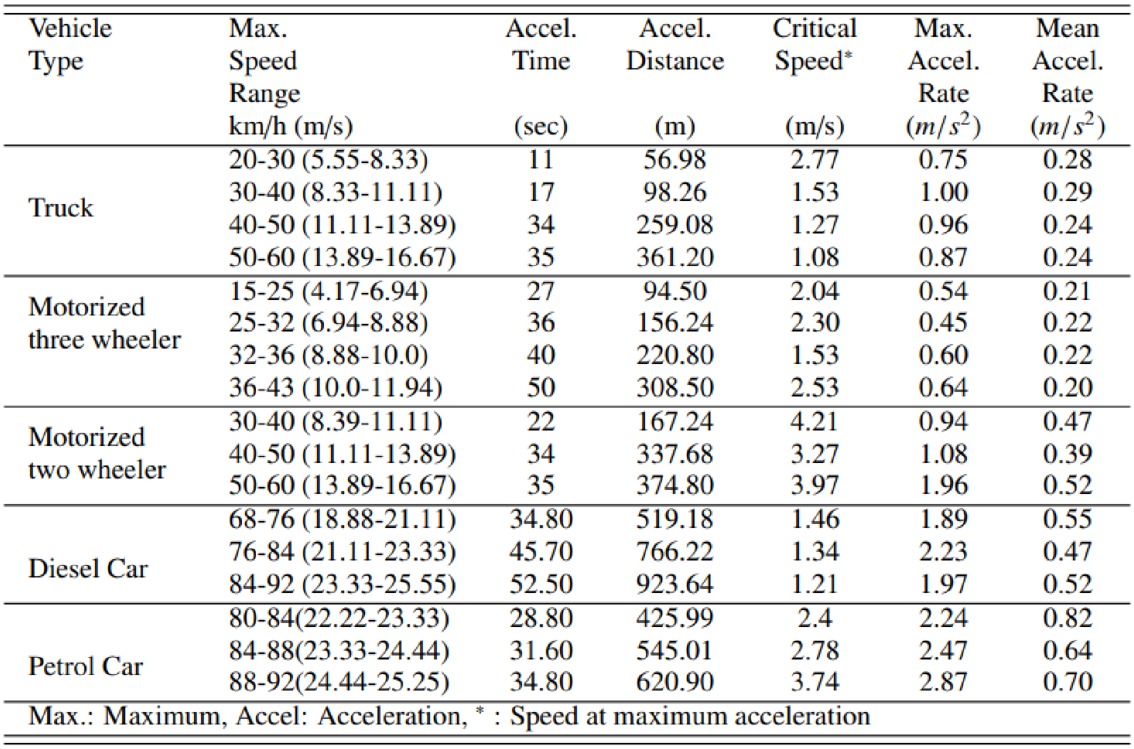
3.2.3 Parameters

Simulation time: 01/06/2022 13:00 to 30/06/2022 13:00

Speed limit: 50km/h

Acceleration: 0.47 m/s². Based on the mean acceleration of a diesel car.

Deceleration: 3.11 m/s². Based on the mean deceleration of a diesel car.

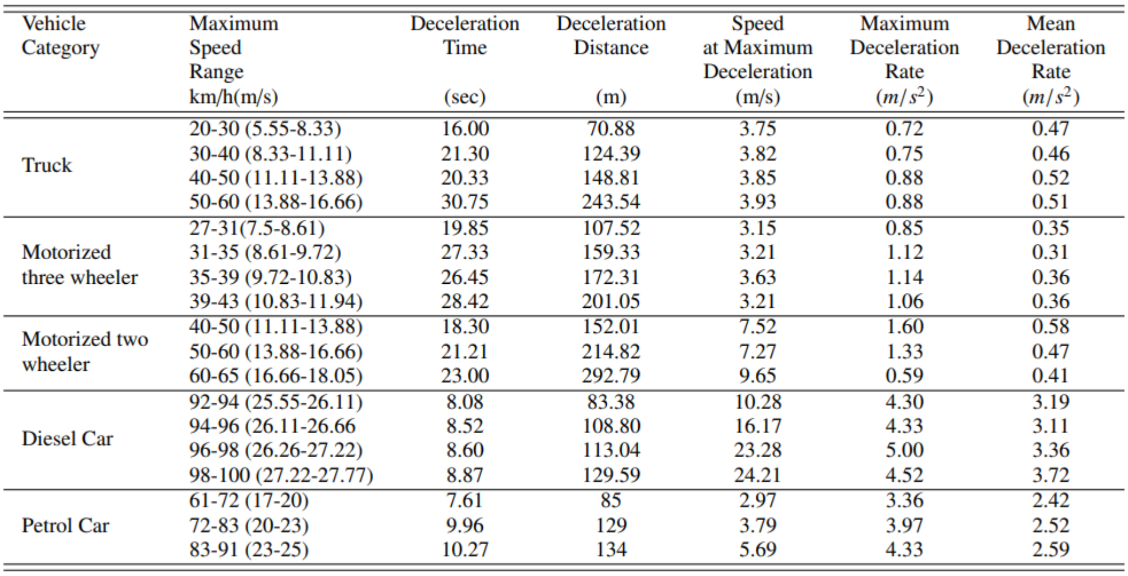


Vehicle Type	Max. Speed Range km/h (m/s)	Accel. Time (sec)	Accel. Distance (m)	Critical Speed* (m/s)	Max. Accel. Rate (m/s^2)	Mean Accel. Rate (m/s^2)
Truck	20-30 (5.55-8.33)	11	56.98	2.77	0.75	0.28
	30-40 (8.33-11.11)	17	98.26	1.53	1.00	0.29
	40-50 (11.11-13.89)	34	259.08	1.27	0.96	0.24
	50-60 (13.89-16.67)	35	361.20	1.08	0.87	0.24
Motorized three wheeler	15-25 (4.17-6.94)	27	94.50	2.04	0.54	0.21
	25-32 (6.94-8.88)	36	156.24	2.30	0.45	0.22
	32-36 (8.88-10.0)	40	220.80	1.53	0.60	0.22
	36-43 (10.0-11.94)	50	308.50	2.53	0.64	0.20
Motorized two wheeler	30-40 (8.39-11.11)	22	167.24	4.21	0.94	0.47
	40-50 (11.11-13.89)	34	337.68	3.27	1.08	0.39
	50-60 (13.89-16.67)	35	374.80	3.97	1.96	0.52
Diesel Car	68-76 (18.88-21.11)	34.80	519.18	1.46	1.89	0.55
	76-84 (21.11-23.33)	45.70	766.22	1.34	2.23	0.47
	84-92 (23.33-25.55)	52.50	923.64	1.21	1.97	0.52
Petrol Car	80-84(22.22-23.33)	28.80	425.99	2.4	2.24	0.82
	84-88(23.33-24.44)	31.60	545.01	2.78	2.47	0.64
	88-92(24.44-25.25)	34.80	620.90	3.74	2.87	0.70

Max.: Maximum, Accel: Acceleration, * : Speed at maximum acceleration

Figure 11 Vehicles Acceleration[40]

Deceleration: 3.11 m/s². Based on the mean deceleration of a diesel car.



Vehicle Category	Maximum Speed Range km/h(m/s)	Deceleration Time (sec)	Deceleration Distance (m)	Speed at Maximum Deceleration (m/s)	Maximum Deceleration Rate (m/s^2)	Mean Deceleration Rate (m/s^2)
Truck	20-30 (5.55-8.33)	16.00	70.88	3.75	0.72	0.47
	30-40 (8.33-11.11)	21.30	124.39	3.82	0.75	0.46
	40-50 (11.11-13.88)	20.33	148.81	3.85	0.88	0.52
	50-60 (13.88-16.66)	30.75	243.54	3.93	0.88	0.51
Motorized three wheeler	27-31(7.5-8.61)	19.85	107.52	3.15	0.85	0.35
	31-35 (8.61-9.72)	27.33	159.33	3.21	1.12	0.31
	35-39 (9.72-10.83)	26.45	172.31	3.63	1.14	0.36
	39-43 (10.83-11.94)	28.42	201.05	3.21	1.06	0.36
Motorized two wheeler	40-50 (11.11-13.88)	18.30	152.01	7.52	1.60	0.58
	50-60 (13.88-16.66)	21.21	214.82	7.27	1.33	0.47
	60-65 (16.66-18.05)	23.00	292.79	9.65	0.59	0.41
Diesel Car	92-94 (25.55-26.11)	8.08	83.38	10.28	4.30	3.19
	94-96 (26.11-26.66	8.52	108.80	16.17	4.33	3.11
	96-98 (26.26-27.22)	8.60	113.04	23.28	5.00	3.36
	98-100 (27.22-27.77)	8.87	129.59	24.21	4.52	3.72
Petrol Car	61-72 (17-20)	7.61	85	2.97	3.36	2.42
	72-83 (20-23)	9.96	129	3.79	3.97	2.52
	83-91 (23-25)	10.27	134	5.69	4.33	2.59

Figure 12 Vehicles Deceleration[40]

Intersection Traffic light time: 40s

Exit Traffic light time: 40s

Dimensions: The Layout used, see Fig.13, is the same as the testbed at CRAAX Lab. The following lengths of roads were defined for the purpose of the experiments.

