MSc Dissertation in Technology Management

AHP evaluation of Smart Traffic Light Technologies as a Key Policy Element in Intersection Traffic Conditions with a Positive Spill over in GHG Emissions

GHG 배출에 따른 긍정적 파급효과가 있는 교차로 교통상황에 대한 핵심 정책요소로서의 스마트 신호등 기술에 대한 AHP 평가.

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Abstract

AHP evaluation of Smart Traffic Light Technologies as a Key Policy Element in Intersection Traffic Conditions with a Positive Spill over in GHG Emissions

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Climate change has become a critical issue around the world. Rising global temperatures caused by pollution, specifically noxious gas emissions, is threatening the survival of all living species, particularly humans, who will number more than 7.9 billion by 2022. This contamination proclivity dates back to the first industrial revolution and reached a tipping point with the implementation of gasoline additives by the automotive industry. Nowadays, the vehicular sector is the world's first source of pollution and the primary cause of rising global temperatures and the subsequent consequences of climate change.

Scientific literature analyzes transportation dynamics and finds that critical moments in emission boost are during the traffic congestion hours when the vehicles are obligated to transit at the most efficient fuel consumption speed. Based on this, it is determined that road intersections are the most common source of traffic congestion due to lack of real-time responsive technologies or devices to handle vehicular traffic demand. Middle-upper and high-income nations have been working on implementing several modern technologies along with city infrastructure upgrades on the back of transportation and urban policies to

reduce vehicular traffic congestion through large investments in the digital transformation of traffic management systems and moving the cities towards smartification.

The problem arises when low- or low-middle-income governments are required to prioritize the needs of their populations and allocate budgets to projects, positioning climate change far behind food, housing, health, education, security, and transportation. Thus, structural problems related to the transportation field continue, resulting in Green House Gas (GHG) contamination. In this scenario, no matter whether the contamination is reduced, diminished, increased, or augmented, the final effect is accounted for as a global temperature change.

To delve deeper into these issues, the current study poses two research questions: If a relationship between increasing GHG-Co2 emissions and vehicular traffic congestion levels at intersections exists? Using a systematic literature review (SLR) as the methodology, over 135 documents related to Smart Traffic Light (STL) and GHG emissions were categorized and filtered, yielding a total of 13 key papers. From the SLR papers' database, a keyword extractor was implemented to identify and extract the architecture, platforms, frameworks, simulators, sensors, methods, and algorithms from each entry. A total of two hundred forty-one STL related technologies were identified, by using a normalization word cloud method it was reduced the total to one hundred thirty-five terms. In a second stage the results were limited to twenty-seven STL terms using a categorization tree map the related or closely related technologies were examined.

The research question was addressed by the SLR identification of studies by Lu Jie, Watson, Bates, and Kennedy, Towojua and Felix Isholab, (Table 1). All these studies provide different methods for identifying the correlation between traffic jams and congestion and increasing GHG emissions.

Table 1 Traffic and GHG literature evidence

RELATION BETWEEN TRAFFIC CONGESTION AT INTERSECTIONS AND GHG		
A. Towojua and Felix A. Isholab	2020	A case for the internal combustion engine powered vehicle
Deborah Gordon	2010	The Role of Transportation in Driving Climate Disruption Energy and Climate Program
EPA	2022	Overview of Greenhouse Gases
FAO	2017	Livestock's role in climate change and air pollution - 3.1 Issues and trends
Lu Jie's	2011	Environmental Effects of Vehicle Exhausts
Watson, AY, Bates, and Kennedy	1989	Global and Local Effects; Air Pollution, the Automobile, and Public Health
Mohammed Al-Turki	2020	On the Potential Impacts of Smart Traffic Control for Delay, Fuel Energy Consumption, and Emissions: An NSGA-II-Based Optimization Case Study from Dhahran, Saudi Ara
Muhammad Ehsan Munawer	2018	Human health and environmental implications of coal combustion and post-combustion wastes
W. Addy Majewski	2012	What Are Diesel Emissions

SLR's intensive technology description, extraction, and normalization resulted in a clear identification of smart traffic light-related technologies, architectures, and frameworks, allowing the creation of a STL technology map, which is intended to be one of the critical steps in the Analytical Hierarchy Process (AHP) by providing an alternative layer or dimension.

The second research question is: Based on the SLR's identification of STL system technologies, which of these technologies are the most suitable to be implemented as an element of the traffic infrastructure at intersections (traffic lights) under budget constraints, targeted at improving traffic flows and reducing GHG-Co2 emissions? This was studied under a multicriteria decision analysis (MCDA), based on an (AHP), aimed to allow decision-makers and policymakers to determine which were the most suitable Fourth Industrial Revolution (4IR) technologies related to vehicular traffic congestion management at intersections.

Developed by Professor Thomas Saaty in the 1970s, the AHP methodology is a multicriteria decision process that helps in choosing from among many alternatives based on a number of selection criteria or variables that are typically hierarchical and frequently at odds with one another. Choosing the selection criteria and sub-criteria carefully, defining them correctly, and ensuring that they are mutually exclusive are issues that were addressed by the SLR technologies. Identification and categorization are essential components of the process. The Saaty Fundamental Scale is used in the survey to perform a paired comparison. The hierarchical structure is top-down: the subject of this method is Objectives> Dimensions (STL Functions, STL Costs, and Traffic Emissions)> Criteria> Alternatives, which allows the transformation of qualitative aspects into quantitative ones, significantly facilitating a comparison between the various alternatives and producing more objective and reliable results.

According to an AHP analysis which was based on an expert survey questionnaire, the cost dimension is the most important factor in implementing STL technologies for upgrading existing traffic light infrastructure at 45.79 percent, followed by the efficiency dimension (41.61 percent). At the alternatives level, experts identified that Inductive Loop Sensors were the best technology for upgrading the intersections and obtaining traffic flow improvements along with a GHG reduction with 23.67 percent agreement, followed by Video Vehicle Detection at 15.02 percent, and GPS-based technologies at 13.37 percent.

The current study aims to address low-income governments' financial constraints which prevent them from investing in digital transformation or smartification. The study uses a SLR to identify the smart technologies, Internet of Things (IoT), and Artificial Intelligence (AI) related to STL state of art to find a correlation and scientific evidence between the traffic at road intersections and the increase in GHG emissions. However, in addition to identifying and providing scientific evidence, the research goes further by evaluating those technologies from the perspective of traffic management experts and practitioners, providing a high degree of reliability of the outcomes. Thus, both decision-makers and policymakers can base their policies on the present study to determine that the Inductive Loop Sensor is the best smart technology for improving traffic flows at intersections and feeding traffic lights with real-time information, despite the high initial investments, which can be understood as a high cost in the short-run but with benefits in terms of efficiency in the long run.

Keywords: *STL, Traffic Congestion, Intersections, GHG, Co2, ICE, Sensors.*
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Chapter 1. Introduction

1.1 Research Background

1.1.1 Environmental background

The level of GHG emissions and its effect on climate change and global warming has become a main concern for governments which are committed to the reduction of contaminating industries by subscribing to international agreements. How GHG emissions will be controlled by the implementation of emerging clean technologies from the fourth industrial revolution fostered by governmental strategies and policies is a key factor in the outlining of future policies.

There have been numerous studies, such as (Jie, 2011; Munawer, 2018; Towoju & Ishola, 2020; US EPA, 2022; Watson et al., 1988) and (FAO, 2017; Gordon, 2010; Khair & Majewsky, 2006) developed in the 18th, 19^{th}, and 20th centuries showing that the emissions of gases by vehicle combustion engines contain a high component of residues (nitrogen, oxygen carbon, dioxide, CO, NOx, Sox, hydrocarbons, aldehydes soot, and benz (a)-pyrene (Sassykova et al., 2019) that directly affect global warming, the ozone layer, and human health. However, despite the results of these investigations, the development of the oil industry has driven the consumption of petroleum derivatives in the industrial sector and the consumption of gasoline or diesel-based vehicles to historical high levels pushing for a competition for economic leadership boosted by developed countries since the first industrial revolution. This has also been exacerbated by the latecomers BRICS (Brazil, Russia, India, China, and South Africa) countries led by China and India in the third and fourth technology revolutions. Energy industry information, disclosed by the US Energy Information Administration - EIA concerning to petroleum consumption. By 2018 United States was the first oil consumer with a share of the world total consumption at 21 percent followed by newcomers like China, India, Russia, and Brazil in the 2nd, 3rd, 5^{th}, and 7th positions respectively (EIA, 2021).

The world environmental situation had led governments to agree with targets set for the middle-run to engage their economies, industry, and governments in the most ambitious challenge in modern human history to reduce GHG emissions drastically as stated in the Montreal Protocol, UN Framework Convention on Climate Change, Kyoto Protocol, Paris Agreement, and COP27. However, the socioeconomic market conditions will not allow all countries to meet these goals even though disregarding the effects of global warming will have an effect on the whole planet.

Countries with the best infrastructure to change their internal productive infrastructure conditions and regulations for moving from an oil-reliant industry towards a cleaner electric-based one are more likely to achieve the agreement's goals, increasing the demand for environmental-friendly goods but at the cost of displacing contamination side-effects of the technology shifting out of their borders by the creation of a new demand for raw materials to provide the emergent energy-efficient industries which in most cases are located in middle- or low-income countries.

The new demand for environmental-friendly goods will boost industries in countries with a large capacity to produce those goods like the G7 integrated by Canada and the United States, France, Germany, Italy, United Kingdom, Japan, and the BRICS countries. In the case of BRICS, the nations are facing a narrow challenge to escape from the middle-income trap, focusing their policies on the optimization of industries to take advantage of the new demand for goods and services for the globalization process, to finally achieve the desired developed or high-income economy status.

Before the industrial revolution, an estimated amount of Co2 produced for humanity was around, 0. 5 billion tons (Macknick, 2011). Since then, the developed economies have produced and released enormous amounts of GHGs, mostly Co2, into the atmosphere. This led to unnatural global warming that had not been seen since the 'ice age.' At that time the temperature was around 12˚C. However, with the advent of the industrial revolution, this temperature increased to 14.4˚C (data recorded in 2015). This means a 50 times increase above the average or the equivalent increase rate of the last 21,000 years (Scotese, 2016). As happened in the first industrial revolution, externalities such as increased air contamination levels caused just by the use of coal which was raised without precedent to keep the costs and consequently access to the goods in reach of the demanding economies (Hanlon, 2020). In developing countries, industry and technology which are still at the first stages are limited by internal constraints about how to invest the scarce financial sources that these countries have. Primarily goods from these economies that are meant for world trade are non-value-added goods comprised of agricultural goods and raw materials extracted from mining.

The state of the art environmental conservation is highly worrisome, with the deforestation of native forests for mining for gold, silver, and coltan; the purifying process for these elements is also done on the site which contaminates the water sources due to intensive use of mercury and sulphates as puffier agents for metals (Favas et al., 2011). The proposed way to stop and revert global warming is by setting our hopes on high-efficient technology, but we are heading to an even more complex panorama with new levels of production of new goods and with local policies intended to achieve the technology transition in developed countries pretending that this will reduce the Co2 footprint without seeing that the shift in goods in developed countries is leading to huge environmental damage in developing countries.

1.1.2 Vehicle industry background

The world is committed to a new industry which will represent one of the biggest changes in market dominance in two centuries. The change from fossil fuels and fuel-based engines to electricity and electricity-based engines: Internal combustion Engines (ICE) vs Battery Electric Vehicles (BEV).

Research shows that the indiscriminate use of fossil fuels has caused or accelerated global warming, inducing with this a generalized climate change that affects life's sustainability in the middle run (Huang et al., 2012; Ring et al., 2012). Different international agreements dissuade governments in most of the countries to link their domestic policies with the reduction of Co2 emissions and energy consumption.

One of the most significant polluting fields in industry is transportation due to the high level of dependency on fossil fuels. The US Environmental Protection Agency (EPA) claims that the transportation industry is the main contributor of greenhouse emissions (Figure 1) which are produced by combustion engines found in vehicles, trucks, ships, trains, and airplanes that run on fossil fuels. Petrol makes up more than 90 percent of the fuel used for transportation, mostly in the form of gasoline and diesel (IPCC, 2007).

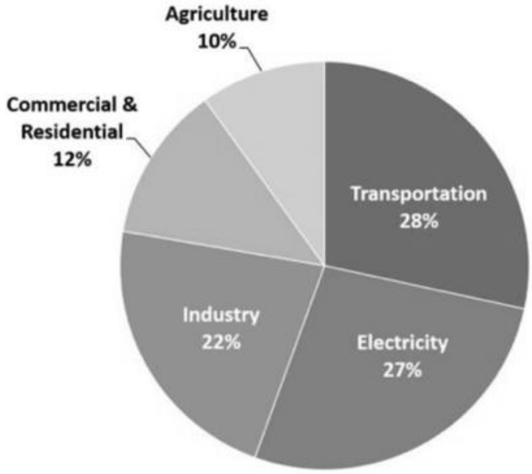


Figure 1 Greenhouse Gas Emission Contributors

Source: US EPA (2021).

Depending on the electric system infrastructure even Battery Electric Vehicles (BEVs), may be contributing to Co2 emissions given the source of energy, which in some countries is powered by thermoelectrical stations which are powered by fossil fuels like coal and diesel thus adding to the primary pollution versus the positive effect of using BEVs for reducing vehicle motion emissions.

Given the current fuel consumption trends, the industry is changing its behavior by fostering the use of electrical vehicles (BEV/EV). The underlying concept behind this new trend is reducing GHG emissions by replacing the current fleet of vehicles using combustion engines with electric engines. However, research shows that this cannot be used at the current juncture to demonstrate the positive effect of the use of BEVs as the main driver for tackling climate change due to GHG emissions.

A relevant fact is how the most industrialized economies of the world are also impacting the environment the most in terms of Co2 emissions (Figure 3). The biggest producers are China, the United States, Europe, India, Russia, and Japan, which are among the top ten emitters accounting for over two-third of annual global greenhouse gas emissions. On other hand, China's energy policies are focused to face a transition from the high dependency on fossil fuels to a more flexible and independent infrastructure by including installations with wind and solar power generation. According to the National Environment Agency NEA these installations were responsible for 14 percent of the electricity generated by 2019 and this percentage grows every year at a rate of 1 percent. This is because of a government scheme with large transfers aimed at fostering clean technologies. This behavior could be explained in part by China's new role in the emergent economies using BEVs placing its economy as the first EV producer in the world but also as the country with the biggest number of BEVs in circulation including public transportation (Qi & Cheng, 2018).

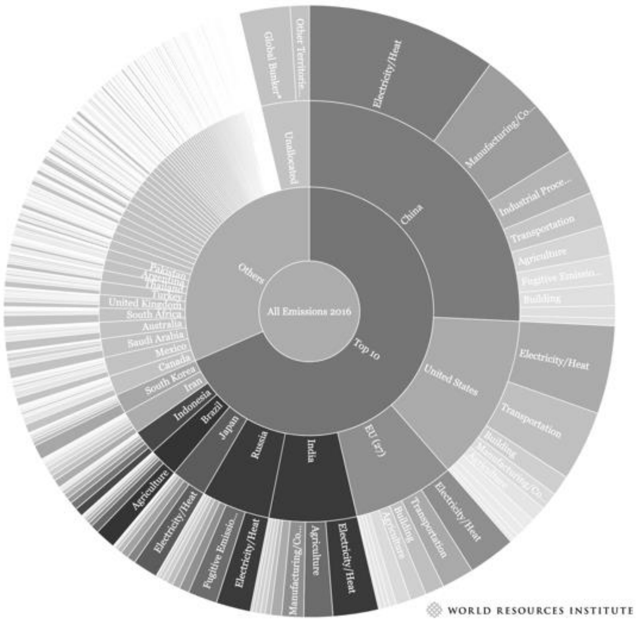


Figure 2 Gas Emissions by Country

Source: World Resources Institute (2021).