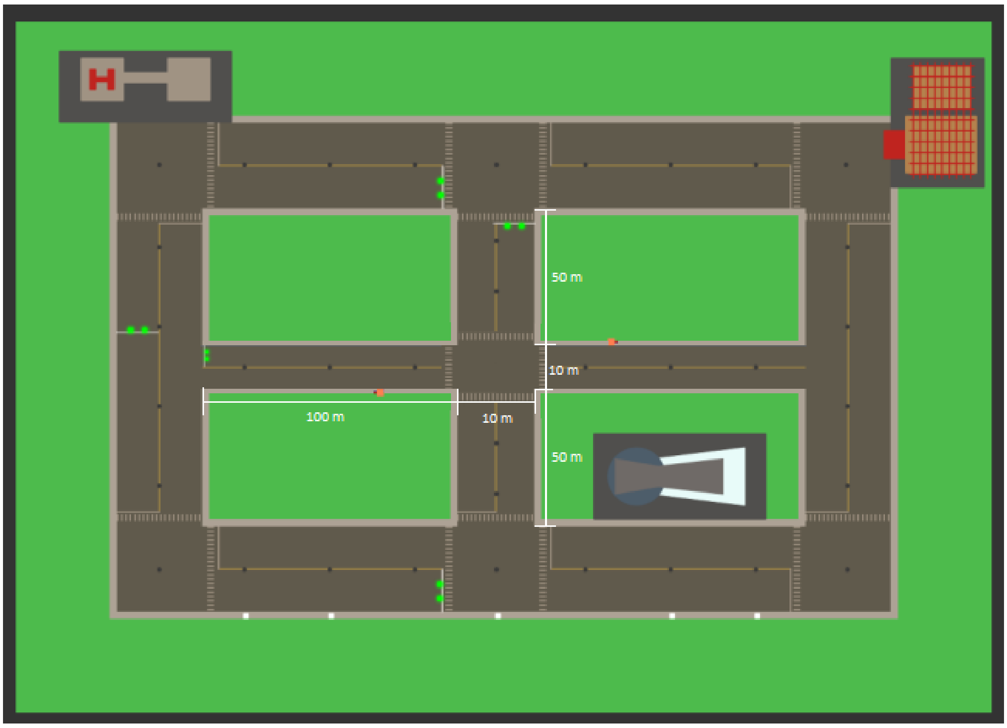


Figure 13 Intersection layout dimensions[41]

3.3 Second Phase: Implementation

3.3.1 Construction of the computational model

For the construction of the computational models, the software FlexSim® was used due to its realistic graphical platform, generating greater confidence regarding the modelled system. The group contacted FlexSim® and the licence for the software was made available for this project. The dimensions previously established based on the testbed were used for all models simulated. Each scenario has 4 sources and 4 sinks, where the vehicles enter and leave the simulation respectively. The reproduction of the layout in the software can be visualised by the following images.

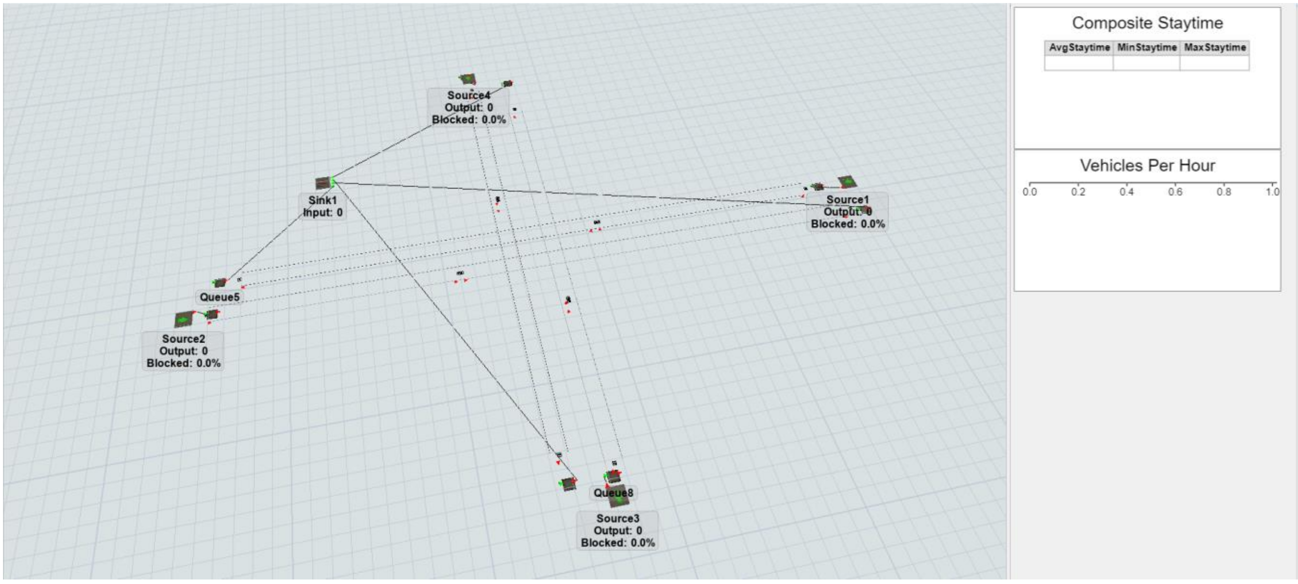


Figure 14 Computational model intersection layout[42]

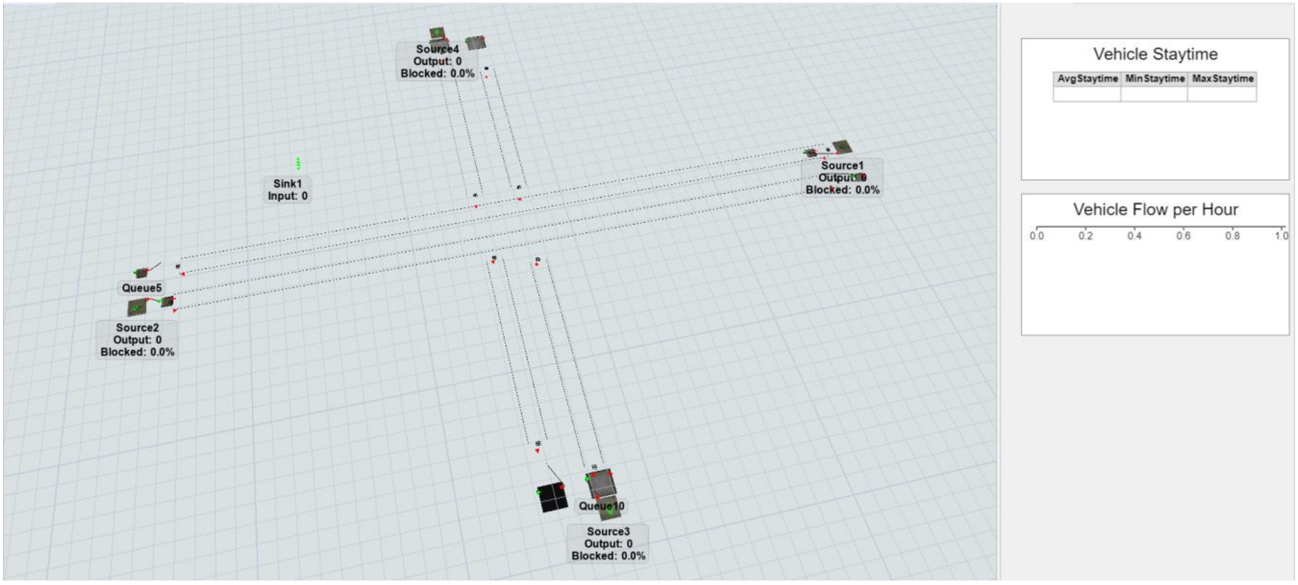


Figure 15 Two-lane Computational model bridge layout[43]