Climate change impact is also relevant for understanding the data as a component of industry trends. The top ten countries generate Co2 by providing a major share of power to the electricity and heating fields and also to the transportation industry's emissions -- the second most contaminating field in the United States 1762.2 Mt CO_2e - 3.1 percent, European Union, and Japan 204.6 Mt CO_2e - 0.43 percent, followed by Russia 258.9 Mt CO_2e - 0.54 percent, China: 917 Mt CO_2e -1.93 percent, and India 305.3 Mt CO_2e - 0.64 percent of global GHGs (Ge et al., 2020). The difficulty stems from the fact that there has been an increase in the number of registered automobiles globally during the last several years largely due to an increase in middle-class purchasing power, easier access to financing, and technological advancements in the automobile manufacturing industry that led to lower prices. According to Gakenheimer (1998), vehicle ownership increased by 10 percent which created a disparity with the speed of adapting road infrastructure and technology to control vehicle flows on the roads linking the use of the private vehicles with an associated congestion effect commonly known as traffic jams.

Currently, there are several components in the supply of transport traffic in cities around the world which are characterized by the type of vehicle and its use and can be divided into sectors such as private vehicles or personal use vehicles, cargo vehicles, and public service vehicles.

The transport sector being one of the major sources of pollution, governments are forced to develop strategies where, by implementing technology or the development of policies or regulations the pollution can be significantly reduced with a direct effect on short and long-term GHG emissions.

1.1.3 Developing countries' backgrounds

The TomTom Traffic Index (2019) determines where the world drivers spend the most time on their daily commutes. The ranking published in 2019 evaluated 416 cities in 57 countries on six continents. The Indian city Bangaluru was at first place as the most congested, displacing another Indian city, Mumbai.

Regarding the Latin American region, six large cities in the region were in the top 20 places, two of them - Bogotá and Lima - among the top ten with the most difficulties in travel.

#	World rank	City	Country	Congestion level
1	1	**Moscow region (oblast)**	Russia	**54%** ↓ 5%p
2	2	**Mumbai**	India	**53%** ↓ 12%p
3	3	**Bogota**	Colombia	**53%** ↓ 15%p
4	4	**Manila**	Philippines	**53%** ↓ 18%p
5	5	**Istanbul**	Turkey	**51%** ↓ 4%p
6	6	**Bengaluru**	India	**51%** ↓ 20%p
7	7	**Kyiv**	Ukraine	**51%** ↓ 2%p
8	8	**New Delhi**	India	**47%** ↓ 9%p
9	9	**Novosibirsk**	Russia	**45%** – 0%p
10	10	**Bangkok**	Thailand	**44%** ↓ 9%p

Figure 3 The Tom Tom Traffic Index 2020

Source: Tom Tom (2020).

Colombia's capital Bogotá was first in Latin America with the worst traffic jams in 2020 (Carlier, 2022). In contrast to the traffic congestion in the city during valley hours, Bogota had an average traffic increase of 53 percent during rush hours. The second-worst congested city in the world is Lima, where travel during rush-peak hours takes 42 percent longer than during off-peak hours. The ranking comprises 12 Latin American cities which were evaluated in 2020, 58 percent of the cities (7) are located in Brazil.

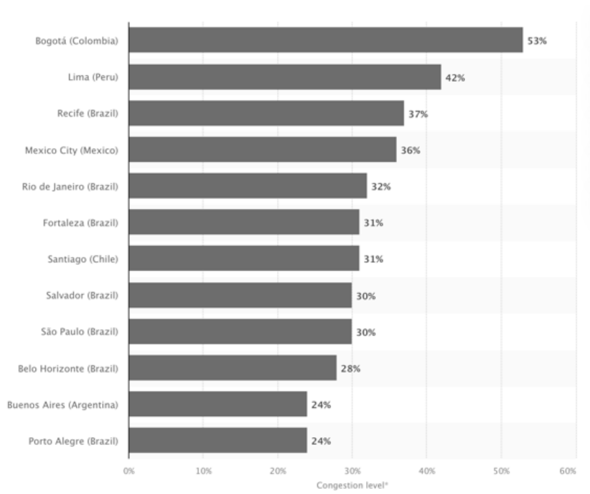


Figure 4 Traffic congestion in Latin America, 2020

Source: Statista (2021).

Every year, INRIX does a study (the INRIX Global Traffic Scorecard) to establish a world ranking that analyzes the sway of traffic jams on six continents, 38 nations, and more than 200 cities. The INRIX Scorecard looks at various factors like the number of hours people lose annually in traffic, the average speed at which they move in the city, and the time they take for short trips. INRIX uses proprietary big data to examine human movement - 500 terabytes of INRIX data from 300 million sources, spanning over 5 million miles of roads, are combined with additional INRIX data sources, such as global parking, fuel, point-of-interest, public transportation, and road weather data. The combined data paints a good picture of urban mobility:

> INRIX collects billions of anonymous data points every day from a diverse set of sources, including connected vehicles, mobile devices, navigation units, fleet vehicles, road and garage infrastructure, and publicly available information on incidents. With coverage on all roads in countries of coverage and lane-by-lane precision, INRIX is the preferred provider of driving and mobility intelligence for leading automakers, businesses, and all levels of government for accurate, real-time, and historical
>
> (INRIX, 2020).

The key results of the INRIX Global Traffic Scorecard related to the present research show that Bogota is the most congested city worldwide moving from the 3rd position in the same ranking in 2017 and under the special conditions developed during the global COVID-19 pandemic (SARS-CoV-2) and against the global trends where lockdowns, quarantines, business restrictions, fostering the use of single passenger vehicles like bicycles and scooters, online classes, and home office policies led the transportation sector to decrease the number of vehicle travel per se. The results show people spent 133 (272 in 2017) hours annually in traffic jams (INRIX, 2020). These results also confirm the traffic trends from the Tom-Tom Traffic Index (2020) which ranked Bogota as the 3rd city in the world with the worst traffic and Statista urban traffic congestion levels 2020. For instance, the Tom-Tom index shows that during rush hour, the average speed in Bogotá was 11 km/h. A driver can anticipate traveling one mile (1.6 kilometers) into the city center at a certain speed during rush hour thanks to an indicator known as the Inner-City Last-Mile Speed. Traffic in only Dublin, Ireland, moves at a slower pace of 6 miles per hour. Traffic in the Colombian capital is well known to locals and visitors, and INRIX's shocking figures show why moving in Bogotá during rush hours may take several hours. This not only affects mobility but also the efficiency of the economy and the air quality index (INRIX, 2020).

2020 Impact Rank(2019)	Urban Area	2020 Hours Lost	YoY Hours Lost	Hours Saved	2020 Last Mile Speed (MPH)	YoY Last Mile Speed	2020 Avg. DVMT
1 (1)	Bogota, Colombia	133	-31%	58	11	22%	-30%
2 (*)	Bucharest, Romania	134	-	-	15	-	-
3 (14)	New York City, USA	100	-28%	40	12	9%	-28%
4 (17)	Moscow, Russia	100	-22%	28	15	0%	-12%**
5 (12)	Philadelphia, PA, USA	94	-34%	48	12	20%	-25%
6 (7)	Paris, France	88	-47%	77	13	30%	-19%
7 (10)	Chicago, IL, USA	86	-40%	59	15	36%	-22%
8 (18)	Quito, Ecuador	87	-40%	57	11	10%	-11%
9 (*)	Zagreb, Croatia	93	-	-	17	-	-
10 (38)	Cali, Colombia	81	-14%	13	12	0%	-6%

Figure 5 INRIX **-** 2020 Global Traffic Scorecard

Source: INRIX (2020).

INRIX is now working on developing algorithms to reduce congestion, the simulation of vehicular traffic for particular scenarios, and estimating the state of the network at a given moment. The Traffic Light System (TLS), which manages more than 1,350 crossings daily in cities in developing nations like Bogotá, uses outdated technology, including present-day timers and halogen illumination. As more units are put into service, the city's carbon footprint will decrease thanks to the LED illumination used in the new Smart Traffic Light System (STLS) and every other component of the complete system that is being deployed.

1.2 Definitions

For the purpose of defining the scope of this research, the first approach is clarifying the underlying traffic conception and the underlying differences between traffic, congestion, transit, and transportation. Both technicians and individuals regularly use the phrase 'congestion' when referring to vehicular traffic. The English Language Oxford dictionary defines congestion as the state of being crowded and full of traffic (Oxford University, 2021a), while traffic means the vehicles that are on a road at a particular time (Oxford University, 2021b). According to the Collins Dictionary, traffic refers to all the vehicles that are moving along the roads in a particular area. The flow of people or vehicles along transportation channels is what the American Heritage Dictionary and the Cambridge Dictionary define as 'vehicular traffic.' In this study this is referred to as the movement of vehicles along roads as well as that of aircraft, trains, and ships:

> …normally the average speed monotonically drops as the density increases leading, eventually, to traffic congestion and jamming.
>
> (Schadschneider et al., 2011).

Traffic jams or congestion or generally speaking 'a jam' is a situation in which there are numerous moving cars, each of which moves slowly and erratically. These definitions are arbitrary and not specific enough when it comes to vehicular traffic. According to Schadschneider et al. (2010) in vehicular traffic, typically the average speed monotonically decreases as the density increases, eventually leading to traffic congestion and jamming. These definitions appear to diverge from the common perception that is closely linked with traffic jams, heavy traffic, or traffic congestion (Schadschneider et al., 2010). Furthermore, (Kerner, 2009) maintains that, 'vehicular traffic is an exceedingly complicated dynamic process connected with the spatiotemporal behaviour of many-particle systems.' Vehicular complexity results from non-linear interactions between three main dynamic processes:

(i) travel decision behavior, which determines demand
(ii) routing of vehicles in a traffic network
(iii) traffic congestion occurrence within the network (Kerner, 2009).

This study approaches the traffic phenomena by differentiating the key terms related to the different vehicular interactions with roads and time and calls this spatiotemporal phenomenon handling the concepts of traffic flows, heavy traffic, traffic breakdown, and traffic congestion:

> Traffic flow phenomena are associated with a complex dynamic behaviour of spatiotemporal patterns. The term spatiotemporal reflects the empirical evidence that occurs in space and time. Therefore, only through a spatiotemporal analysis of real measured traffic data, the understanding of features of real traffic is possible. In other words, spatiotemporal features of traffic can only be found, if variables are measured in real in space and time
>
> (Kerner, 2009).

Common sense among citizens has established a relation between 'traffic' in terms of transit and transportation with a high level or volume of vehicles. However, findings in literature show that more clarity is necessary when 'traffic' is used for defining the action developed for vehicles for moving along a determined space and timeslot. Therefore, traffic refers to the number of vehicles, space, and time which determine the Peak Hour Factor (PHF) (University of Idaho, 2020). This definition does not imply that 'traffic' by itself refers to heavy traffic, slow traffic, or a traffic jam. The relation between the number of vehicles, space, and time refer to the 'flow' of vehicular elements. Hence, an uninterrupted flow is the iteration of vehicles on a road regulated by rules and the drivers' behavior:

> *Vehicle-vehicle interactions and interactions between cars and the road govern flow. For instance, the unbroken flow of traffic on an interstate highway is provided by the automobiles.*
>
> (University of Idaho, 2020)

The second type of flow is interrupted flow, which is managed by the infrastructure for traffic control. 'Interrupted flow is flow managed by an external mechanism, such as a traffic signal' (University of Idaho, 2020). An uninterrupted flow is mainly governed by vehicle-to-vehicle and vehicle-to-road interactions, whereas in an interrupted flow the main source of regulation of the flow depends on vehicle-to-signals interactions (Donges, 1999).

There are two derivate flow conditions based on PHF. The first is the average speed at which vehicles will move along a road when the density of other vehicles is low. Speed is characterized by low density. Drivers no longer worry about other automobiles in this situation (Tarko et al., 2019). As a result, driving is done at speeds that are consistent with the specifications of the vehicles, the state of the road, and the established speed limit. The second flow condition is Jam Density, which refers to situations where excessively high densities can completely stop traffic on a road (Morbidi et al., 2014).

The optimal speed limit for vehicles is outlined by the best engine performance with less fuel consumption. This relation is contained in the cruising speed which is the speed at which a vehicle travels most efficiently with respect to fuel consumption (Collins English Dictionary, 2020). This is also known by techniques such as eco-drive and hypermiling (Zaharia & Clenci, 2013).

Intelligent Transportation Systems (ITS) are sophisticated software programs created to provide cutting-edge services connected to various forms of transportation and traffic management. By providing users with additional information, these applications enable drivers to use transportation networks more wisely and, in theory, increase security. In other words, ITS[1] refers to all programs that work to assure safety, traffic management, driving assistance, and a variety of other functions.

The technology used in ITS is extremely diverse, as are its applications. These include management systems like those in charge of vehicle navigation, traffic signal control systems, variable message signs, automatic license plate recognition, high-speed cameras for monitoring, and many other systems that all share the trait of being control systems with some intelligence. Another kind of application that fits into ITS is one that gathers data in real-time and provides feedback based on a variety of readings or sources, such as weather data, information about the state of the roads and traffic, bridge de-icing systems as an example of an application related to infrastructure, parking guidance systems, or any other vehicle system that needs to make decisions based on reading data. Systems will be able to adjust to the past in the future and make choices that are consistent with predicted methods.

In the United States, there is a research and development program that has to do with ITS (https://www.its.dot.gov) which can serve as an example of the type of systems and

[1] ITS is any transport system that allows the scientific and automated operation and management of the transport system, and the improvement of the efficiency and safety of transport through the development and use of means of transport and transport facilities with high technology and transportation information, including electronic controls and communications (MOLIT, 2021).

applications that are integrated into this very broad technological framework. Making a list of all the systems and developments that can be included in ITS is a very intense job, so these brushstrokes serve to understand what we mean when we talk about Intelligent Transportation Systems.

Communications Vehicle to Vehicle (V2V) and/or Vehicle to Infrastructure (V2I) to increase safety and Car2x or V2X communications, aim to improve the coexistence between cars and the environment through which they circulate and communicate with the rest of the vehicles in the environment to make them 'notice' their presence, and consequently to circulate with greater accuracy and prudence (Miller, 2008).

Traffic, public transport, and freight fleet statistics are accessible today from many sources which can be used for improving mobility in general. In addition, it is possible to think about introducing data which corresponds to our personal vehicles in the 'network' thus weaving an even greater network of mobility data that will allow improving aspects such as congestion, which can only be achieved because of it. The objective is to have transport management systems that are efficient, safe, and respectful of the environment.

The aim of the Dynamic Applications for Mobility is investigating technologies that can facilitate the quickest, most effective, and environmentally friendly transportation of people and products. This can be accomplished by moving the aforementioned items and persons between different modes of transportation (such as a car, train, ship, or plane) or between different routes using a Mobility as a Service (MaaS) platform (Chang et al., 2015). The concept is that in the future it will be feasible to move people or commodities from point A to point B, and that both the route and the mode of transportation can be changed automatically along the way to get them there as quickly and efficiently as possible.

Time management on the road is an application of the current weather and future weather predictions. Thanks to data collected by the vehicles in these current weather conditions, it will be possible to take decisions about the route, the weather conditions, and driving in the future.

Applications for the environment that use real-time information synthesis: These are known as Real-Time Information Synthesis, which are entirely focused on the environment and deal with how anonymous data on tailpipe emissions can be combined with other environmental data so that transport managers can manage the transportation network taking into account the environmental impact it leads to.

The Smart Traffic Light (STL) system is meant to improve traffic conditions using a holistic vision: the data from cars, driving habits, and other variables which can be included in a global system that is equipped with dozens of applications connected with cars and mobile or city sensors which are capable of finding the best solution for traffic improvement, increasing efficiency, and reducing GHG emissions.

Technology along with a policy package is being implemented in some developing countries based on an intelligent traffic control system with traffic lights, which allows a permanent connection via a protocol of communications V2I[2] or V2V[3], and can thus collect information both from the vehicles on the roads, and from historical databases that contain time tables, peak hours, off-peak hours, usage trends, national and local regulations, as well as information posted on the cloud provided by various traffic management applications such as Waze, Google Maps, and Kakao Maps. All this information is used by a traffic light to be able to establish the best response time and prioritize the green and red signals for vehicles, pedestrians, and bicycles.