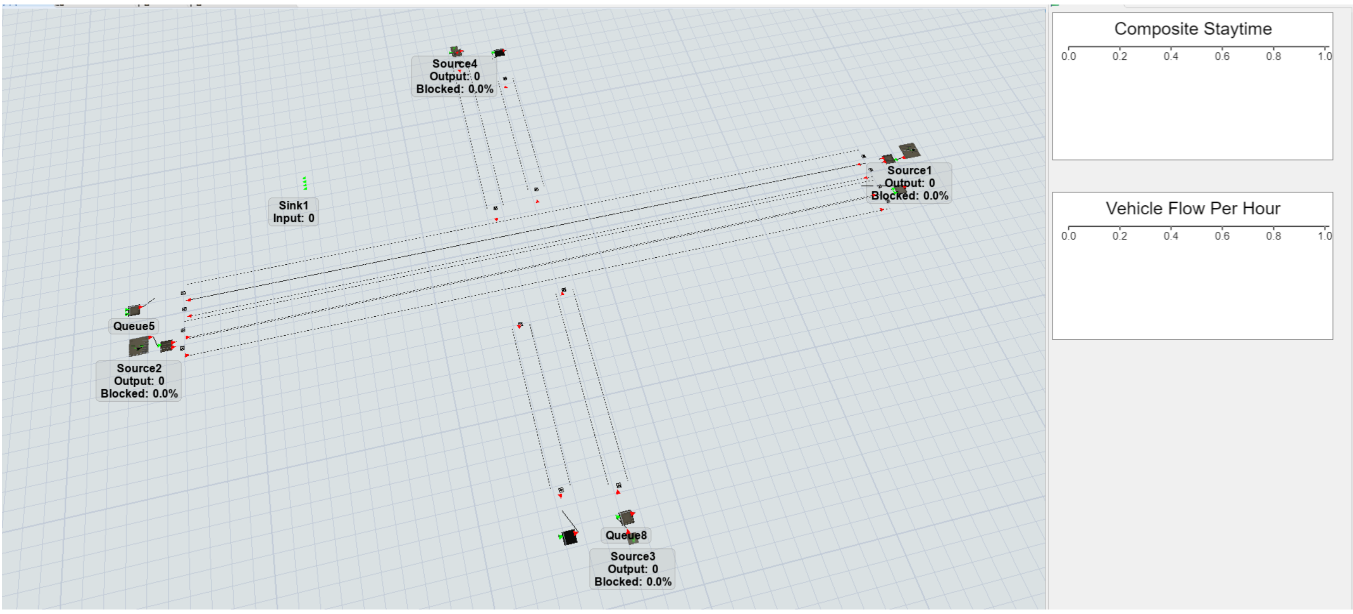


Figure 16 Computational model Four-lane bridge layout[44]

3.3.2 Definition of the experimental project

Intersection and a two-lane bridge

The first experiment compares an intersection scenario and a two-lane bridge scenario with a two-lane road passing underneath.

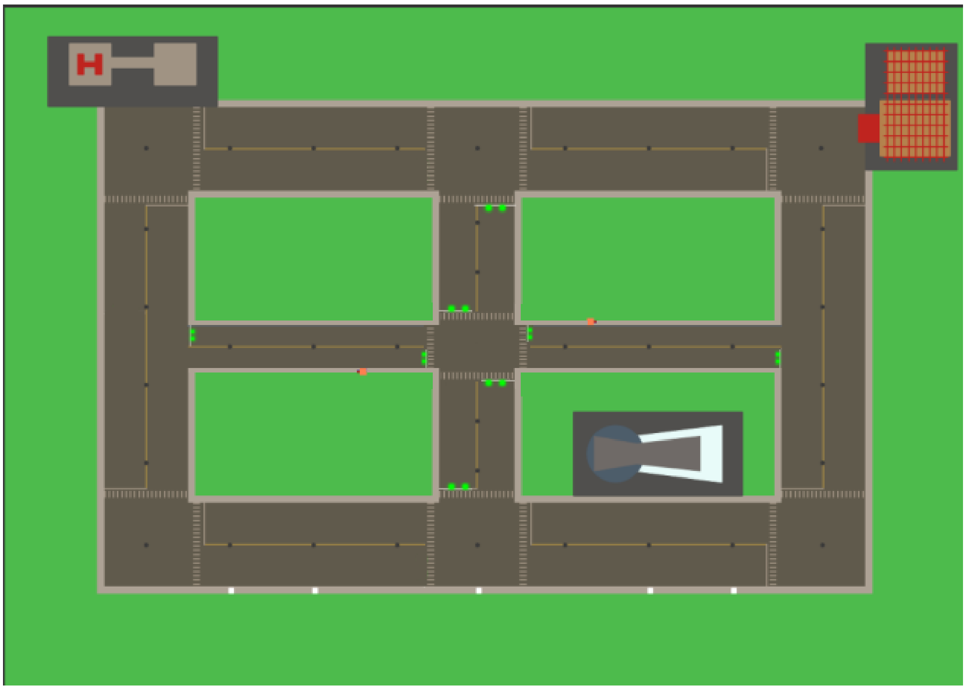


Figure 17 Intersection layout[45]

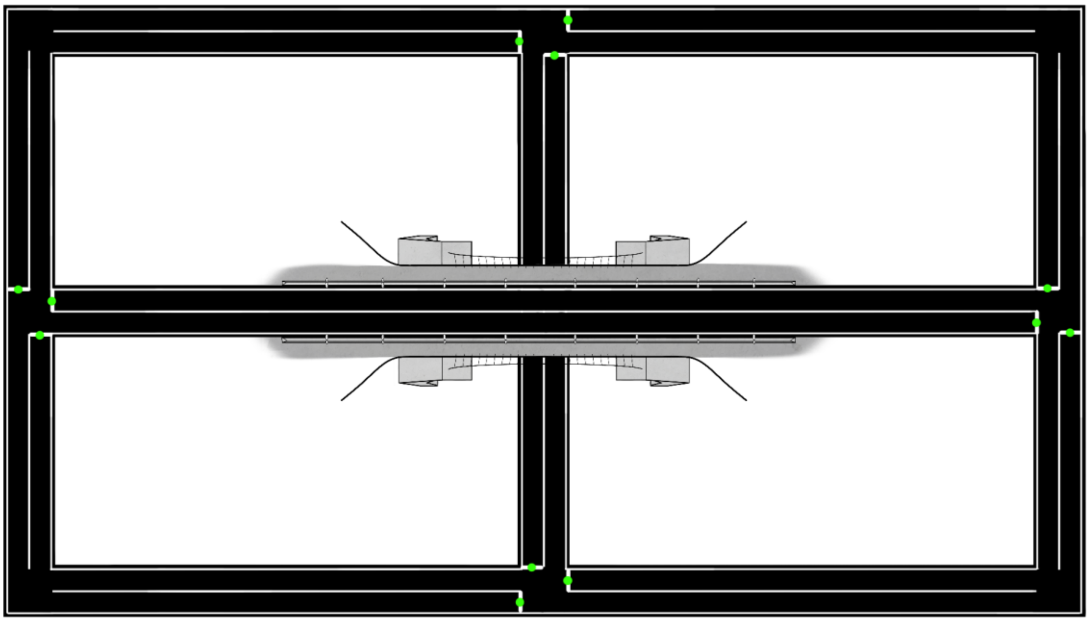


Figure 18 Two-lane bridge layout[46]

In this experiment the following 3 Items will be analysed:

1. **C02 Emission daily caused by vehicles idling in the intersection**

An hour of automobile idling burns approximately one-fifth of a gallon of gas and releases nearly 4 pounds of CO2 into the air [47]. The group will simulate the impact of C02 emission daily in an intersection while idling.

- Pounds to kg conversion

  4 lb × 0.45359237

  = 1.81436948 kg

- 3600 s - 1.81436948 kg 1 hour = 3600s

  1s - C02 Emission [kg/s]

  C02 Emission = 0.00050399 [kg/s]

- Assuming that the red-light time is equal to car idle time:

  Intersection Daily CO2 Emission **=** Vehicles daily x Red Light Time [s] x C02 Emission [kg/s]

2. **Average Stay time comparison**

The average time between the entrance and exit of the system or average time that the vehicle takes from point A to point B.