The final effect of traffic optimization is reflected in the shorter time of use of the vehicles, calculated in hours of use/day and in the respective reduction of fuel consumption. By reducing this consumption, combustion is reduced and so are GHG emissions. The purpose of the Smart Traffic Light (STL) system or STLS is to make the current technology-based ICE most energy-efficient with regard to the technology designed and developed with the aim of reducing GHG emissions and disincentivizing the commercialization of new goods.

By increasing the efficiency of traffic flows on the roads it will be possible for drivers to drive under cruising speed, achieving higher speeds of around 80-100 km/h which provides efficiency in terms of time/saving-money/saving thus reducing fuel consumption in a range of the 20-50 percent in most cases (Zaharia & Clenci, 2013).

In the end fuel consumption is the ratio that determines the terms of the environmental impact and the efficiency of the proposal (Rakha & Ding, 2003). This proposal conviction is walking in a direction where the world can reduce consumption by optimizing the current energy use. We are not going to achieve any goal if we keep the same production trend.

Currently, China and India are ready to supply most of the goods from the new technology wave, but at a high cost for humanity.

Our decision as rational consumers is to decide whether we want a world with cutting-edge-energy-efficient technology with greenhouse gases or a world with consumption in a smart way directing the technology to improve Co2 absorption using biotechnology or increasing reforestation and reducing desertification, conserving the oceans and seas, and reutilizing the GHGs. Currently, energy-efficient is a synonym for more devices that consume less energy, but in the end, they are, actually more devices. The goal of climate change is not just to turn energy-efficient; it is to reduce energy consumption.

1.3 Motivation

The current study aims to address low-income governments' financial constraints which prevent them from investing in digital transformation or smartification.

The study implemented a SLR to identify the state of the art in smart technologies, IoT, and AI related to STL to find a correlation and scientific evidence between traffic at road intersections and the increase in GHG emissions.

However, in addition to identifying and providing scientific evidence, the research also evaluated the technologies from the perspective of traffic management experts and practitioners, providing a high degree of reliability for the outcomes. Thus, both decision-makers and policymakers can base their policies on the present study to determine that the Inductive Loop Sensor is the best smart technology for improving traffic flows at intersections and feeding traffic lights with real-time information, despite the high cost of the initial investment, which can be understood as a high cost in the short-run but with benefits in terms of efficiency in the long run.

1.4 Problem statement

Although the traffic management systems in the world have experienced important developments based on automatization and the development of the adaptive control in ITS (Alrawi, 2017) in the last 20 years, the traffic and transportation systems still experience limitations in effective traffic management which affects the cities' performance in terms of economic losses and contamination (Dubey & Borkar, 2015). These lead the cities to deal with vehicular traffic congestion and the side-noxious environmental effects as also the increase in fuel consumption of GHG -Co2 (Al-Turki et al., 2020). Emissions have been a complex phenomenon leading to city management problems in the last few years (Salazar-Cabrera et al., 2020). These include:

- According to the UN the densification of major cities in the world was around 55 percent when by 2018 and is projected to reach an average of 68 percent by 2050.
- Budget restrictions by city or national governments to adopt or upgrade cities' transportation infrastructure in terms of housing, roads, networks, and facilities (Hooda et al., 2016a).
- Increasing pressure on the transportation system is accompanied by consumer behavior which tends to improve the resources efficiently and increase the means of transportation and consequently the volume of vehicles by 20 percent per year with their respective emissions (Hooda et al., 2016b).
- In a scenario of traffic congestion, one of the most critical and determinant spots are intersections (Santamaría & Fernando, 2014).

The transport sector’s fuel consumption accounts for 70 percent of the total oil consumption. According to Al-Turki et al. (2020), this consumption leads to a proportional amount of GHG-Co2 emissions being released into the environment. Al-Turki et al. (2021) estimated that these emissions had reached 560 million pounds of Co2 by 2011 in Dhahran, Saudi Arabia.

Variations in the urban population ratios in the world's biggest cities turn into an increase in passengers (Salazar-Cabrera et al., 2020). This is reflected in the transportation demand primarily in developed countries which is satisfied by the existing transportation infrastructure and/or the public transportation system but, in most cases, it is very likely that cities need to experiment with a reduced capacity to meet the transportation demands due to lack of financial resources, planning or technology penetration like Massive Transportation Systems (MTS) comprised of subways, monorails, and trains. Furthermore, improving an old city's infrastructure implies upgrading from narrow roads to a highway infrastructure for which it is necessary to demolish the existing construction which in very old city areas implies destroying or putting in danger national or world heritage. This scenario leads consumers to optimize the scarce resources that they have: time and money.

Based on consumer maximization behavior, the rationale for satisfying transportation needs is accessing an affordable means of transportation under ownership that increases a feeling of autonomy among consumers and their families. This aggregated behavior in the market with consumers replicating the same rationale will increase the means of transportation (cars, motorbikes, scooters, bicycles, hybrids) and consequently the volume of vehicles. Thus, the demand for infrastructure increases by the differential between the variations in the volume of vehicles and the square meters on the roads (which remains static). With these new conditions, cities in developing countries turn crowded with diverse and affordable vehicles and their pollutants. This is evidenced in vehicle composition variations, which show an increase in motorbike sales (Statista, 2022). In a situation of more vehicles and more traffic, arises the problem of fuel consumption and efficiency per travel, which is reduced by the pre-existing traffic congestion.

Vehicles are designed to be efficient in a so-called hypermiling, which is a constant top speed with the lowest energy (fuel) consumption. Currently, that speed is calculated at around 60-90 km/h. All vehicles moving under this speed are consuming more energy and in the case of the Internal Combustion Engine Vehicles which are fossil fuel-based, with more energy consumption they are also emitting more Co2 and GHG-related emissions (Zaharia & Clenci, 2013).

Statistical evidence points out that the transport segment is one of the biggest contributors of pollutant emanations comprised mostly of GHG and Co2 from urban traffic congestion at road intersections. This has become a pressing challenge for reversing climate change effects (Berrittella et al., 2011).

As vehicle density increases, traffic flows are reduced in terms of flow and density. This is a determinant factor in the levels of energy consumption in the mechanics of fossil-fuel-based/ Internal Combustion Engine (ICE) vehicles that lead to an exacerbation of the problem due to the contaminating additives expelled with the gas emissions such as lead, soot, sulphur, nitrous oxide, and hydrofluorocarbon (Alrawi, 2017).

1.5 Research objective

This research's objective is exploring the traffic correlations at intersections with vehicular fuel consumption and consequently with GHG-Co2 emissions. Its aim is identifying the current STLS hardware enabler technologies in scientific literature to provide an expert evaluation and response under MCDA-AHP as a key element for decision/policymakers. Despite the algorithms' high relevance in STLS' performance, the present research does not evaluate this technology as an AHP layer component.

1.6 Research questions

RQ1: Does a relationship exist between vehicular traffic congestion levels at intersections and increasing GHG-Co2 emissions?

RQ2: Based on the SLR identification of STL system technologies, which of these technologies are the most suitable to be implemented as an element of the traffic infrastructure at intersections (traffic lights) under budget constraints, targeting improving traffic flows and reducing GHG-Co2 emissions?

1.7 Research methodology

This research uses a systematic literature review (SLR) to evaluate the 4IR technologies proposed for the Smart Traffic Lights (STL) system. SLT also addresses the first research question by collecting all the evidence from scientific literature which lays the foundations for the correlation between traffic congestion at road intersections and the increasing levels of pollutant emissions.

SLR was conducted in five stages according to progressive query string improvements. The first string (intelligent traffic system, traffic, GHG) identified 52 related documents of which six met the STL established criteria. The second string (smart traffic system, traffic) identified 18 related documents of which not one met the STL established criteria. The third string (STL, traffic) identified 22 related documents of which five met the STL established criteria. The fourth string (STL, traffic, SLR), identified 19 related documents of which six met the STL established criteria. The fifth and last string (intelligent traffic light, GHG, AHP), identified 14 related documents of which seven met the STL established criteria. The SLR criteria for this methodology was based on Prisma2020 as follows: relevance, availability, file access, year of scoring, and citations ratio (Page et al., 2021a).

A second methodology is proposed for evaluating the technologies identified in SLR for addressing the second research question and the thesis' aim of evaluating the technologies' feasibility and suitability at road intersections for governments with budget constraints. The methodology developed for this is the Analytic Hierarchy Process (AHP), methodology that belongs to a Multicriteria Decision Analysis (MCDA) subject in Operations Research.

The current study uses the AHP technique created by Professor Thomas Saaty to address a number of specific issues in traffic-sustainable decision-making processes. AHP is a multicriteria decision-making technique that helps in choosing between various options based on a number of selection criteria or variables that are typically hierarchical and frequently at odds with one another.

The objective, criteria, and sub-criteria (if appropriate) form the hierarchical structure, followed by alternatives to compare this structure. A key component of this process is ensuring that the selection criteria and sub-criteria are carefully chosen, well defined, and mutually exclusive.

One of the keys to the success of this method is the Saaty Fundamental Scale, which is used for performing the paired comparison (Equal Importance, Weak Importance, Moderate/Weak Importance of One over Another, Moderate Plus Importance, Essential or Strong Importance, Strong Plus Importance, Demonstrated Importance, Very, Very Strong Importance, and Absolute Importance). Without diving into mathematical specifics, it should be mentioned that the method's ability to evaluate the consistency of our choice to validate it as the best alternative is one of its merits. The AHP process can be summarized in six steps:

- Defining the problem: Once the technologies based on SLR are identified and classified, AHP's objective is defined under the limits and descriptions of the research questions established for this research.

- Determining evaluation criteria: The criteria for STLS in this research are divided into three dimensions:

i. STLS Performance.
ii. STLS Costs.
iii. Traffic Emissions.

For STLS Functions the following were determined: Intersection Delays, Stopped Delays, Deceleration Delays, Travel Time, and Queue Length. For STLS Costs the following were determined: Construction Costs, Maintenance Costs, and Operation Costs. For STLS Emissions the following were determined: Fuel Consumption, Co2 Emissions, Construction Congestion as a criterion set:

1. Determine AHP hierarchy: The STLS hierarchy was determined.
2. Normalize the comparison matrix pairwise.
3. Calculate priority vectors.
4. Calculate the consistency ratio (Alemdar et al., 2021a).
5. Results.

1.8 Research contribution

The GHG Co2 footprint and carbon neutrality control and reduction policies are the greatest agreement in the history of humanity. Any action aimed at evaluating the current sources of pollutant emissions is going to have a multiplication effect in the near future on our planet and will be decisive in the survival of human beings as a species on the planet. Policymakers and decision-makers need scientifical and reliable information that provides the best probabilities to achieve the goals set in the Paris Agreements, COP26, and the Sustainable Development Goals (SDGs). As the world is entering a new phase in history after facing the worst COVID-19 pandemic in recent years, the economic effects on the most vulnerable economies are increasing with inequalities and poverty. Cities and governments in developing countries will be able to develop national plans for meeting the environmental agreements by investing large amounts of money in a transition from contaminating and pollutant technologies to green and clean ones generating a considerable reduction of emissions. The critical part of these agreements is how middle and low-income nations and governments will leverage the technological transition when the investment priorities are focused on solving structural problems like nutrition, health, education, and conflict, relegating environmental concerns to the last level of public investments. Thus, identifying the most efficient technologies which are feasible to implement under these budget restrictions for solving current major problems such as traffic congestion and with a proven positive impact on pollutant emission reductions will determine the success and continuity of these policies and meeting the global agenda in terms of climate change.

1.9 Research novelty

The present research identifies STLS technologies with an impact on GHG reduction as a positive spillover of traffic congestion optimization. The research methodology is split in two methodologies: A Systematic Literature Review (SLR) and an Analytic Hierarchy Process (AHP).

SLR dives into two critical objectives in the research, first collecting and extracting the technologies implemented in smart traffic control from the selected scientific literature, filtering these technologies according to the traffic management infrastructure where they have been implemented and selecting those related solely to smart traffic light systems.

These outcomes feed into the AHP process by providing alternatives for the evaluation methodology.

The second objective is identifying and collecting evidence from the experiments that provide a direct relation between the employment of smart traffic light system technologies and GHG emissions reduction.

The AHP process engages with GHG-Co2 emissions reduction by improving traffic flows at intersections with optimal implementation of STLS technologies as an element of the traffic infrastructure under budget constraints by establishing 11 STLS-related criteria. These are evaluated pairwise with 11 STLS technology alternatives.

AHP provides a novel insight into the STLS evaluation by including not just technology performance criteria, but also costs and emissions criteria.

1.10 Outline

The rest of this thesis is structured as follows. Chapter 2 presents a literature review which addresses STL technologies' identification and evidence collection to support the thesis related to the correlation between traffic congestion at intersections and the increase in noxious emissions. Chapter 3 describes the development of both SLR and AHP methodologies.

Chapter 4 introduce the datasets obtained from the survey questions and the output data differentiated first by the dimensions layer, criteria layer, and the alternatives layer and finally summarizes the data and compares the results for criteria versus alternatives.

Chapter 5 synthesizes all the data and the AHP methodology and presents the results and the relations among efficiency, costs, and emissions by comparing the statistical data obtained from AHP.

Chapter 6 presents the findings, conclusion, and implications for meeting the SDGs and climate change agreements while also highlighting the best combination of technologies and their effect on the cost and efficiency dimensions. Figure 6 illustrates the structure and interaction of methodologies in the present research.

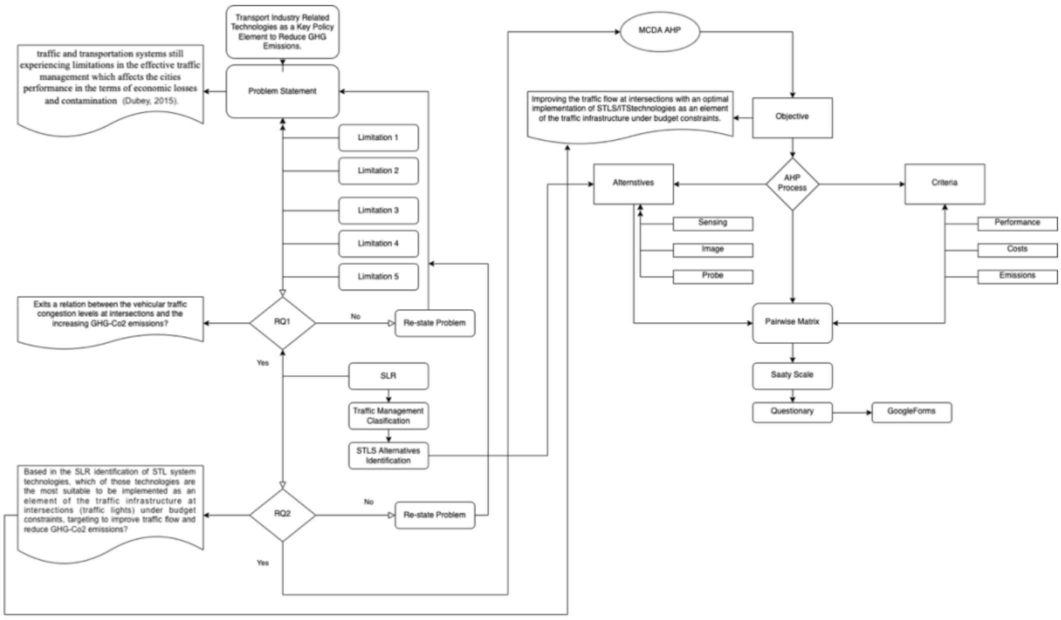


Figure 6 Research framework

Source: (Author development)

Chapter 2. Literature Review

Traffic congestion (jams) is a leading problem in cities whether they were built with old or modern road infrastructure. There are many factors that affect the volume of vehicles on the roads, one of which is the massive urbanization in the cities and the expansion of the metropolitan areas. Another reason is the lack of effective massive transportation systems to compete with private vehicles. Production too plays a key role in a demand for vehicles by offering very low-priced vehicles and finally policies in each city may affect the performance of the traffic according to restrictions related to them. Road congestion results in longer average vehicle wait time, more fuel used, and more air pollution, which costs the nations socially and economically. Thus, one of the main issues in cities is traffic congestion.

The present literature review evaluates the traffic optimization methods with more impact on GHG emissions reduction implemented under specific models for improving the efficiency of STLS at road intersections. Currently, emerging nations employ a time-based traffic signaling system, which includes a set amount of time at each junction. Numerous studies have been done to design an adaptable traffic system.

Generally, the scientific evidence points out that most of the GHG contribution deposited in the environment is sourced from the transportation sector with the current market share coming from power trains (US EPA, 2021). As the world trend is underlined by a constant increase in vehicle ownership Gan et al. (2020) explain that most of the research related to traffic congestion is focused on efficiency variables such as time, speed, and frequency. The present research approaches traffic congestion improvement technologies from an environmental perspective which evaluates traffic interruptions and the implementation of STL technologies for travel enhancement mostly focused on road intersections.

As explained by Alrawi (2017) with a future emissions estimation model, 35.2 percent of the emissions from vehicles are produced in traffic conditions. The model is evaluated with regression equations applied to the selected datasets (Alrawi, 2017).

The impact of AI (artificial intelligence) based in sensing data technology provides proof of how the adoption of these technologies became the main driver for developing traffic management technologies comprising the sensing technology (hardware) but also including algorithms (software) and methods for the data management as in Kabalisa and Altmann (2021).

The findings from the SLR review show that the most implemented technology in traffic congestion reduction with STL is the vehicular ad-hoc network or VANET. VANET's ad hoc nature distinguishes it from other types of vehicle networks, such as those formed between the different sensors that modern automobiles have (parking sensors, rain, braking, speedometers, gyroscopes, GPS) and it primarily focuses on providing information to the driver. Due to this, VANET has special characteristics in aspects such as throughput, reliability, node speed, and bandwidth utilization compared to other wireless networks.

Other approaches are delay-tolerant applications (Zhao & Cao, 2008). For instance, apps that provide internet connectivity for commercialized applications to provide advertisements for local stores, meeting schedules in conference rooms, and information concerning adjacent available parking spaces.

To meet delay requests of all applications, traffic data contains highly significant data that must be discovered and properly exploited. To clear traffic for emergency vehicles and reduce congestion, traffic data may also be usefully employed to calculate real-time traffic flows and dynamically regulating traffic lights. In a VANET environment, a fuzzy priority-based intelligent traffic congestion control and emergency vehicle management system is therefore the first choice provided (ITCC). To increase safety and highway capacity without the need for new road construction, Varaiya (1993) presented an Intelligent Vehicle/Highway System (IVHS) that blends control, communication, and computing technologies.

Chen et al. (2006) makes a similar suggestion. They describe a WSN-based Intelligent Transport System (WITS), along with specifics on how WSN features solve the challenges that traditional ITS confront in receiving and disseminating information. They created hardware and software for the WITS node and suggested techniques for optimizing individual intersections and the whole traffic network. They advocate using a solar cell to power the sensor node, easing the problem of low battery power. Due to the extremely mobile and sometimes interrupted nature of vehicle ad hoc networks, the transmission of data might be complicated.

Guerrero-Ibáñez et al. (2018), underline the issues associated with transport systems in modern societies like traffic jams, contamination, and safety and offer a thorough analysis of how sensing devices might be used to create greener Intelligent Transportation Systems (ITS) to solve these issues. Both types of sensors, known as in-vehicle and in-road sensors, are essential parts of the ITS data collection architecture and can be found in cars. The six categories of in-vehicle sensors are safety sensors, diagnostic sensors, convenience sensors, environmental monitoring sensors, driving monitoring sensors, and traffic monitoring sensors. Based on where they are used, in-road sensors are divided into two categories: intrusive sensors and non-invasive sensors. The authors contrasted the advantages and disadvantages of various sensor types. They analyzed the current state of sensor technology integration with transportation systems and offered suggestions for the future (Guerrero-Ibáñez et al., 2018).

Skordylis and Trigoni (2011) built an ambient traffic monitoring system that shares bandwidth with several VANET applications in an effort to reduce traffic congestion and pollution. They created two effective processes for gathering and sharing data: the delay-bounded minimal cost forwarding (D-MinCost) and the delay-bounded greedy forwarding

(D-Greedy) protocols, which work together to cut down on communication while still satisfying user-specified delay-sensitive requirements.

Chapter 3. Data and Methodology

The present research uses two methodologies: A Systematic Literature Review (SLR) and an Analytic Hierarchy Process (AHP).

3.1 Systematic Literature Review (SLR)

SLR was developed using preferred reporting items of systematic reviews and meta-analyses under the PRISMA2020 model as a reviewing methodology, but slightly modified to match specific requirements of the research as it is enough for identifying architectures, frameworks, technologies, algorithms, and simulations/simulators in the area of Smart Traffic Light Systems (STLS) and their related technologies with GHG emissions from vehicles in traffic conditions, mostly at road intersections. As STLS is a new, constantly growing and changing technology it is very important to determine the big picture of all related and interconnected technologies and normalize terms that are ambiguously used in different research but with the same significance or aim.

A specific kind of literature review known as an SLR compiles and critically evaluates numerous studies or research papers using a methodical methodology. There are multiple types of literature reviews, but not all of them can be described as systematic. The SLR methodology is a systematic search method to review research literature and prepare complete and rigorous scientific papers review following the steps:

1. Define the search question also including the pertinent keywords with synonymous expressions as recommended by Kabalisa.
2. Specify the requirements for inclusion and exclusion. The research establishes what information interests' people and what does not. Before beginning a search, these criteria are defined a priori (Mubarkoot & Altmann, 2021).

3. Select resources: Choose the sources of information that will be used for the search from all those available (Mubarkoot & Altmann, 2021).
4. Set the query. It is vital to translate the search query into a query or question that the search engine can understand because many sources of information are automatic and rely on search engines for access.
5. Conduct the search and only keep the data that satisfies the requirements; using the suggested query, we apply the inclusion and exclusion criteria to all the data provided by the various information sources.
6. Finally, read the information and draw conclusions.

3.1.1 Journal search and indexing databases

The selection of the search database service was done to get the first order and second order information sources to find the dependability of the literature review's outputs and their impact on the research. Google Academic, Web of Science, and Scopus, the most popular services for scientific information and the recommended instruments for research evaluations are compared in this study.

According to Martin-Martin et al. (2018) there are differences between research services. This research services as Google Scholar, Web Of Science or Scopus are based on a scient-metric analysis of 2,448,055 citations to 2,299 highly-cited works (Martín-Martín et al., 2018; (Mubarkoot & Altmann, 2021). Simple numerical evidence derived from a qualitative analysis revealed that Google Scholar consistently had the highest percentage of citations across all fields (93 percent–96 percent), well outpacing Scopus (35 percent–77 percent) and Web of Science (27 percent–73 percent); 95 percent of the citations from Web of Science and 92 percent from Scopus were found using Google Scholar. A majority of the citations discovered by Google Scholar (48 percent-65 percent) came from sources other than journals, including theses, books, conference papers, and unpublished materials (Figure 7).

Table 2 Percentage of Citations

	% GS (all cit.)	% WoS (all cit.)	% Scopus (all cit.)	% WoS cit. in GS	% Scopus cit. in GS	% WoS cit. in Scopus
Overall	94	52	60	95	92	93
Humanities, Literature & Arts	93	27	36	88	84	83
Social Sciences	94	3	43	93	89	89
Business, Economics & Management	96	28	35	93	92	89
Engineering & Computer Science	93	52	63	94	90	94
Physics & Mathematics	96	59	64	97	94	94
Health & Medial Sciences	94	54	62	95	91	93
Life Sciences & Earth Sciences	95	62	67	96	93	95
Chemical & Material Sciences	94	73	77	95	94	96

Source: Martín-Martín et al. (2019).

When compared to the sources that were already in Scopus or Web of Science, the percentage of documents that were not in English ranged from 19 percent to 38 percent (Martín-Martín et al., 2018). Even though many authors are oriented towards using academical database sets as Scopus, Web of Science, and Science Direct based on frequency of use as an indicator (Kabalisa & Altmann, 2021), for the present research a quantitative approach is presented to justify the inclusion of Google Scholar. The primary findings were first assessed by determining whether there were any topical variations in the number of citations overlaps between Google Scholar, Web of Science, and Scopus in the citations that they located in academic work. According to Martin-Martin et al. (2018), the three databases collectively discovered 46.9 percent of all citations (Figure 7). A majority of the citations, including most of the citations discovered by Web of Science and Scopus, were found using Google Scholar. In contrast, Web of Science and/or Scopus, rather than Google Scholar, only found 6 percent of all the citations. Google Scholar and Scopus (7.7 percent), Google Scholar and Web of Science (2.5 percent), and other search engines discovered an extra 10.2 percent of all the citations; 36.9 percent of all the citations were only discovered using Google Scholar (Martín-Martín et al., 2018).

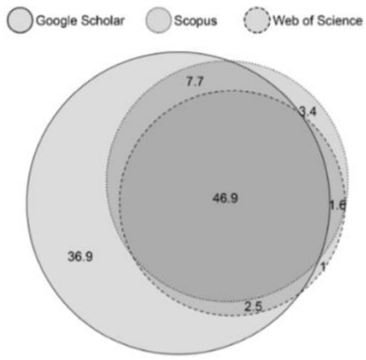


Figure 7 Citation Overlapping
Source: Martín-Martín et al. (2018).

Further it was determined if the citation documents that only Google Scholar found were of a different category than non-unique Google Scholar citations. Although journal articles were still the most common type of documents, all subject areas except health and medical sciences (48 percent), had more than 50 percent other types of papers that Google Scholar threw up. However, Prins et al. (2016) caution against using Google Scholar in place of Web of Science or Scopus for citation evaluations.

The inclusion of lower-quality citation documents may lessen the extent to which citation counts accurately reflect the academic effect, hence it cannot be believed that Google Scholar's highest citation counts are always higher than Web of Science and Scopus. The impact on education, for instance, may be reflected in some of the citations from masters' theses. Consequently, based on the assessment type to be used, it may be essential to eliminate some citation kinds from the citation count (Prins et al., 2016). The aforesaid is not conclusive for all the programs due to the Prins scope for social sciences programs and the specific scope of the research. More research is needed to arrive at Martin-Martin et al.'s findings related to the field of natural sciences and engineering, despite the evidence from the Spearman Coefficient Correlation by measuring the correlation between Google Scholar and Scopus as a random variable (Appendix 1). The Spearman Coefficient Correlation was implemented to evaluate Google Scholar and Web of Science as random variables (Appendix 2).

In both the approaches, the correlation shows that more citations were found in Google Scholar. With the present evidence related to the Citation Overlap and Spearman

Coefficient Correlation, the search database platform for conducting the literature review is limited to Google Scholar which in compared research demonstrates that it contains a high and a representative quantity of journal papers and citations which overlap with Scopus and Web of Science.

3.1.2 SLR Methodology

A Critical Appraised Topic (CAT) was used as the first methodology to approach the research questions. CAT is a literature review methodology that includes a summary of the evidence on a particular topic, typically a succinct summary of a search and critical appraisal of the literature related to a focused research question. In this research it addresses RQ1. This summary of evidence should be kept in an easily accessible location so that it can be used for making research pronouncements. This is not as thorough as a Systematic Literature Review (SLR), which compiles the strongest available data on a subject and applies several criteria to filter the results.

Generally, CAT is employed as a single evaluated study, but more than one method may be included as is the case in the present research due to the nature of the two research questions which are related to specific fields of study: GHG emissions and traffic congestion. The evaluated fields for the CAT literature review are year of issue, name of the journal, and related research question. When done from a single article, the result is a critical appraisal document, which is a way of collecting the evaluations because they are topic centered. Therefore, the criteria query implemented in Google Scholar comprises the key terms: *Emissions, emitted, gases, combustion engines, engines, GHG, and environment*. These key terms were incorporated as a query with the goal of obtaining the closest-topic-related articles from scientific journals to comprise the inputs for the CAT query string: *Gases emitted by combustion engines for vehicles contain a high component of residues that directly affect global warming.*

The plain query found a mean of 18.400 results. The cleaning process incorporated in the second stage used a filter which was determined by the second criterion which is the issuance interval. In this case, it is important to define a milestone that allows one to determine the beginning of the interval.

As the research is related to technologies like Artificial Intelligence, Machine Learning, and the Internet of Things implemented in the Smart Traffic Light Systems and this is a relatively new technology the developments intended for improving the reliability start in 2012 when the research institute Traffic21 in the Carnegie Melon University developed an adaptative signal control in an attempt to reduce GHG emissions in Pittsburg (Rubinstein, 2012).

The date from the Traffic21-Pitsburg project determines the beginning of the range for our interval which ranks till the year of the research literature review elaboration in 2020. Once the query with the issuance interval was used, the outputs reduced to 17.000 results which is 7.6 percent less. Google Scholar arranged the information by defect according to the level of relevance. Once the results were obtained the third criterion was implemented. All these criteria include the 21 results to be evaluated by the CAT literature review.

From a total of 20 results, three books and zero papers were obtained in the CAT literature review after the execution of the queries and selection of the papers. Under SLR this number was reduced to 14 papers, and it was evidenced that there was a need to execute a new query with more delimited key terms: ITS, Traffic, GHG.

SLR criteria were tightened to fit more closely with the research questions instead of the topic of the research. One of these changes is expressed in terms of the interval of the paper’s issuance. This change responds to the need to fit the technical requirements including the emerging technologies from the Fourth Digital Revolution which are mostly accepted as IoT, LoRa, AI, Big Data, Radar, Machine Learning AR, VR, Lidar, V2V, V2I, V2X to ensure the pertinence in time for STLS/ITS.

The most accurate period for including papers comes along with the Fourth Digital Revolution which is mostly accepted to start in 2015 (Schwab, 2015). This means that the papers between 2015 and 2021 will be preferable. Identified by the continuous query depurating process the key paper PRISMA2020 was originally aimed at health sciences and medical reports but it also contains essential reflections for a cross-discipline research base in the identification, screening, eligibility, and inclusion phases (Salazar-Cabrera et al., 2020).

3.1.2.1 Systematic literature review (SLR) PRISMA2020

The present research adopts the PRISMA Declaration as a method for the presentation of STLS-GHG traffic systematic reviews and meta-analyses (Urrútia & Bonfill, 2010). Due to a proliferation of published material, the PRISMA Declaration of 2009 meant an improvement in scientific publications that, without a doubt, gives researchers and specialists many advantages in consulting information and proposing new research (Moher et al., 2009).

Beyond the establishment of guidelines for the presentation of meta-analyses and systematic reviews, the PRISMA Declaration proposes a checklist of 27 concepts (Appendix 3) which, following the structure of a scientific article, specifically detail what is important in each section and, in addition, propose a flowchart (Figure 9) to illustrate the process of the revision which starts with a formulated question, followed by establishing an explicit method for the successive stages of the review, a search, identification and selection of relevant studies, a description and analysis of quality, risk of bias, data extraction and interpretation of results (Page et al., 2021b).

Table 3 SLR PRISMA for Abstracts

Section and Topic	Item #	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	
Information sources	4	Specify the information sources (e.g., databases, registers) used to identify studies and the date when each was last searched.	
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	
Synthesis of results	6	Specify the methods used to present and synthesise results.	
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	
		Present results for main outcomes, preferably indicating the number of included studies and participants for each.	
Synthesis of results	8	If meta-analysis was done, report the summary estimate and confidence/credible interval.	
		If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	
Interpretation	10	Provide a general interpretation of the results and important implications.	
OTHER			
Funding	11	Specify the primary source of funding for the review.	
Registration	12	Provide the register name and registration number.	

Source: Page et al. (2020).

Compared to PRISMA 2009, in PRISMA 2020 the concepts are modified, and sub-topics are added for a more organized presentation and a more exhaustive treatment of the information.

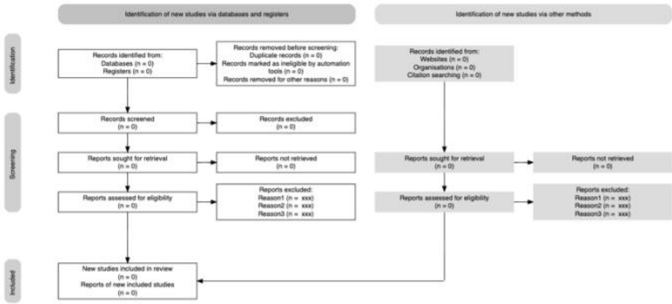


Figure 8 PRISMA 2020

Source: (Page et al., 2021a).