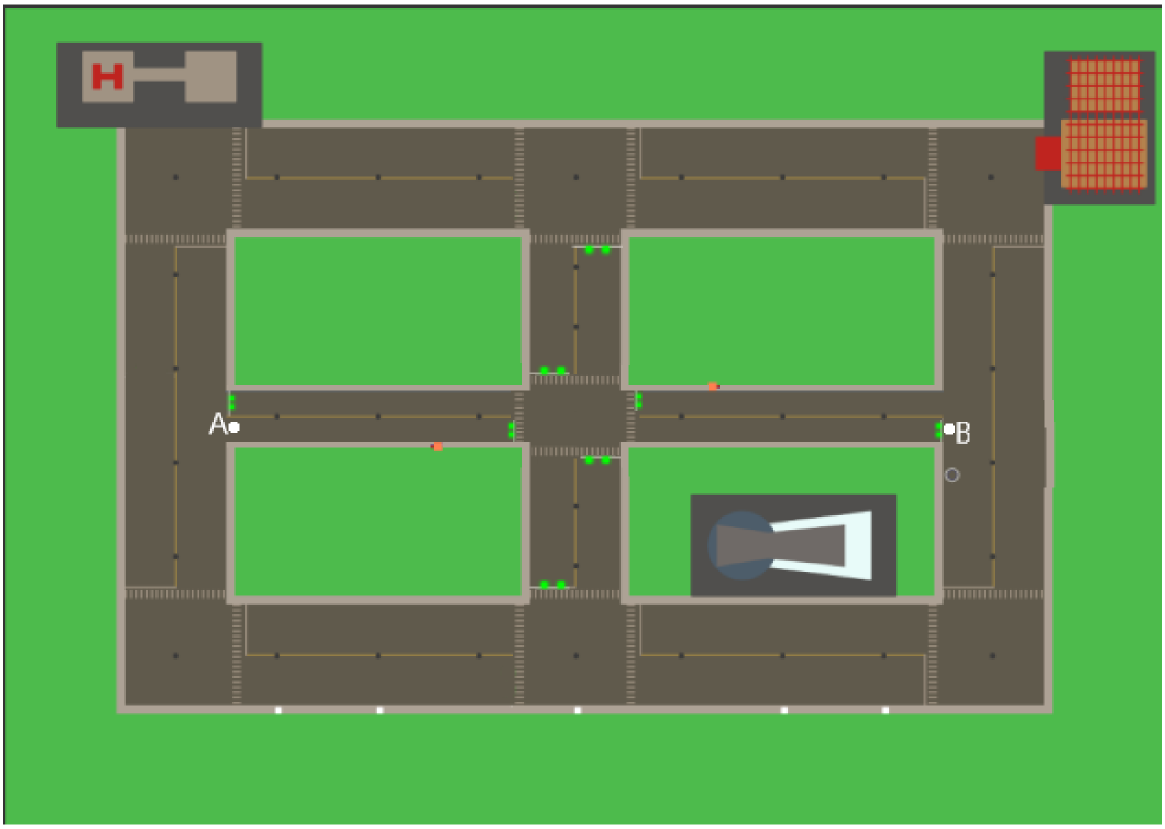


Figure 19 Intersection Layout[48]

3. **Vehicle Flow [Vehicles per hour]**

Analysis of the impact of changes on the flow of vehicles.

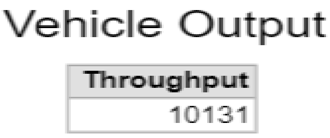
Two-lane bridge and four-lane bridge

The second experiment compares a two-lane scenario and a four-lane bridge scenario, analysing the impact of the changes on the flow of vehicles.

3.4 Execution of experiments and analysis

Intersection and Two-lane bridge

1. C02 Emission daily caused by vehicles idling in the intersection



Vehicle Output

Throughput
10131

Figure 20 Flexsim print. Intersection Vehicle flow daily[49]

Intersection Daily CO2 Emission = Vehicles daily x Red Light Time [s] x C02 Emission [kg/s]

Intersection Daily CO2 Emission = 10131 x 40 x 0.0005039

Intersection Daily CO2 Emission = **204.2369076 kg**

Intersection Yearly CO2 Emission = **74546.47 kg**

The 74546.47 kg of CO2 represents the emission reduction yearly when implementing the 2- Lane bridge in place of the intersection.

A tree can absorb between 10 and 40 kg of CO2 per year on average[50]. Considering the absorption as 40 kg per year, 18664 trees would be necessary to compensate for the CO2 emission produced in the intersection.

2. Average stay time comparison

Vehicle Staytime

AvgStaytime	MinStaytime	MaxStaytime
84.14	54.14	95.12

Vehicle Staytime

AvgStaytime	MinStaytime	MaxStaytime
44.29	15.12	55.12

Figure 21 Intersection(left) vs two-lane (right) average stay comparison[51]

We can observe a reduction of 72.07% on the minimum stay time, 42.05% on the maximum stay time and 47.36% average stay time between point A and point B.

3. Vehicle Flow [Vehicles per hour] comparison

As the same distribution for the vehicle inter-arrival time was used for both scenarios, the output of vehicle per hour confirms the equality of the parameters used in the comparison.

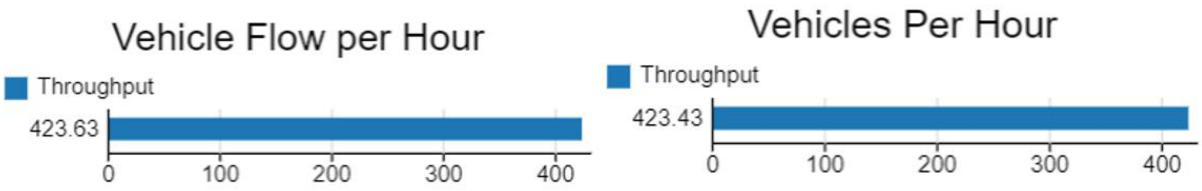


Figure 22 Intersection(right) vs two-lane (left) vehicle flow[52]

Now considering the car traffic ranging from a uniform distribution of a minimum of 2 and a maximum of 10 seconds of inter-arrival time in the 2 entrances of the bridge. The following flow of vehicles has been obtained in the 2-lane bridge scenario:

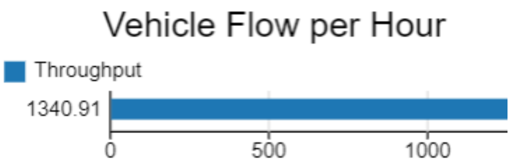


Figure 23 Two-lane vehicle flow[53]

The simulation shows an increase of 68.42% on the vehicle flow per hour, going from 423.43 vehicle per hour in the intersection scenario to 1340.91 vehicle per hour in the 2-lane bridge scenario.

Two-lane bridge and four-lane bridge

1. **Vehicle Flow [Vehicles per hour] comparison**

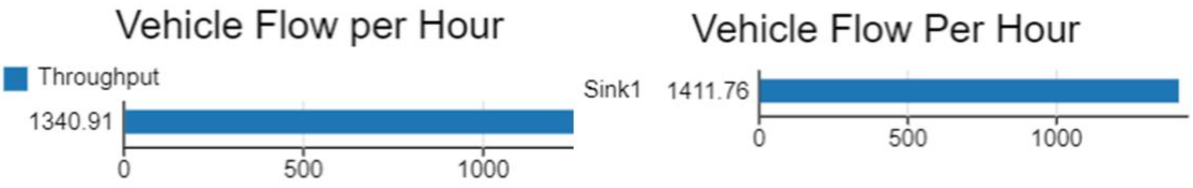


Figure 24 Two-line vehicle flow(right) vs four-line vehicle flow left[54]

Using the same vehicle input for both scenarios, the results show an increase of 5% on the vehicle flow, approximately 71 vehicles per hour.

3.5 Conclusions and Recommendations for future work

Regarding the implementation in the study object, it was possible to visualise a significant impact of the application of the proposed layout on the behaviour of vehicle traffic, simply by the reduction of travel time and increase of vehicle flow.

It is suggested to use Expertfit for future projects as it is the world's top statistical distribution tuning software. By taking real measurements of a transport system and the system you are modelling. It is possible to use this data to achieve a distribution curve that best fits the values. This software then allows you to find the correct distribution that reflects the reality of the data. By collecting data and running it through Expertfit, the model can be even more accurate in replicating the real-world system[55].

Therefore, this work aims to serve as a reference for future analysis of integrated vehicle traffic systems to discrete event simulations in Smart Cities.

5. Choosing the design of the bridge

The current smart bridge (seen below in Figures 25 and 26) is a small suspension bridge that is built over a road. The bridge has an elevation mechanism but does not work on the current testbed. There is a two-lane road and currently, there is no sidewalk for pedestrians or a bike lane.

Figure 25 CRAAX smart bridge[56]

Figure 26 CRAAX smart bridge[57]

The shape and design of the bridge depending on the overall goal of the bridge and the city it is being built around. Our team decided that the suspension bridge was best suited for the design. Additional smart features will be added to the design to further improve the concept. From the images above of the current smart bridge, the cables are unrealistic and would not support a real-life bridge. In our concept, it is important to make the bridge more durable and sturdier. In addition, the team will consider including a bike and a pedestrian lane next to a two-lane road.

Suspension bridges are a great option when choosing the type of bridge. They have many advantages and looking at the recently built bridges – they are the most popular among constructors. Suspension bridges are made of a deck slab that is suspended using ropes, chains, or high-tensile strength steel cables. The roadway is supported by steel cables that are attached to two towers and are secured by anchors at both ends of the bridge. The anchors are made from solid concrete blocks. The weight of the traffic is transferred across the bridge evenly due to the suspension cables which transfer the force of the compression of the two towers. The force of tension is constantly acting on the cables, which are stretched because the roadway is suspended from them.

Advantages of suspension bridges:

- low-cost construction,
- flexibility in the span
- ease of maintenance,
- flexibility in the location,
- aesthetic appearance.

Disadvantages of suspension bridges:

- longer construction time,
- lesser wind resistance,
- limitations of cables.

To create the new design the design process started with ideation sketches. Ideation sketches are quick sketches to be able to communicate ideas with the people included in the designing process. In ideation sketches there does not need to be paid attention to details and can be made use of icons. So a small reverence is the stick figure, to show the path for the pedestrians and bikers. This is an efficient way to show the deck layout.

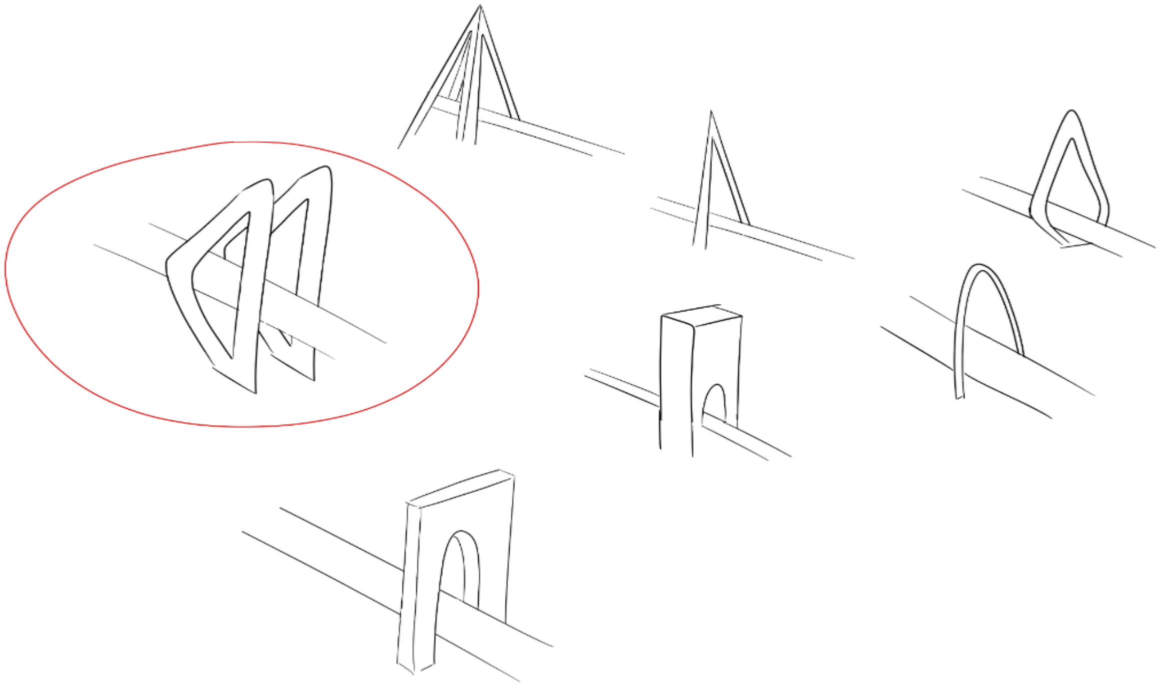


Figure 27 Initial (ideation) sketches[58]

As seen in the ideation sketches above (Figure 27), the team explored several different designs for how we could suspend the bridges. These were conceptualised through our ideation and based on research done on other suspension bridges around the world. For the sketches, it is needed to keep in mind, that it will be a suspension bridge. Hence, there were limits to the design possibilities. The new structure should be as strong as the original construction, and even more durable. For production possibilities, the ability to really manufacture the design should be considered, therefore the team opted for organic shapes. In the end, the team decided to focus on the futuristic, triangular pillars seen circled above.

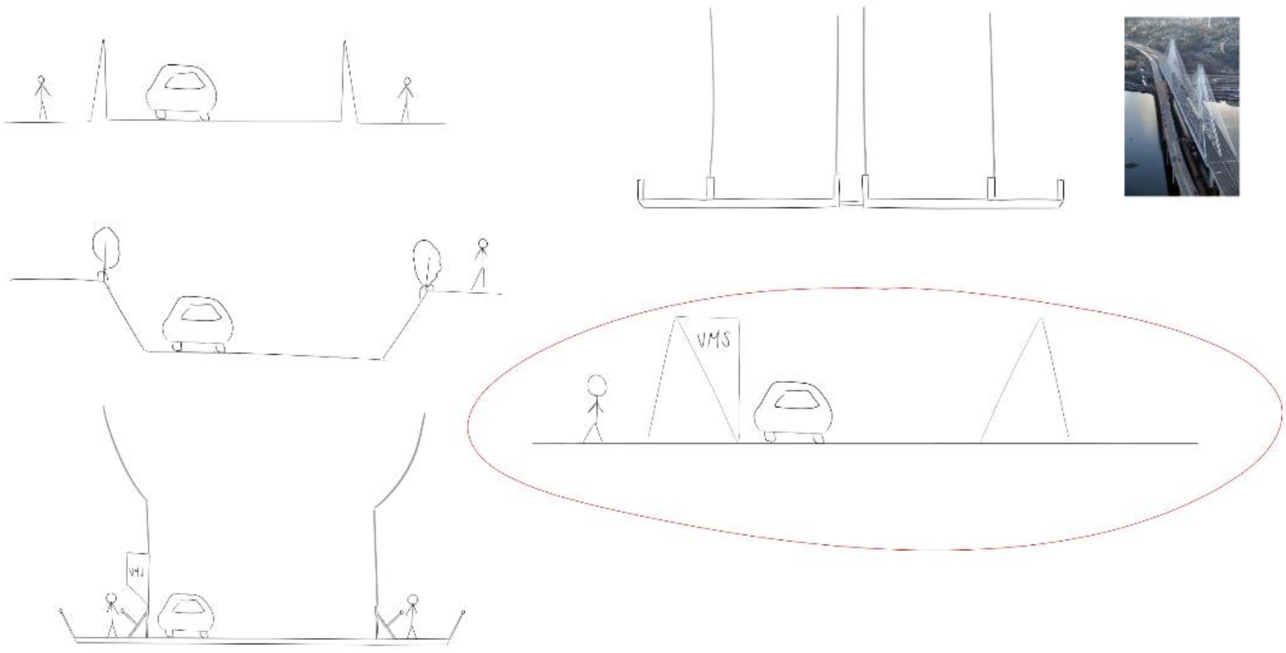


Figure 28 Initial (ideation) sketches - level view[59]

In Figure 28, the team explored diverse ways to include the pedestrian walkway in the design.