The PRISMA Declaration emerged as a measure to facilitate professionals' work as a manifesto to standardize the work. For this reason, a door was opened for this declaration to be established as a rule and as a cross-field method of work around the world. This is a significant improvement in the quality of systematic reviews and will gain the recognition that it deserves from the scientific community (Yepes-Nuñez et al., 2021).

SLR's aim is identifying the current 4IR the so-called Smart Traffic Lights technologies from scientific literature aimed at improving traffic management at intersections. SLR obtained a sequential upgrading of the queries strings, executed in Google Scholar (six) obtaining 135 documents related to STL and GHG emissions, which were categorized at five different levels, from 1 to 5 where1 is the worst and 5 the best according to the criteria proposed for this review as the accessibility status, year of publication (a range of 5 years was considered), number of citations, citations/year, STL/GHG closeness, academic source (university repositories or external), and contents as architectures, platforms, frameworks, simulators, sensors, methods, and algorithms. A total of 13 papers met the established criteria and were selected as key papers for this research.

From the SLR papers' database a keyword extractor was implemented for each paper to identify and extract the architectures, platforms, frameworks, simulators, sensors, methods, and algorithms contained in them. Once obtained, the full technologies description for the database (241) was done. The biggest limitation at this stage was the multiplicity of terms and technologies related to the same devices or processes. For tackling this issue, a normalization was developed by eliminating in first instance the synonyms reducing them to 135 terms using a word-cloud technique and in the second instance using the related or closely related terms by checking the description of each one thus reducing the terms to 27 by using a categorization tree map.

RQ1 *Does a relation exist between vehicular traffic congestion levels at intersections and the increasing GHG-Co2 emissions?* was approached by the SLR identification in (Jie, 2011; Munawer, 2018; Towoju & Ishola, 2020; US EPA, 2022; Watson et al., 1988) (Table 1). All these studies provided different methods for identifying the correlation between traffic jam/congestion and the increasing GHG rates. The intensive technologies' description, extraction, and normalization executed in SLR produced a clear identification of Smart Traffic Light related technologies and architectures and frameworks which allow the creation of a STL technology map which is a critical step in the AHP process as it provides alternative layers or dimensions.

3.2 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) methodology developed by Professor Thomas Saaty, is used in the present research for solving a series of specific problems in traffic-sustainable decision-making processes which are under budget constraints. It is aimed at finding the most suitable technology for implementing STLS at road intersections to reduce traffic congestion and generate a positive spill over through GHG emissions' reduction.

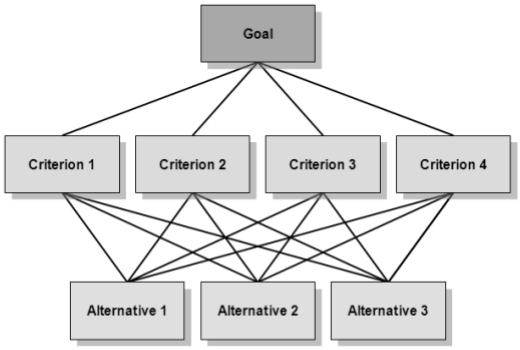


Figure 9 Analytic Hierarchy Process
Source: (Apostolos Panagiotopoulos, 2022).

The AHP process can be summarized in six steps:

1. Defining the problem: Once the technologies based on SLR are identified and classified, the AHP objective is defined under the limits and descriptions of the research questions.
2. Determining evaluation criteria: The criteria for STLS in this research are divided into three: STLS Functions, STLS Costs, and Traffic Emissions. For STLS Functions the following were determined: Intersection Delays, Stopped Delays, Deceleration Delays, Travel Time, and Queue Length as criteria set. All of them were obtained from scientific literature.
3. Determine AHP hierarchy: The STLS hierarchy was determined as a top-down scheme (Appendix 5), topping the model was the AHP Objective followed by the first layer comprised of three dimensions - Efficiency, Construction, and Emissions. This was followed by a second layer which indicates and explains each criterion and a final layer containing the technology alternatives for STL which are divided into three categories - Sensing Techniques, Image Processing, Probe Vehicle Techniques (Figure 11).
4. Pairwise and normalize the comparison matrix.
5. Calculate priority vectors.
6. Calculate the consistency ratio (Alemdar et al., 2021a).

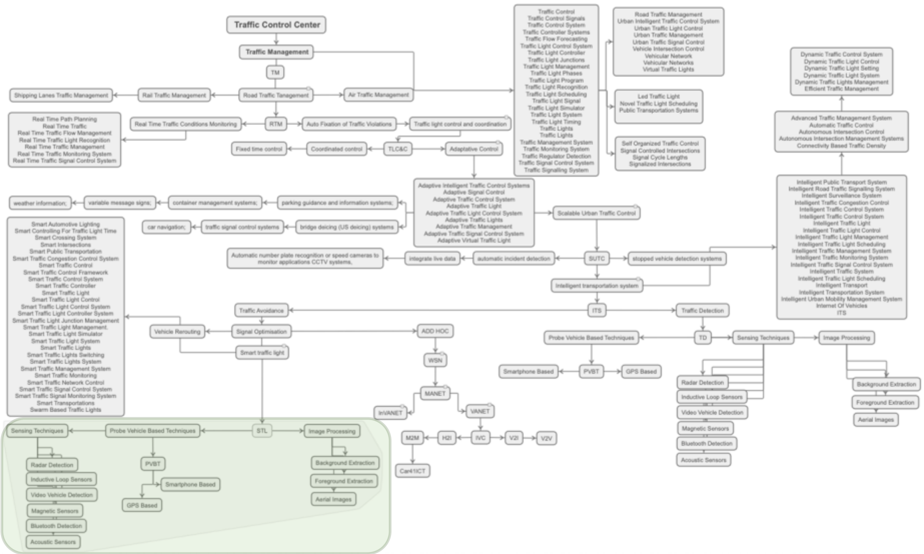


Figure 10 AHP alternatives selection based on SLR

Source: Author development

The proposed method for the AHP questions is based on a first questionary set based on a three-layer Analytic Hierarchy Structure model. The set of questions is divided into two stages. The first stage evaluates the AHP objective (improving traffic flows at intersections to win optimal implementation of STL/ITS technologies as an element of the traffic infrastructure under budget constraints) with the first layers or dimensions (Efficiency, Costs, and Emissions).

Equation 1 Boolean 'or' dimensions decisions

$$P \mid C, P \mid E, C \mid E$$

The second stage evaluated the second layer or criteria (Intersection Delays, Stopped Delays, Travel Time, Deceleration Delays, Queue Length, Construction Costs, Maintenance Costs, Operation Costs, Fuel Consumption, Co2 Emissions, Construction Congestion Costs) with the third layer or alternatives - Sensing Techniques, Image Processing, and Probe Vehicle-Based techniques (Figures 12 and 13).

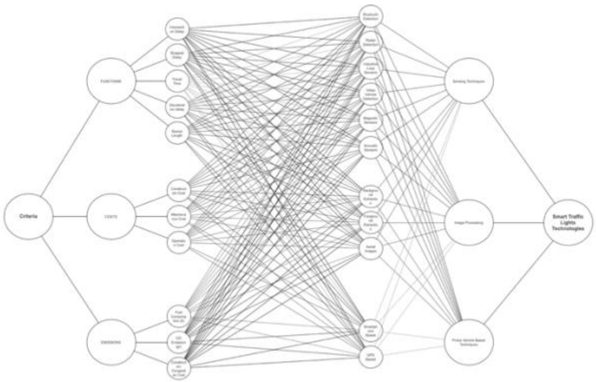


Figure 11 Detailed three-layer analytic hierarchy structure

Source: Author development

A second questionary set was also proposed based on a four-layer analytic hierarchy structure, targeted to increase the level of accuracy from the experts' evaluation related to the second layer’s (Intersection Delays, Stopped Delays, Travel Time, Deceleration Delays, Queue Length, Construction Costs, Maintenance Costs, Operation Costs, Fuel Consumption, Co2 Emissions, Construction Congestion Costs) evaluation with the third layer or alternatives (Bluetooth Detection, Radar Detection, Inductive Loop Sensors, Video Vehicle Detection, Magnetic Sensors, Acoustic Sensors, Background Extraction, Foreground Extraction, Aerial Images, Smartphone-based, GPS-based). This will provide more information to the expert panel concerning the technologies for capturing information for STLS.

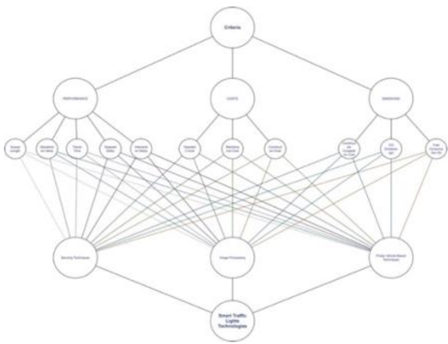


Figure 12 Simplified three-layer analytic hierarchy structure

Source: Author development

3.2.1 AHP Survey questionnaire

The weight of each criterion was quantified concerning the fundamental objective of improving traffic flows at intersections with optimal implementation of STLS/ITS technologies as an element of the traffic infrastructure under budget constraints. To achieve this, the first stage of the questionary compared the AHP objective with the three dimensions in layer one (Equation 1).

In the second stage, the second-criteria layer's (Intersection Delays, Stopped Delays, Travel Time, Deceleration Delays, Queue Length, Construction Costs, Maintenance Costs, Operation Costs, Fuel Consumption, Co2 Emissions, Construction Congestion Costs) relation proposed in Equation 2 was compared with the third-alternatives layer (Bluetooth Detection, Radar Detection, Inductive Loop Sensors, Video Vehicle Detection, Magnetic Sensors, Acoustic Sensors, Background Extraction, Foreground Extraction, Aerial Images, Smartphone-based, GPS-based).

Equation 2 Boolean 'or' criteria decisions

$$P\,|Ql,\ P\,|Dd,\ P\,|Tt,\ P\,|Sd,\ P\,|Id,\ P\,|Oc,\ P\,|Mc,\ P\,|Cc,\ P\,|Ccc,\ P\,|Co2,\ P\,|Fc$$

The expert respondents followed the Saaty scale (Table 5) aiming to choose the most important option and quantify how much important is (intensity). Finally, the STLS "alternatives"were evaluated for each criterion (Table 6).

Table 4 The Saaty Fundamental Scale for Pairwise Comparisons

The Fundamental Scale for Pairwise Comparisons

Intensity of Importance	Definition	Explanation
1	Equal importance	Element ***a*** and ***b*** contribute equally to the objective
2	Weak Importance	
3	Moderate/weak importance of one over another	Experience and judgment slightly favor element ***a*** over ***b***
4	Moderate Plus Importance	
5	Essential or strong importance	Experience and judgment strongly favor element ***a*** over ***b***
6	Strong Plus Importance	
7	Demonstrated importance	Element ***a*** is favored very strongly over ***b***; its dominance is demonstrated in practice
8	Very, very strong improtnace	
9	Absolute importance	The evidence favoring element over ***a*** over ***b*** is of the highest possible order of affirmation

Source: Saaty, 2001

3.2.2 Criteria description

C1P: Performance

C1P.1 Intersection Delays: Is the extra distance travelled by a car before it reaches free-flowing speed after it approaches the intersection (Shatnawi et al., 2018).

C1P.2 Stopped Delays: Is the time spent waiting for a car when its speed is 0 (practically, a vehicle is stationary when its speed is less than 5 mph) (Shatnawi et al., 2018).

C1P.3 Travel Time: The total time taken to travel a particular distance. The average journey time is based on the runs for a specific connection or corridor (United States Department of Transportation, 2022).

C1P.4 Deceleration Delays: Is the lag time a vehicle experiences when slowing speed (Shatnawi et al., 2018) (United States Department of Transportation, 2022).

C1P.5 Queue Length: An important signalized intersection performance metric. Queue length data can be used for assessing intersection performance and identifying issues that could benefit from signal program adjustment (Tišljarić et al., 2018).

C2C: Costs

C2C.1 Construction Costs: The total expenses incurred for the development of a built asset, such as STLS. In general, construction costs are expenses related to the actual construction activity. On some projects, the value of the contract with the main contractor may also be taken into account (Abdelmohsen et al., 2016).

C2C.2 Maintenance Costs: The fact that prompt maintenance lowers maintenance costs in the future allows us to determine that maintenance expenses are equal to the element's replacement costs (Maji & Jha, 2007; Ng et al., 2009).

C2C.3 Operation Costs: Most of the running expenses are salaries, but there are additional charges for rent, research, training, licensing, and training (Kurrek & Devitt, 1997).

C2E: Emissions

C3E.1 Fuel Consumption: A vehicle's stop-and-go and low speed increase the consumption of fuel, which is a non-renewable resource. It should be taken into account when designing to reduce fuel consumption (Alemdar et al., 2021b).

C3E.2 Co2 Emissions: Vehicles emit more emissions at low speeds and while they are resting. It is one of the parameters to be taken into account in intersection/corridor designs due to environmental concerns (Alemdar et al., 2021b).

C3E.3 Construction Congestion Costs: Engineers can utilize the Construction Congestion Cost System (CO3) to determine the extent and effects of traffic congestion, including the cost to road users that can be anticipated during a construction project (Carr, 2000).

Table 5 AHP Dimensions and Criteria

Dimensions		
D1E : Efficiency	D2C : Cost	D3E : Emissions
Criteria		
D1CE.1 Intersection Delay D1CE.2 Stopped Delay D1CE.3 Travel Time D1CE.4 Deceleration Delay D1CE.5 Queue Length	D2CC.1 Construction Cost D2CC.2 Maintenance Cost D2CC.3 Operation Cost	D3CE.1 Fuel Consumption D3CE.2 Co2 Emission D3CE.3 Construction Congestion Cost

Table 6 AHP Alternatives

Alternatives		
G1A : Sensing Techniques	G2A : Image Processing	G3A : Probe Vehicle Based Techniques
G1A1. Bluetooth Detection G1A2. Radar Detection G1A3. Inductive Loop Sensors G1A4. Video Vehicle Detection G1A5. Magnetic Sensors G1A6. Acoustic Sensors	G2A1. Background Extraction G2A2. Foreground Extraction G2A3. Aerial Images	G3A1. Smartphone Based G3A2. GPS Based

3.2.3 Data normalizing

A large portion of the literature examines key indicators and assessment methods related to smart mobility, intelligent transportation systems, and public transportation using a variety of approaches, including AHP, FAHP, Group AHP, and TOPSIS (Ishizaka & Labib, 2011). In the current study, an AHP analysis was used in the technology assessment for smart traffic lights.

The ITS development's application functions or project implementation were measured using the AHP indicators to create the evaluation platform (Chen & Deng, 2018; Vaidya & Kumar, 2006). Despite the limitations of the AHP model in handling cumbersome datasets, its comparative reliability over other methods is demonstrated by different authors as stated by Rohitratana and Altmann (2012) by identifying criteria such as architecture, functionality, and low costs as determinants for AHP selection.

Although absolute results cannot be expressed by using ratio scales, AHP has the advantage of being able to evaluate the preference scale using numerical, verbal, or pictorial means. AHP was created to deal with the ambiguity of human judgment. One of the most popular methods is using a fuzzy set to calculate the verbal discretion ratio scale (Ishizaka & Labib, 2011).

To determine the significant indicators and assessment framework of ITS for public transportation, the dimension and indicators were reviewed to construct an AHP structure and compute the weight of each indicator. In addition, opinion questions were added to collect views and recommendations on the development of an Advanced Public Transportation System (APTS) and the assessment methodology for developing APTS in low-income countries (Choosakun & Yeom, 2021).

A questionnaire was chosen as a collection tool for pairwise comparisons for AHP. Further, and ITS expert's database with 400 entries was created which comprised of academic, transportation institutes, mobility laboratories research, transportation initiatives, conferences, think tanks, alliances, and university lab professionals' emails. This was expected to obtain a 0.05 percent response rate (20 respondents) to nurture the AHP model.

Following the definitions of the objective, criteria, and alternatives, the weighting of the various criteria was done, for which a series of questionnaires were sent to experts in the field, who answered some questions to provide value to the paired matrix of comparisons. These questionnaires were designed in such a way that the experts could assess the relative importance of one or another characteristic of the same level and then give each pair of criteria a value for the pairwise comparison, ranging from 1 to 9 based on the scale proposed by Saaty (Table 3) (Rohitratana & Altmann, 2012).

Equation 3 $G\mu$ diagonal inverse-relationship versus arithmetic mean

$$R_a = \begin{Bmatrix} 1 \swarrow & \frac{1}{a} \\ a_1 & 1 \end{Bmatrix} \quad R_b = \begin{Bmatrix} 1 & \frac{1}{a_2} \\ a_2 & 1 \end{Bmatrix}$$

$$G\mu = \begin{Bmatrix} 1 \swarrow & \sqrt{\frac{1}{a_1 a_2}} \\ \sqrt{a_1 a_2} & 1 \end{Bmatrix}$$

Through discussions with experts and professionals in ITS planning and technology development, six ITS experts were included in the final modelling process. Respondents had to have prior ITS experience, including involvement in ITS entities or projects. The electronic questionnaire was attached with an explanation of the study's goal, the AHP model, the Saaty scale, and the description of dimensions and indicators and emailed to the experts. For the present research, the expert pairwise comparison data from the questionary was evaluated under Super Decisions 3.0. This software allows the input of a single dataset per respondent; thus, several simulations of the datasets should be run, thirty for the expected number of responses in this research.

To tackle aforementioned disadvantage, a statistical approach was proposed by initially treating and unifying the data with measures of central tendency, for instance, the mean, but this measure has a limitation as it is excessively affected by extreme values and, consequently, can be very distant from being a depiction of the sample. Hence, this was not used because of its extremely biased distributions.

Equation 4 Arithmetic mean

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

As Krejčí and Stoklas (2018) demonstrated the weighted arithmetic mean approach should not be used to combine local priorities of alternatives into global priorities in AHP. Various cases were studied by the authors and the outputs show that the Weighted Arithmetic Mean (WAM) technique failed to accurately capture the preference data found in the local Pairwise Comparison Matrix (PCM) of alternatives. On the other hand, it became clear that the Weighted Geometric Mean (WGM) approach accurately reflected the preference data included in the local PCM. Thus, the weighted geometric mean approach should be used instead.

The ratios of the global priorities of alternatives when WAM is used rely on the normalization method selected for the local alternatives. Even worse, when using the WAM aggregation approach, a rank reversal may happen purely as a result of the normalization method that is used. Additionally, the reciprocity criterion is broken when WAM is used to aggregate the local priority ratios.

Equation 5 Geomean in unitary distribution

$$G = \sqrt[n]{x_1 * \ x_2 * \ \ldots . x_r} = \sqrt[n]{\prod_{i=1}^{r} x_i}$$

WAM also displays other odd behavior, such as an inability to maintain equality of pairwise comparisons or the production of an unexpected global ranking from directly opposing preference information when it would seem reasonable to expect indifference between the alternatives on a global scale (Krejčí & Stoklasa, 2018). Thus, implementing a geometric mean meets the requirements of the data collected as this measure of central tendency is more representative than the arithmetic mean when the variables evolve cumulatively with multiplicative effects, are objectively defined and unique, consider all the values of the distribution in the calculation, and the extreme values have less influence because they are defined by-products instead of sums.

Equation 6 Geomean in non-unitary distributions (pooled or not)

$$G = \sqrt[n]{x_1^{n_1} * x_2^{n_2} * \dots x_r^{n_r}} = \sqrt[n]{\prod_{i=1}^{r} x_i}$$

Hence, for the six respondents' questions, each question was evaluated agreeing with the Saaty scale (Table 3), after which the geometric mean was calculated to show the effect of the values' distribution. For instance, analyzing the first layer of 'dimensions' the relation between efficiency and costs was represented by the question: Which of the following dimensions are most important for a GHG - Co2 reduction in road intersections with Smart Traffic Lights? (Table 6). The obtained data output using the mean is 6 which in the Saaty scale represents 'Strong plus important,' meanwhile, by using the geometric mean the output is 4 which is 'Moderate plus important.'

In terms of data illustration, there is a vast difference in the outputs that efficiency has strong importance instead of moderate-plus importance as compared to costs. This extreme output can also be evidenced in Table 8 when comparing costs and emissions with values of 6 and 4 respectively. This does not mean that in all the questions the valuation using the mean has extreme values (Table 7) but it demonstrates how reliable the measure is. By analyzing these findings using measures of the central tendency to simplify the data input process in the analysis software the most suitable option is accepting the geometric mean which is a more reliable interpretation of the full dataset from the respondents' survey.

Equation 7 Integrated model

$$\left[\left(\sum_{1}^{n} n_1 \geq n_1\right) * \left(\sum_{1}^{n} n_2 \geq 0 = n_2\right) * \left(\sum_{1}^{n} n_3 \geq 0 = n_3\right) * \left(\sum_{1}^{n} n_{\dots} \geq 0 = n_{\dots}\right)\right]^{\left(\frac{1}{n>0}\right)}$$

An integrated model was proposed (Equation 7) to handle the data from the 30 respondents and evaluated a determine range by summing up and considering just the positive values to determine n for the $G\mu$.

Table 7 AHP survey data – Dimensions E | C

DIMENSIONS

Efficiency Vs Cost

1. Which of the following dimensions is most important with respect from the other for a GHG - Co2 reduction in road intersections with Smart Traffic Lights? * Remember: The GHG-Co2 emissions is considered in a scenario with fossil fuelled vehicles (ICE)	1.1 How much? [Equal importance]	1.1 How much? [Weak Importance]	1.1 How much? [Moderate/weak importance of one over another]	1.1 How much? [Moderate Plus Importance]	1.1 How much? [Essential or strong importance]	1.1 How much? [Strong Plus Importance]	1.1 How much? [Demonstrated importance]	1.1 How much? [Very, very strong importance]	1.1 How much? [Absolute importance]					
D2C: Costs						6								
D2C: Costs			3											
D1P: Efficiency							7							
D1P: Efficiency	1													
D1P: Efficiency							7							
D1P: Efficiency	1									#	Σ			
	2	0	3	0	0	0	14	0	0	3	19	Mean	6	Strong Plus Importance
												Geo Mean	4	Moderate Plus Importance

Table 8 AHP survey data – Dimensions E | Em

DIMENSIONS

Efficiency Vs Emmisions

2. Which of the following dimensions is most important with respect from the other for a GHG - Co2 reduction in road intersections with Smart Traffic Lights? * Remember: The GHG-Co2 emissions is considered in a scenario with fossil fuelled vehicles (ICE)	2.1 How much? [Equal importance]	2.1 How much? [Weak Importance]	2.1 How much? [Moderate/weak importance of one over another]	2.1 How much? [Moderate Plus Importance]	2.1 How much? [Essential or strong importance]	2.1 How much? [Strong Plus Importance]	2.1 How much? [Demonstrated importance]	2.1 How much? [Very, very strong importance]	2.1 How much? [Absolute importance]					
D3E: Emissions							6							
D3E: Emissions				3										
D1P: Performance						5								
D1P: Performance			2											
D3E: Emissions	1													
D1P: Performance	1													
	2	0	2	3	0	5	6	0	0	5	18	Mean	4	Moderate Plus Importance
												Geo Mean	3	Moderate/weak importance of one over another

Table 9 AHP survey data – Dimensions C | Em

DIMENSIONS

Cost Vs Emmisions

3. Which of the following dimensions is most important with respect from the other for a GHG - Co2 reduction in road intersections with Smart Traffic Lights? * Remember: The GHG-Co2 emissions is considered in a scenario with fossil fuelled vehicles (ICE)	3.1 How much? [Equal importance]	3.1 How much? [Weak Importance]	3.1 How much? [Moderate/weak importance of one over another]	3.1 How much? [Moderate Plus Importance]	3.1 How much? [Essential or strong importance]	3.1 How much? [Strong Plus Importance]	3.1 How much? [Demonstrated importance]	3.1 How much? [Very, very strong importance]	3.1 How much? [Absolute importance]				
D3E: Emissions					5								
D3E: Emissions				4									
D3E: Emissions					5								
D2C: Costs	1												
D3E: Emissions							7						
	1	0	0	4	10	0	7	0	0	4	22	6	Strong Plus Importance
												4	Moderate Plus Importance

3.2.4 The AHP Methodology

The pairwise comparison scale used in Saaty's AHP permits qualitative judgments to be converted into numerical values, including intangible aspects. A judging matrix (Equation 4) was assumed for computing the priority of the elements.

Equation 8 Judgmental matrix

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,n} \\ a_{2,1} & a_{2,2} & a_{2,n} \\ a_{n,1} & a_{n,2} & a_{n,m} \end{bmatrix}$$

To form the matrix of paired comparisons, the reciprocal values for the values assigned through the questionnaires by the experts were included in the scale, that is, the reciprocity property expressed in Equation 5 was transformed into Equation 6 (Saaty, 2001).

Equation 9 Reciprocity property

$$a_{ij} = x$$

Equation 10 Applied Reciprocity property

$$a_{ji} = \frac{1}{x}$$

where a_{ij} is the pairwise comparison ranking amid a level's element i and element j about the upper level. The following rules apply to the a_{ij} entries:

Equation 11 Pairwise comparison ranking

$$a_{ij} > 0; \frac{a_{ij=1}}{a_{ji}}; \ a_{ii} = 1 \ \forall i$$

According to Saaty the priority of the elements may be calculated by obtaining matrix A's primary characteristic vector of a linear transformation *w*, which is represented in Equation 8 (Saaty, 2001).

Equation 12 Vector of a linear transformation

$$AW = \lambda_{max}W$$

When the vector *W* is normalized, it becomes the vector of priorities of one level's constituents in relation to the higher level. Where λ_{max} is the biggest linear transformation and a non-zero vector of the matrix *A* is *max*. When the pairwise comparison matrix satisfies transitivity for all pairwise comparisons and supports the following relationship, it is regarded as consistent (Berrittella et al., 2011):

Equation 13 Pairwise transitivity

$$a_{ij} = a_{ik} * a_{kj}$$

$$\forall_{i,j,k}$$

3.2.4.1 Consistency ratio

According to Saaty, for maintaining sufficient consistency when determining priorities from paired comparisons, the number of components studied must be less than or equal to nine. In each series of evaluations, AHP allows for inconsistencies and also provides a way to measure them (Saaty, 2001). If element A is favored by two agents and element B is selected by three agents, then element A should be preferred because of its product above element C: 6.

The AHP - Inconsistency Ratio (IR) model checks the consistency of all such triple judgments for a comparison group and provides a decimal value as a measure of the consistency's inconsistency, which should be less than or equal to 0.10 (Saaty, 2001).

The consistency ratio (CR) is a statistic that may be used for assessing the consistency of the judging matrix. It is defined as:

Equation 14 Consistency Ratio

$$CR = \frac{CI}{RI}$$

The Random Index is referred to as *RI*, whereas the Consistency Index is *CI*. Table 9 provides Saaty's (2001) presentation of the average consistencies (*RI* values) of matrices generated arbitrarily:

Equation 15 *CI* for a matrix of order *n*

$$CI = \frac{\lambda_{\max - n}}{n - 1}$$

For matrices of size four, this barrier is 0.08, while for matrices of size three, it is 0.05. In general, a consistency ratio of 0.1 or less is considered acceptable. If the value is higher, the conclusions might not be correct, and they should be re-obtained (Saaty, 2001).

Table 10 RI random matrix

RI values										
SIZE	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The preferences are combined as follows to create the final priorities of the alternatives a_i after the local priorities of elements at various levels are available:

Equation 16 Final priorities of the alternatives

$$S(a_i) = \sum_k w_k S_k(a_i)$$

where w_k is the element k's local priority and $S_k(a_i)$ is the higher level's alternative ai's priority regarding element k (Berrittella et al., 2011).

To tackle RQ2: *Based in the SLR identification of STL system technologies, which of those technologies are the most suitable to be implemented as an element of the traffic infrastructure at intersections (traffic lights) under budget constraints, targeted at improving traffic flows and reducing GHG-Co2 emissions?* a Multicriteria Decision Analysis (MCDA) based on an Analytical Hierarchy Processes (AHP) was executed. The aim was allowing decision-makers and policymakers to determine which were the most suitable 4IR technologies related to vehicular traffic congestion management at intersections.

Developed by Professor Thomas Saaty in the 1970s, the AHP methodology is a multicriteria decision process that helps in choosing from many alternatives based on a number of selection criteria or variables that are typically hierarchical and frequently at odds with one another. Choosing the selection criteria and sub-criteria carefully, defining them correctly, and ensuring that they are mutually exclusive are issues that are addressed by the SLR technologies identification and categorization is one of the essential components of the process.

The Saaty Fundamental Scale is used in the survey to do the paired comparison. This is one of the keys to the effectiveness of this method because this scale enables the transformation of qualitative aspects into quantitative ones, significantly facilitating a comparison between the various alternatives and producing more objective and reliable results. The hierarchical top-down structure provides the Objectives, Dimensions (STL Functions, STL Costs, and Traffic Emissions), Criteria, and Alternatives to compare.

Chapter 4. Data

4.1 AHP's Objective

The AHP analysis was initially comprised of the objective or goal of the survey which is also closely related to the first and second research questions in this study (Figure 14).

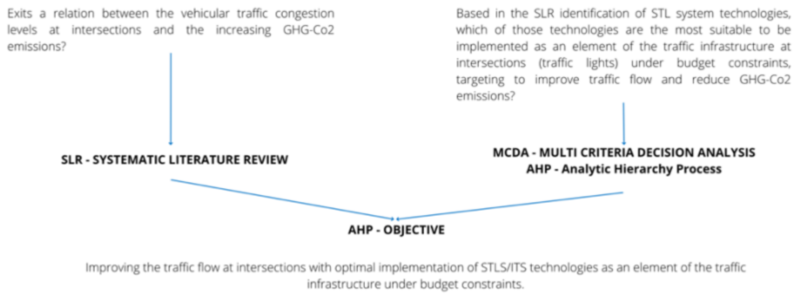


Figure 13 AHP objective in relation to the research questions in the study

Thus, the research should work towards minimizing the negative effects of traffic jams at intersections for a positive impact on climate change. The relation ratio can be identified in the collection of nodes that have some logical relationship in a frame; in this case, this is 0.00000000 (Table 11).

Table 11 Cluster matrix model

Cluster Matrix				
Clusters A	**1.Objective**	**2.Dimensions**	**3.Criteria**	**4.Alternatives**
1.Objective	0.000000	0.000000	0.000000	0.000000
2.Dimensions	1.000000	0.000000	0.000000	0.000000
3.Criteria	0.000000	1.000000	0.000000	0.000000
4.Alternatives	0.000000	0.000000	1.000000	0.000000

4.2 First Layer: Dimensions

The benchmarks used for evaluating the criteria are represented in the first layer as follows: Technical advancements in STL systems related to ecological efficiency: Efficiency D1E; Costs involved in the construction, maintenance, and operation of the STL system infrastructure in the transportation system at intersections: Cost D2C; and the impact of demand for fossil fuels over fuels with lower GHG -Co2 target D3E Emissions as represented in Table 12.

Table 12 Cluster unweighted matrix

Cluster Unweighted Matrix					
Clusters	Nodes	Objective	01E : Efficiency	D2C :Cost	D3E : Emissions
1.Objective	Objective	0.00000000000	0.00000000000	0.00000000000	0.00000000000
2.Dimensions	D1E : Efficiency	0.61441100000	0.00000000000	0.00000000000	0.00000000000
	D2C :Cost	0.26836900000	0.00000000000	0.00000000000	0.00000000000
	D3E : Emissions	0.11722100000	0.00000000000	0.00000000000	0.00000000000

The analysis starts by introducing the first layer's assessment, formed by D1E: Efficiency, D2C: Cost, and D3E: Emissions dimensions as shown in Table 10. Nodes in the criteria cluster are connected from the 'Objective' node, and each is equally weighted at 0.25 before judgments. All the nodes connected from a parent node have priority in the column below that node. The nodes in each cluster in a column have a priority that adds to 1. The matrix is square; each node is represented by a column and a row. The nodes are organized by the cluster that they are in (Table 12).