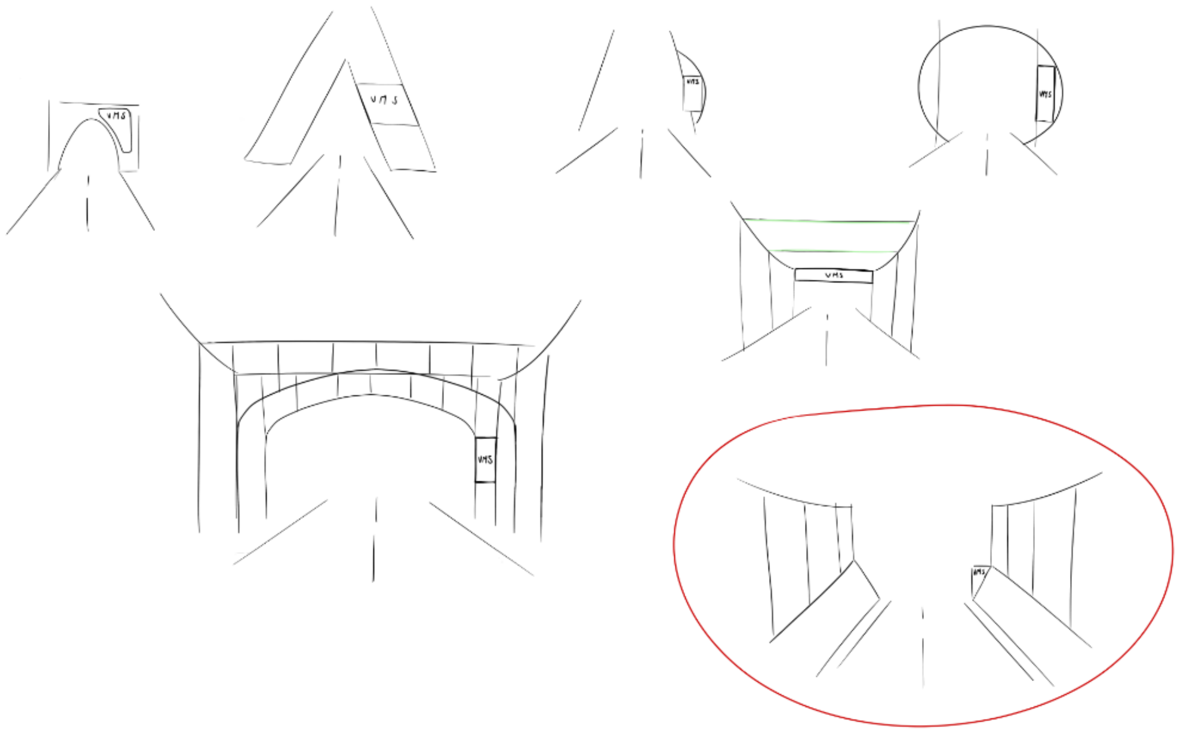


Figure 29 Initial (ideation) sketches[60]

As seen above in Figure 29, the team explored different layouts of the bridge and how it would connect to the road. It was important to get out ideas onto paper to determine which design was best. In the end, the sketch with the red circle around it was chosen.

6. Choosing the smart features of the bridge

Once the team had agreed on the look of the bridge, it was time to choose the smart features of the bridge. As it was mentioned in the research part of the report, every smart bridge is different. The technology should be adapted to environmental parameters, traffic, and the use of the bridge. For the project, the team agreed on the most important functions that the prototype should have.

6.1 VMS

Variable-message sign (VMS), seen in Figure 30, is an electronic and smart display very often used to manage traffic. It gives travellers the most crucial information in text and graphic form, which results in more efficient traffic. VMS signs are visible in all types of weather, due to the long-life LED technology that has been implemented in them. Each sign can show different information, symbols, and warnings, which makes VMS extremely versatile and suitable for providing traffic information for a variety of situations including emergencies and road closures [61].

Figure 30 Example of VMS[62]

The goal of the project is to use the bridge as a tool for creating more efficient traffic in a smart city. Hence, the team has decided on using VMS signs at each end of the smart bridge, as seen in Figure 30. The sign would provide the users with the information on the state of traffic congestion in the city (how long it would take you to get to a certain place), a warning about the speed limit (the speed will be adjusted to the current state of traffic congestion), and eventually information about any accident that has happened on the bridge. In this way, the traffic participants get more informed and feedback about their surroundings.

Figure 31 Schematic visualisation of VMS used in the bridge [63]

6.2 Sensors

The main characteristic of smart bridges is that they are equipped with a network of sensors. They monitor the structural health of the bridge, the weather, traffic, and air quality. The main goal of sensors is to ensure that the bridge is performing optimally and to prevent any potential disaster. For the prototype of the smart bridge, two sets of sensors have been chosen, the first set is responsible for monitoring the structural health, and the second is for monitoring and optimizing the traffic.

Sensors monitoring the structural health:

- Strain gauges

A strain gauge is a type of electrical sensor, which is responsible for measuring strain, stress, and force. It converts applied force, pressure, tension, or weight into a change in electrical resistance which can then be measured. Strain gauge technology used in a bridge is usually applied to the stay cables[64]. The use of strain gauges, allows efficient and effective real-time monitoring making inspections more thorough.

- Anemometers

An anemometer is a device used to measure wind speed and direction. Usually, an anemometer has three or four cups attached to horizontal arms, which are attached to a vertical rod. When the wind blows, the cups rotate, making the rod spin. The anemometer counts the number of turns which is used to calculate wind speed. However, other anemometers calculate wind speed in different ways. In a hot-wire anemometer, an electrically heated thin wire is placed in the wind. The amount of power needed to keep the wire hot is used to calculate the wind speed. It is extremely important to observe both wind speed and direction in the case of a bridge. What is more, it is often also necessary to also monitor the vertical axis of the wind, due to the height above ground [65].

- Accelerometers

Accelerometers are used for measurement of displacement response of the entire bridge under live loads which may cause stress and lead to damage. The force caused by vibration or a change in motion (acceleration) causes the mass to "squeeze" the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration [66]. It is crucial that these vibrations or acceleration of motion of a structure can be accurately assessed to ensure that bridges can be effectively maintained.

By keeping a close eye on the structural health of the bridge via different sensors, the risk of damage or a fault can be significantly reduced and in turn, prevented. Overall, sensors are a wise investment for a bridge as the initial cost is high but over time less maintenance will be required on the bridge.

Sensors monitoring traffic situation:

- Microwave Motion Sensor (Microwave Radar Detector)

A microwave motion sensor applies electromagnetic radiation. It emits waves which are then reflected to the receiver. If the waves bounce back altered, there is an object moving [67]. Installation and maintenance of these sensors do not require pavement modifications. Unlike inductive loops, which are embedded in the pavement. Instead, they are typically mounted on a structure next to the road. Depending on the type of electromagnetic wave used, microwave radar detectors can measure either vehicle presence, or vehicle presence as well as speed. They are also widely used to detect pedestrians waiting at pedestrian crossings [68]. With these sensors, the amount of traffic can be accurately detected. This is important to predict the best routes for individuals on navigation tools.

- Air quality sensors

Traffic has a massive impact on the environment. By monitoring the air quality, it is possible to adjust the speed limits to control the traffic in the most eco-friendly way. Non-Dispersive Infrared (NDIR) sensors are measuring the attenuation of infrared radiation (of a specific wavelength) in the air. The sensors consist of an infrared radiation source (bulb), a light-water tube, and an infrared detector with an appropriate filter. The signal from the infrared detector is amplified more and then the attenuation of the radiation caused by the collision with carbon dioxide is evaluated using additional electronics. On this basis, the actual CO_2 concentration in the air is calculated [69]. The sensors are accurate and stable in the long term.

With these measurements of the air quality, actions can be taken to lower the emissions when extreme or unhealthy conditions occur. By lowering the speed, advising to keep the winds closed or manipulating the traffic to better divided over locations so there is not one spot with too many emissions what can be bad for the health of the people in the traffic.

6.3 Smart lights

The last smart feature that is implemented in the prototype is smart lightning across the bridge. Lighting is a key element in the structure of the bridge, the drivers' safety must be kept as a priority, hence driving visibility must be perfect. It should not distract the driver but improve his or her experience of driving across the bridge. Lampposts and smart lighting sensors are therefore chosen to be implemented in the prototype, as seen in Figure 32. The streetlights are equipped with timers and motion detectors, their key role is to optimize energy consumption.