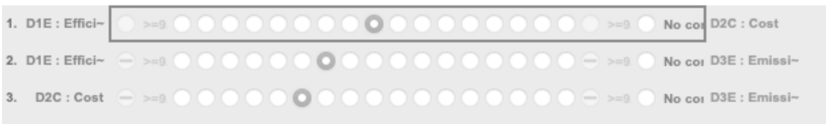


Figure 14 Cluster nodes comparison, dimensions' layer

The weights of the first layer's variables can be established (Table 13).

Table 13 Dimension layer's output

DIMENSION	OUTPUT	%
D1E: Efficiency	0.41606073	41.60%
D2C: Cost	0.45793393	45.70%
D3E: Emissions	0.12600534	12.60%

It can be seen that the inconsistency ratio (inconsistency 0.00885) is 4 percent lower than that established for a 3x3 matrix as expressed in Equation 11 and Table 9.

4.3 Second layer: Criteria

The next step was addressing the second layer's variables, starting with those associated with variable D1E: Efficiency characteristics. These are D1CE.1-Intersection delays, D1CE.2-Stopped delays, D1CE.3-Travel time, D1CE.4-Deceleration delays, and D1CE.5 Queue length.

4.3.1 Efficiency dimension data analysis

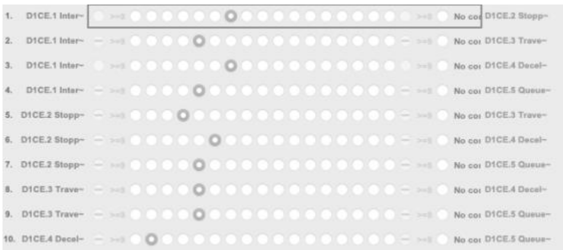


Figure 15 Cluster nodes comparison, efficiency criteria layer

The weights of the first layer's characteristics referring to variable C.1: Economic characteristics are given in Table 13.

Table 14 Efficiency dimension's output

DIMENSION	OUTPUT	%
D1CE.1 Intersection Delay	0.37661118	37.60%
D1CE.2 Stopped Delay	0.3193406	31.90%
D1CE.3 Travel Time	0.15849311	15.80%
D1CE.4 Deceleration Delay	0.10833501	10.80%
D1CE.5 Queue Length	0.0372201	3.72%

It also meets the inconsistency (inconsistency 0.026073) criterion.

4.3.2 Cost dimension data analysis

The analysis continued with the second layer's variables associated with the variable D2C: Cost characteristics: D2CC.1: Construction Costs, D2CC.2: Maintenance Costs: and D2CC.3: Operation Costs. After this the AHP modelling process was executed again.

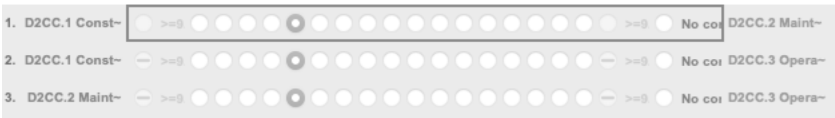


Figure 16 Cluster nodes comparison, cost criteria layer

Table 15 Cost dimension output

DIMENSION	OUTPUT	%
D2CC.1 Construction Cost	0.55906505	55.90%
D2CC.2 Maintenance Cost	0.35218891	35.20%
D2CC.3 Operation Cost	0.08874604	8.87%

It also meets the inconsistency (inconsistency 0.05156) criterion.

4.3.3 Emission dimension's data analysis

The second layer's variables refer to variable D3E: Emissions characteristics. These are D3CE.1 Fuel consumption, D3CE.2 Co2 Emissions, and D3CE.3 Construction Congestion Costs. This will end the weighting of the different criteria.

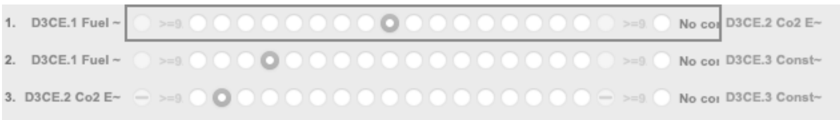


Figure 17 Cluster nodes comparison, emissions criteria layer

Table 16 Emissions dimension output

DIMENSION	OUTPUT	%
D3CE.1 Fuel Consumption	0.4440361	44.40%
D3CE.2 Co2 Emission	0.48872497	48.80%
D3CE.3 Construction Cong. Cost	0.06723893	6.70%

With this, the inconsistency (inconsistency 0.00885) criterion is achieved.

4.4 Third layer: Alternatives

As the survey questions are based on the nodes of the network between the second layer 'Criteria' and the third layer 'Alternatives,' this permutation produces different sets of 55 comparisons. The next section synthesizes the data related to technology selection for each criterion based on AHP outputs.

At this stage, the study analyzed the third layer criteria (D1CE.1 Intersection Delays, D1CE.2 Stopped Delays, D1CE.3 Travel Time, D1CE.4 Deceleration Delays, D1CE.5 Queue Length, D2CC.1 Construction Costs, D2CC.2 Maintenance Costs, D2CC.3 Operation Costs, D3CE.1 Fuel Consumption, D3CE.2 Co2 Emissions, D3CE.3 Construction Congestion Costs) with the alternatives (G1A1: Bluetooth Detection, G1A2: Radar Detection, G1A3: Inductive Loop Sensors, G1A4: Video Vehicle Detection, G1A5: Magnetic Sensors, G1A6: Acoustic Sensors, G2A1: Background Extraction, G2A2: Foreground Extraction, G2A3: Aerial Images, G3A1: Smartphone-based G3A2: GPS-based after which the AHP modelling process was executed again under Super Decisions 3.0.

Appendix 4 gives information on the questionnaire that was given to the experts. A judging matrix was created for each expert based on the pair-wise comparisons. The priorities were calculated using this matrix, and the consistency index was also calculated.

The geometric mean approach was used for integrating the priorities stated by the experts; the data obtained is given in Table 16.

Table 17 AHP data output Criteria versus Alternatives

DIMENSION NAME	CRITERIA																					
	D1CE.1		D1CE.2		D1CE.3		D1CE.4		D1CE.5		D2CC.1		D2CC.2		D2CC.3		D3CE.1		D3CE.2		D3CE.3	
G1A1. Bluetooth Detection	0.0291	2.91%	0.0217	2.17%	0.0831	8.31%	0.0330	3.30%	0.0317	3.17%	0.0159	1.59%	0.0229	2.29%	0.0732	7.32%	0.0262	2.62%	0.0217	2.17%	0.0298	2.98%
G1A2. Radar Detection	0.0291	2.91%	0.0217	2.17%	0.2020	20.20%	0.3268	32.68%	0.2512	25.12%	0.1464	14.64%	0.1581	15.81%	0.1314	13.14%	0.0208	2.08%	0.0220	2.20%	0.0298	2.98%
G1A3. Inductive Loop Sensors	0.0963	9.63%	0.2367	23.67%	0.1627	16.27%	0.0626	6.26%	0.3158	31.58%	0.3376	33.76%	0.3519	35.19%	0.2330	23.30%	0.2345	23.45%	0.0607	6.07%	0.2628	26.28%
G1A4. Video Vehicle Detection	0.2550	25.50%	0.3174	31.74%	0.0457	4.57%	0.0415	4.15%	0.0344	3.44%	0.1917	19.17%	0.0333	3.33%	0.1231	12.31%	0.0262	2.62%	0.0197	1.97%	0.0559	5.59%
G1A5. Magnetic Sensors	0.1973	19.73%	0.1233	12.33%	0.0457	4.57%	0.1776	17.76%	0.0344	3.44%	0.0236	2.36%	0.0333	3.33%	0.0306	3.06%	0.0684	6.84%	0.0197	1.97%	0.2123	21.23%
G1A6. Acoustic Sensors	0.0554	5.54%	0.0344	3.44%	0.0457	4.57%	0.0421	4.21%	0.0344	3.44%	0.0232	2.32%	0.1356	13.56%	0.1175	11.75%	0.0240	2.40%	0.0197	1.97%	0.0447	4.47%
G2A1. Background Extraction	0.0474	4.74%	0.0344	3.44%	0.0457	4.57%	0.0421	4.21%	0.0344	3.44%	0.1025	10.25%	0.0333	3.33%	0.0306	3.06%	0.0240	2.40%	0.0197	1.97%	0.0295	2.95%
G2A2. Foreground Extraction	0.0482	4.82%	0.0344	3.44%	0.0454	4.54%	0.0421	4.21%	0.0344	3.44%	0.0236	2.36%	0.0333	3.33%	0.0304	3.04%	0.0240	2.40%	0.0155	1.55%	0.0345	3.45%
G2A3. Aerial Images	0.0704	7.04%	0.0344	3.44%	0.0457	4.57%	0.1480	14.80%	0.0344	3.44%	0.0236	2.36%	0.0333	3.33%	0.0304	3.04%	0.2861	28.61%	0.2622	26.22%	0.0298	2.98%
G3A1. Smartphone Based	0.0528	5.28%	0.0344	3.44%	0.0457	4.57%	0.0421	4.21%	0.0344	3.44%	0.0236	2.36%	0.0333	3.33%	0.0304	3.04%	0.0240	2.40%	0.2983	29.83%	0.0298	2.98%
G3A2. GPS Based	0.1190	11.90%	0.1070	10.70%	0.2327	23.27%	0.0421	4.21%	0.1606	16.06%	0.0883	8.83%	0.1315	13.15%	0.1693	16.93%	0.2417	24.17%	0.2406	24.06%	0.2411	24.11%
Incosistency	0.0518		0.0744		0.06805		0.053		0.055		0.1619		0.0903		0.1764		0.1255		0.1634		0.1002	

Chapter 5. Results

The questionnaire was delivered between June 10 and December 24 in 2022 and it was aimed at professionals in the fields of smart traffic lights, traffic, transportation, and climate change. The aim of the survey was determining the priorities at different levels of the implementation of smart traffic light technologies under budget constraints, which is a main limitation for governments in low-middle income countries. The survey was sent to 408 experts by email; there were 200 system errors in the delivery of the emails. A total of seven answers were collected in the study period and used for simulating the model and obtaining hypothetical results.[4]

The best smart traffic light system as a transportation strategy to lessen the negative effects of climate change was aimed at supporting environmentally friendly technology alternatives. Analyzing the first layer 'Dimensions' we concluded that COST is the most important consideration in the implementation of STL with 45.79 percent of the experts agreeing. This is also a limitation for accessing technology. Even though expected, this

4 Is worth mentioning here that of the seven answers analyzed in the present study four met the expert requirements established for AHP in this study.

finding is surprising due to the paradox with budget restrictions. Even ‘Costs’ as the first consideration for experts are not absolute, because these are closely followed by the ‘Efficiency’ dimension (41.61 percent) which in terms of traffic makes more sense. Also, surprisingly, in opposition to the aim of the study, the ‘Emissions’ dimension was the last consideration for the implementation of STL systems. This result may be related to lack of evidence or knowledge concerning traffic efficiency, fuel consumption, and GH2 emissions. In the second layer, ‘Criteria,’ the dimension D1CE which is related to the efficiency states that ‘Intersection delays’ was the most important (37.60 percent) followed closely by ‘Stopped Delays’ (31.90 percent). In the dimension D2CC, related to costs, the most important indicator is ‘Construction costs’ (55.90 percent_, followed by ‘Maintenance costs’ (35.20 percent) which is also an important ratio to consider and finally ‘Operation costs’ with a low impact of 8.87 percent. The last dimension D3CE, related to the emissions considered ‘Co2 emissions’ as the most important indicator (48.80 percent) followed by ‘Fuel consumption.’ Hence, for the outputs from the first layer ‘Dimensions’ the experts’ considerations are more prone to interpret the STLS Construction Costs (55.9 percent) as the main indicator for STLS’ implementation. According to the experts, the main objective of the implementing systems is aimed at solving traffic issues related to ‘Intersection delays’ (37.60 percent) and ‘Stopped delays’ (31.90 percent).

Table 18 STLS’ AHP priorities

	Name	Value	%
DIMENSIONS	2D2C : Cost	0.45793	45.79%
	1D1E : Efficiency	0.41606	41.61%
	3D3E : Emissions	0.12601	12.60%
CRITERIA	6D2CC.1 Construction Cost	0.25601	25.60%
	7D2CC.2 Maintenance Cost	0.16128	16.13%
	1D1CE.1 Intersection Delay	0.15669	15.67%
	2D1CE.2 Stopped Delay	0.13286	13.29%
	3D1CE.3 Travel Time	0.06594	6.59%
	10D3CE.2 Co2 Emission	0.06158	6.16%
	9D3CE.1 Fuel Consumption	0.05595	5.60%
	4D1CE.4 Deceleration Delay	0.04508	4.51%
	8D2CC.3 Operation Cost	0.04064	4.06%
	5D1CE.5 Queue Length	0.01549	1.55%
	11D3CE.3 Construction Congestion Cost	0.00847	0.85%
ALTERNATIVES	3G1A3. Inductive Loop Sensors	0.23672	23.67%
	4G1A4. Video Vehicle Detection	0.15016	15.02%
	11G3A2. GPS Based	0.13366	13.37%
	5G1A5. Magnetic Sensors	0.07836	7.84%
	9G2A3. Aerial Images	0.07089	7.09%
	6G1A6. Acoustic Sensors	0.0542	5.42%
	7G2A1. Background Extraction	0.05312	5.31%
	10G3A1. Smartphone Based	0.05092	5.09%
	8G2A2. Foreground Extraction	0.03282	3.28%
	1G1A1. Bluetooth Detection	0.0287	2.87%

The environmental implications of traffic performance and the possible slipover of emissions into the environment do not seem to be relevant. This is reflected in the results for 'Emissions' (12.60 percent) which comprised mostly of 'Co2 emissions' (48.40 percent) and 'Fuel consumption' (44.40 percent). The experts expressed that 'Video Vehicle Detection' and 'Magnetic Sensors' were the best options for tackling 'Intersectional delays' (25.50 percent and 19.73 percent respectively). Video Vehicle Detection was also proposed for reducing 'Stopped delays' (31.74 percent) followed by Inductive Loop Sensors (23.67 percent). For the case of 'Travel Time,' implementing GPS-based Technologies (23.27 percent) and Radar Detection (20.20 percent) were recommended. 'Deceleration delays' can be addressed through Radar Detection (32.68 percent) and 'Queue length' by Inductive Loop Sensors (31.58 percent).

For the 'Costs' dimension, the experts proposed the most affordable Inductive Loop Sensors (33.76 percent) for reducing 'Construction costs.' This technology was also proposed for maintenance reduction (35.19 percent) and reduction in Operation Costs (23.30).

Finally, the technologies with a bigger impact in the 'Emissions' dimension for fuel consumption reduction were Aerial Images (28.61 percent), GPS-based Technologies (24.17 percent), and Inductive Loop Sensors (23.45 percent). For Co2 'Emissions reduction' Smartphone-based Technologies (29.83 percent), Aerial Images (26.22 percent), and GPS-based Technologies (24.06 percent) were preferred and for 'Construction congestion costs' the implementation of Inductive Loop Sensors was proposed.

The AHP analysis based on the experts' survey concluded that the Cost dimension was the most relevant factor in implementing STL technologies for upgrading the existing traffic lights infrastructure (45.79 percent) followed by the Efficiency dimension (41.61 percent). This means that STL's construction, operation, and maintenance is the first factor in traffic management digital Transformation (DX) for decision-makers and policymakers. This result was expected since the AHP model is aimed at governments with budget restrictions. Another conclusion is that despite the performance of the STL technologies, cost reductions will determine which technologies are implemented.

This outcome is also compatible with its second rank as in terms of efficiency STL technologies are not considered critical for improving traffic flows in low-income economies and lastly the 'Emissions' dimension is the least considered option which also aligns which the concern of the present research that governments do not rank climate change as a priority.