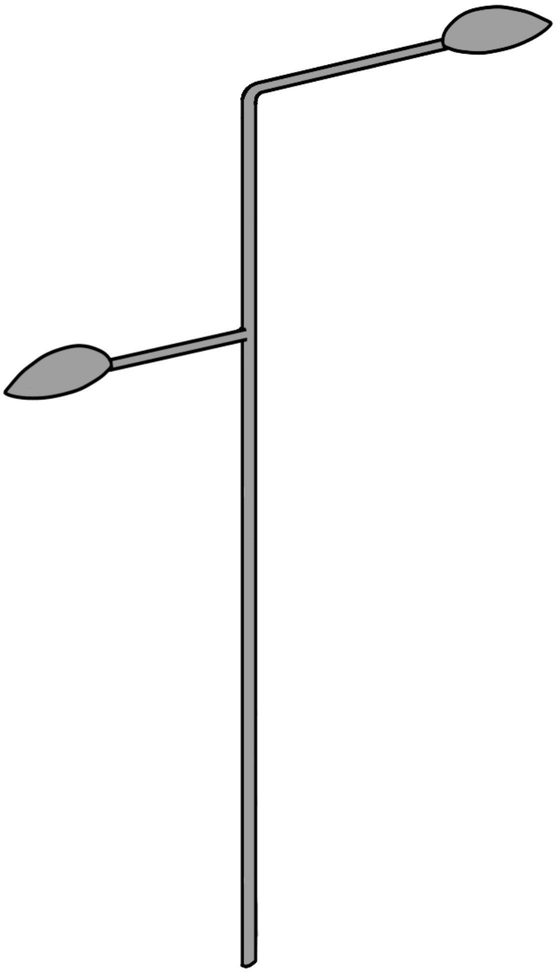


Figure 32 Schematic visualisation of smart lamppost used in the bridge [70]

7. Proposed prototype of the bridge

7.1 Final design of the bridge

The final prototype is represented in the sketches below. In comparison with the current bridge in the testbed (seen in Figure 19,20), the prototype has a pedestrian walkway, a bike lane, and a smart lamppost along the road. It is a suspension bridge with two triangular concrete pillars and added cables to increase the sturdiness of the bridge. The bridge has a more modern and smarter design than the previous and also has the smart features implemented into it further described below.

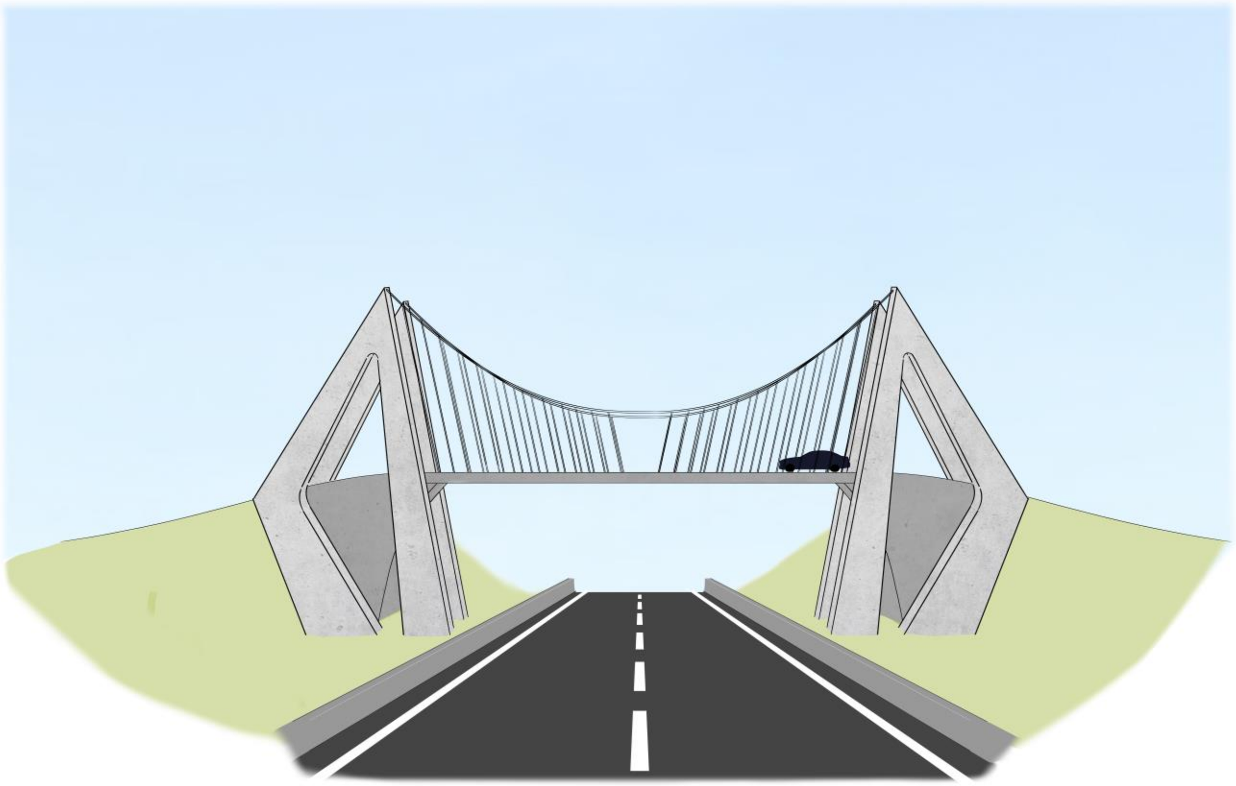


Figure 33 Side view of the bridge[71]

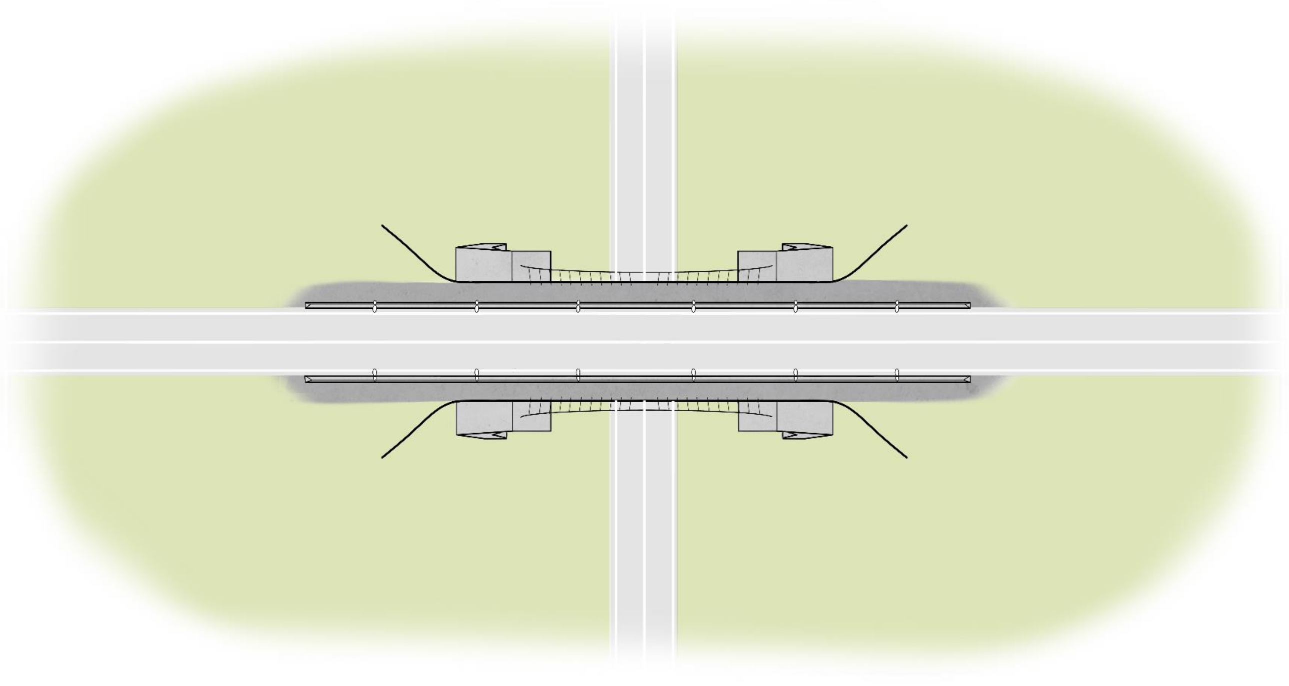


Figure 34 Top view of the bridge[72]

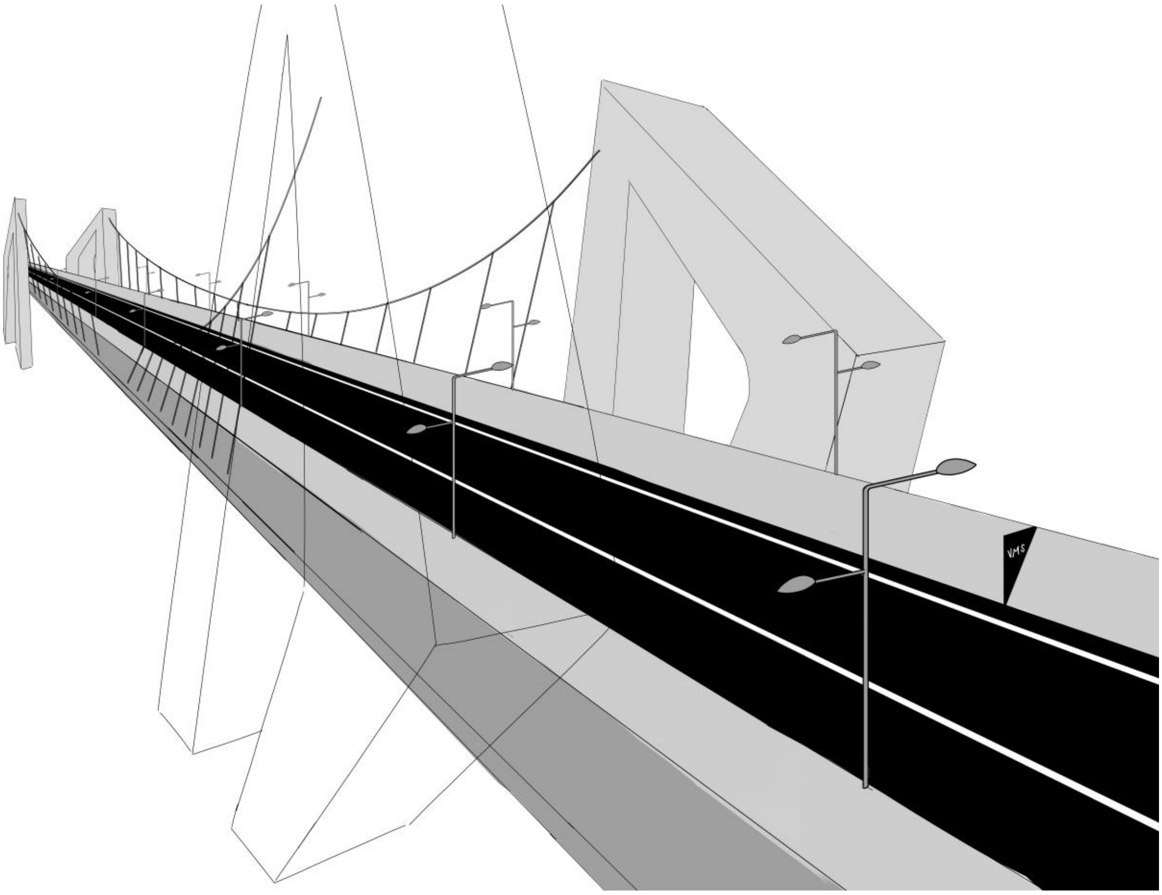


Figure 35 Full view of the bridge[73]

7.2 Description of how the bridge works

The main objective of the project was to redesign a bridge so that it could be integrated into a smart city and can improve the traffic flow. To achieve this several smart features would have to be implemented into the bridge. Each smart feature is shown below (Figure 30) in a different colour. The green dots represent the accelerometers, red dots represent strain gauges, yellow dots represent anemometers, navy microwave motion sensors, and blue air quality sensors. Using these smart features allows us to constantly monitor the performance of the bridge while also being able to detect any potential malfunctions or mechanical failures. Motion sensors will allow us to monitor the number of cars passing over the bridge, which will be important to help the flow of traffic.

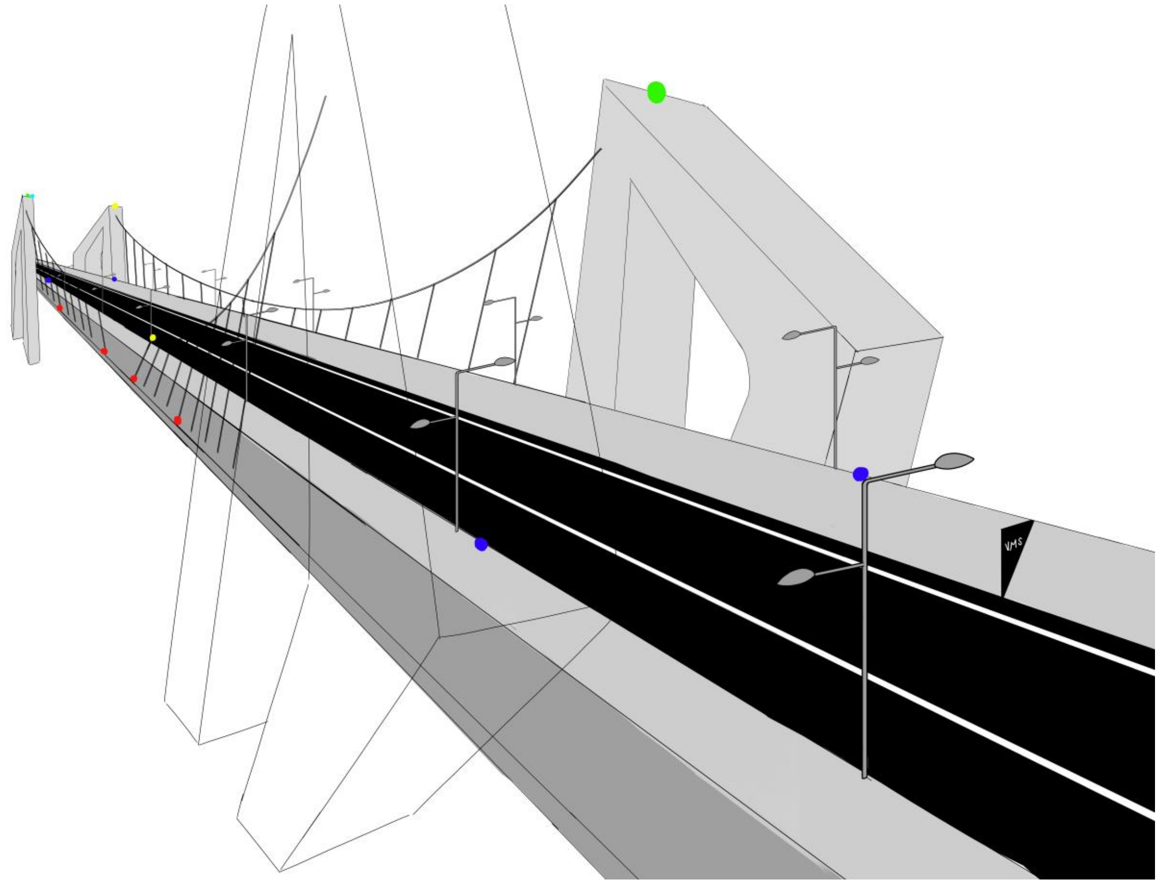


Figure 36 Full view of the bridge with marked places for sensor[74]

8. Conclusions, discussion, recommendations, and limitations

Smart bridges are essential to the innovation of the modern world. In this project we were tasked with designing and developing a smart bridge that integrates into a smart city. The smart city is built on a testbed in the CRAAX research lab at UPC Vilanova. We used the bridge as a tool to improve the flow of traffic in the smart city. This was achieved by the integration of smart technology to improve the quality of experience and quality of service. To ensure we were reducing traffic flow in the smart city we performed simulations to compare different smart city layouts; an intersection, on a two-lane bridge, and a four-lane bridge.

As a result of the simulation, it was possible to visualise the impact of the proposed 2-lane bridge layout on the behaviour of vehicle traffic in terms of average travel time decrease and increase of traffic flow. The four-Lane bridge showed a modest increase of 5% on the vehicle flow, but ,considering the higher project costs, the two-lane bridge was chosen as the final layout. The two-lane bridge design eliminated the 74546.47 kg of $C0_2$ emitted in the intersection yearly, showed a 47.36% reduction on average travel time and an increase of 68.42% on the vehicle flow.

From these results we were able to design and sketch a two-lane suspension bridge with a pedestrian walkway with additional smart features included. This project allowed the team to explore the innovations of the modern world and the modern technologies arising with it. Despite the time constraints and the uncertainty about the initial objective of the project, all the client's interests have been successfully achieved. The project was challenging for the team but allowed us to develop many new skills and ways of thinking.

8.1 Personal assessment

The project has allowed the team to combat a real engineering problem that may occur in the future. This project had many demands in terms of teamwork, time constraints, engineering, and cultural differences.

One of the most important points of this project has been the team cooperation to reach the final product. Defining objectives, planning, and prioritising in each of the stages. Even so, project management could have been one of the points that we should have given more priority at the beginning of the project, as effective management and planning would have allowed us to reach the end goal more efficiently.

We have been able to divide a complex problem into various stages, with different objectives. Observing how each one of these was being established, modified, and finalised to reach the final document and design.

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