At the alternatives level the experts identified *Inductive Loop Sensors* as the best technology for upgrading the intersections and obtaining traffic flow improvements along with a GHG reduction (23.67 percent) followed by *Video Vehicle Detection* (15.02 percent) and *GPS-based Technologies* (13.37 percent), despite these being counterintuitive due to the high implementation costs. These dimensions have an inner relation with cost preferences. In the "efficiency criteria" dimension intersection delays, stopped delays, and travel time were identified in the top five considerations. This can be seen as a high cost in the short-run but with benefits in terms of efficiency in the long-run.

Chapter 6. Conclusions

A systematic literature review was conducted in the first stage of the research as part of the methodology to identify the authors and papers related to the first research question (RQ1). Evidence and methods to tackle this question were identified (Table 3), additionally SLR produced valuable data to feed the AHP hierarchy tree model.

AHP was nurtured using SLR data providing the model criteria and alternatives; it was also well oriented to tackle the second research question (RQ2). The results of the AHP analysis show that governments can focus their efforts on improving the transit and transportation infrastructure, specifically at road intersections by implementing STL systems based in first instance on *Inductive Loop Sensors* and in the second instance on *Video Vehicle Detection*. The decision for opting for these technologies will have positive implications as they will reduce cost and maintenance and lead to high efficiency in controlling and optimizing intersection and stop delays at road intersections. This infrastructure implementation may be considered more feasible for policymakers and decision-makers by virtue of its reduced costs, time taken for implementation, and the benefits in the short and long run as compared to other technologies like vehicle transition from ICE to BEV and windmill and solar panel farms. An additional attraction of this technology is that Co2 reduction is a consequence of a positive spillover of traffic management improvement which also comes with an economic benefit of reducing fuel consumption, the time used for travelling/commuting, and finally the positive effects on human health as it leads to a reduction in noise and poisonous emissions and a reduction in stress, respiratory, and skin diseases.

Even though the Video Vehicle Detection technology for STL systems was expected to be a suitable technology under budget constraints, the Inductive Loop Sensors' results are a surprise. Further research is needed to confirm this result by including more experts from different countries, especially from low-middle-income countries.

A pairwise comparison among different segments was done to compare perceptions about technology. This can be divided into three segments -- low-income economies which was the approach of this research and middle-income, high-income economies, and finally a non-expert' group. The differences in the preferences will provide valuable insights related to technology trend behavior and provide insightful outputs for more robust policies (Rohitratana & Altmann, 2012). Future studies are expected to go deeper not just in hardware technologies but also include architectures and algorithms as part of the model or under another model capable of evaluating them together.

The two research questions were addressed, along with the methodologies and methods of responding to each question. The first methodology, SLR, presents different challenges as identified in the diverse papers analyzed. The first limitation was finding homogeneous papers with regard to the research core, 'Smart Traffic Lights System Technologies to Improve Intersection Traffic Conditions with a Reduction in GHG Emissions.' The term *intersection* is an example of how the literature review was affected and this needed to be progressively adjusted six times for the query string and the results.

To find papers with the term 'intersections,' the term had to be modified once several papers addressed the same issue using terms such as 'crossroads,' 'street joints,' 'road intersections,' 'junction,' 'juncture,' and 'cross,' which narrowed the output of the reviewed research papers. This limitation was also recognized once SLR was used for determining the current technologies existing in relation to STL; the same correction process was executed along the six string queries to obtain as many papers as possible by extending STL to 'STLS,' 'TLS (traffic light system),' 'traffic detection,' 'traffic avoidance,' and 'RTM (road traffic management).'

The results of these technologies' identification and subsequent classifications are given in Figure 11. Due to lack of traffic information in low-income economies, the method for comparing the efficiency of STL technologies to improve traffic at intersections was also limited. In road intersection technology, a scheduled, fixed system is based primarily on traffic flow statistics with certain levels of outdating. This difficult, makes sense, and is compatible with the research questions. Thus, the proposal is adapting or changing traffic lights by including sensors/sensing technology.

Due to this lack of data, the first proposed approach was selecting a road intersection with traffic statistics as a representative case (Figure 18).

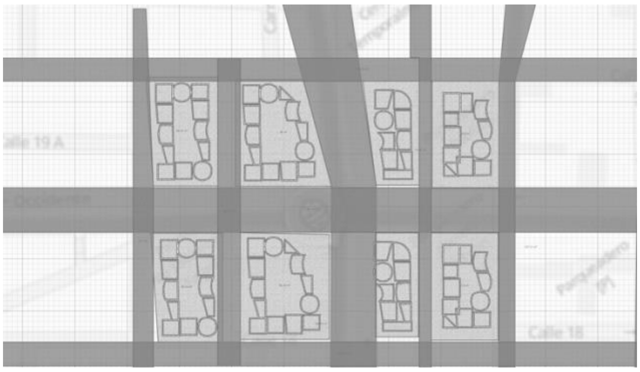


Figure 18 Intersection proposal - Bogota, Av. Jimenez, 19th Street

This selection indicates that Bogota is one of the most congested cities in the world (Tom Tom, 2020). Data was collected during a specified period (5 days), a Digital Twin was developed (Figure 19) for the intersection, and simulation was used for testing the most efficient SLR technology for STL with traffic data collection.

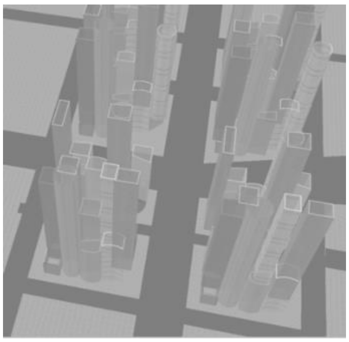


Figure 19 Bogota Digital Twin prototype: Av. Jimenez, 19th Street

Once we had developed the full infrastructure of Av. Jimenez, 19th Street, the model should run the same traffic flow captured from the data collection and implement the technology solutions identified in SLR: Bluetooth Detection, Radar Detection, Inductive Loop Sensors, Video Vehicle Detection, Magnetic Sensors, Acoustic Sensors, Background Extraction, Foreground Extraction, Aerial Images, Smartphone-based, GPS-based, and also include AI algorithms like MDP, YOLO, STLSD, STLSDT, and STLSDE (Rezgui et al., 2019). This level of simulation is extensive and time-consuming, and the data collected does not guarantee the accuracy of the predictions due to the short period of collection and the effects of seasonality on traffic.

The methodology under consideration was evaluated till one method was obtained that addressed the previous limitations and was achievable in the short run. In lieu of simulating, an MCDA was chosen to seek opinions from experts and practitioners in the traffic management industry. While 'AHP' simplifies the limitations of the simulation methodology considerably, it also introduces new limitations in the form of bulky statistical processing of the data. This issue was tackled by replacing WAM with WGM as explained in Chapter 3.2.3: 'Data normalization.'

Bibliography.

(2) (PDF) Some Thoughts on Global Climate Change: The Transition for Icehouse to Hothouse Conditions. (n.d.). Retrieved April 7, 2021, from https://www.researchgate.net/publication/275277369_Some_Thoughts_on_Global_Climate_Change_The_Transition_for_Icehouse_to_Hothouse_Conditions

• *Latin American cities with the worst traffic 2020 | Statista*. (2018). https://www.statista.com/statistics/889551/south-america-traffic-rush-hour/

Abdelmohsen, A. Z., Asce, S. M., El-Rayes, K., & Asce, M. (2016). Optimal Trade-Offs between Construction Cost and Traffic Delay for Highway Work Zones. *Journal of Construction Engineering and Management*, *142*(7), 05016004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001132

Al-Turki, M., Jamal, A., Al-Ahmadi, H. M., Al-Sughaiyer, M. A., & Zahid, M. (2020). On the Potential Impacts of Smart Traffic Control for Delay, Fuel Energy Consumption, and Emissions: An NSGA-II-Based Optimization Case Study from Dhahran, Saudi Arabia. *Sustainability 2020, Vol. 12, Page 7394*, *12*(18), 7394. https://doi.org/10.3390/SU12187394

Alemdar, K. D., Tortum, A., Kaya, Ö., & Atalay, A. (2021a). Interdisciplinary Evaluation of Intersection Performances—A Microsimulation-Based MCDA. *Sustainability 2021, Vol. 13, Page 1859*, *13*(4), 1859. https://doi.org/10.3390/SU13041859

Alemdar, K. D., Tortum, A., Kaya, Ö., & Atalay, A. (2021b). Interdisciplinary Evaluation of Intersection Performances—A Microsimulation-Based MCDA. *Sustainability 2021, Vol. 13, Page 1859*, *13*(4), 1859. https://doi.org/10.3390/SU13041859

Alrawi, F. (2017). The importance of intelligent transport systems in the preservation of the environment and reduction of harmful gases. *Transportation Research Procedia*, *24*, 197–203. https://doi.org/10.1016/J.TRPRO.2017.05.108

Andreas Schadschneider, Debashish Chowdhury, K. N. (2010). *Stochastic Transport in Complex Systems: From Molecules to Vehicles*. https://books.google.co.kr/books?id=dRcxsa4sobQC&printsec=frontcover&dq=Stochastic+Transport+in+Complex+Systems+from+Molecules+to+Vehicles&hl=es&sa

=X&redir_esc=y#v=onepage&q=Stochastic Transport in Complex Systems from Molecules to Vehicles&f=false

Apostolos Panagiotopoulos. (2022). *Analytic Hierarchy Process - File Exchange - MATLAB Central*. Matlab. https://www.mathworks.com/matlabcentral/fileexchange/79643-analytic-hierarchy-process

Bances Santamaría, M. V., & Mario Fernando, R. M. (n.d.). *Vista de SEMÁFOROS INTELIGENTES PARA LA REGULACIÓN DEL TRÁFICO VEHICULAR*. Retrieved April 22, 2022, from http://revistas.uss.edu.pe/index.php/ING/article/view/113/215

Berrittella, M., Certa, A., Enea, M., & Zito, P. (2011). An Analytic Hierarchy Process for the Evaluation of Transport Policies to Reduce Climate Change Impacts. *SSRN Electronic Journal*, *1*. https://doi.org/10.2139/ssrn.962379

Carlier, M. (2022). *• Consumers' reasons for virtual car acquisition 2021 | Statista*. https://www.statista.com/statistics/1253692/reasons-why-car-shoppers-prefer-virtual-purchase-process/

Carr, R. I. (2000). Construction Congestion Cost (CO 3) Traffic Impact and Construction Cost . *Journal of Construction Engineering and Management*, *126*(2), 114–121. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:2(114)

Chang, J., Hatcher, G., D., H., Schneeberger, J., Staples, B., Sundarajan, S., Vasudevan, M., Wang, P., Wunderlich, K., & Noblis, I. (2015). *Estimated benefits of connected vehicle applications : dynamic mobility applications, AERIS, V2I safety, and road weather management applications*. https://doi.org/10.21949/1503647

Choosakun, A., & Yeom, C. (2021). Developing Evaluation Framework for Intelligent Transport System on Public Transportation in Bangkok Metropolitan Regions Using Fuzzy AHP. *Infrastructures 2021, Vol. 6, Page 182*, *6*(12), 182. https://doi.org/10.3390/INFRASTRUCTURES6120182

Climate Change Report Looks at Nuclear Power, Other Options. (2007). International Atomic Energy Agency. http://www.iaea.org/NewsCenter/News/2007/climatechange_ipcc.html

Cruising speed definition and meaning | Collins English Dictionary. (n.d.). Retrieved December 19, 2020, from https://www.collinsdictionary.com/dictionary/english/cruising-speed

Donges, E. (1999). Conceptual framework for active safety in road traffic. *Vehicle System Dynamics*, *32*(2), 113–128. https://doi.org/10.1076/VESD.32.2.113.2089

Dubey, P. P., & Borkar, P. (2015). Review on techniques for traffic jam detection and congestion avoidance. *2nd International Conference on Electronics and Communication Systems, ICECS 2015*, 434–439. https://doi.org/10.1109/ECS.2015.7124941

EIA. (n.d.). *International Energy Statistics -Total oil (petroleum and other liquids) consumption.* 2021. Retrieved October 8, 2021, from https://www.eia.gov/international/data/world/petroleum-and-other-liquids/annual-refined-petroleum-products-consumption?pd=5&p=0000000000000000000000000000000000000000000000g&u=0&f=A&v=mapbubble&a=-&i=none&vo=value&t=C&g=00000000000000000000000000000000000

FAO. (2017). *Livestock's role in climate change and air pollution 3.1 Issues and trends*.

Favas, P. J. C., Pratas, J., Gomes, M. E. P., & Cala, V. (2011). Selective chemical extraction of heavy metals in tailings and soils contaminated by mining activity: Environmental implications. *Journal of Geochemical Exploration*, *111*(3), 160–171. https://doi.org/10.1016/J.GEXPLO.2011.04.009

Ge, M., Friedrich, J., & Vigna, L. (2020). *4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors*. https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Gordon, D. (2010). *The Role of Transportation in Driving Climate Disruption Energy and Climate Program*. www.CarnegieEndowment.org/pubs.

Guerrero-Ibáñez, J., Zeadally, S., & Contreras-Castillo, J. (2018). Sensor Technologies for Intelligent Transportation Systems. *Sensors 2018, Vol. 18, Page 1212*, *18*(4), 1212. https://doi.org/10.3390/S18041212

Hanlon, W. W. (2020). Coal Smoke, City Growth, and the Costs of the Industrial Revolution. *The Economic Journal*, *130*(626), 462–488. https://doi.org/10.1093/EJ/UEZ055

Hooda, W., Bhole, A., Yadav, P. K., & Chaudhari, D. D. (2016a). An image processing approach to intelligent traffic management system. *ACM International Conference Proceeding Series*, *04-05-March-2016*. https://doi.org/10.1145/2905055.2905091

Hooda, W., Bhole, A., Yadav, P. K., & Chaudhari, D. D. (2016b). An image processing approach to intelligent traffic management system. *ACM International Conference Proceeding Series*, *04-05-March-2016*. https://doi.org/10.1145/2905055.2905091

Huang, J. Bin, Wang, S. W., Luo, Y., Zhao, Z. C., & Wen, X. Y. (2012). Debates on the Causes of Global Warming. *Advances in Climate Change Research*, *3*(1), 38–44. https://doi.org/10.3724/SP.J.1248.2012.00038

INRIX. (2020). 2020 Global Traffic Scorecard. *INRIX Research*. https://inrix.com/scorecard/

Ishizaka, A., & Labib, A. (2011). Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, *38*(11), 14336–14345. https://doi.org/10.1016/J.ESWA.2011.04.143

ITS 국제협력센터. (n.d.). Retrieved November 10, 2021, from https://intl.its.go.kr/sp/02_02

Jie, L. U. (2011). *Environmental Effects of Vehicle Exhausts, Global and Local Effects A Comparison between Gasoline and Diesel*.

Kabalisa, R., & Altmann, J. (2021). AI Technologies and Motives for AI Adoption by Countries and Firms: A Systematic Literature Review. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *13072 LNCS*, 39–51. https://doi.org/10.1007/978-3-030-92916-9_4/TABLES/2

Kerner, B. S. (2009). *Introduction to Modern Traffic Flow Theory and Control*. https://books.google.co.kr/books?id=4g7f1h4BfYsC&printsec=frontcover&dq=Modern+Traffic+Flow+Theory+and+Control&hl=es&sa=X&redir_esc=y#v=onepage&q=Modern Traffic Flow Theory and Control&f=false

Khair, M., & Majewsky, W. (2006). *Diesel emissions and their control*. https://books.google.com/books?hl=es&lr=&id=-XZ0EAAAQBAJ&oi=fnd&pg=PA3&dq=Diesel+Emissions+and+Their+COntrol+&ots=DMg1o1gAHx&sig=3KcmnYqbqsSsOg9EPcBvuaTwdTQ

Krejčí, J., & Stoklasa, J. (2018). Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean. *Expert Systems with Applications*, *114*, 97–106. https://doi.org/10.1016/J.ESWA.2018.06.060

Kurrek, M. M., & Devitt, J. H. (1997). *Education in Anaesthesia The cost for construction and operation of a simulation centre*.

Macknick, J. (2011). Energy and CO2 emission data uncertainties. In *Carbon Management* (Vol. 2, Issue 2, pp. 189–205). https://doi.org/10.4155/cmt.11.10

Maji, A., & Jha, M. K. (2007). *Modeling Highway Infrastructure Maintenance Schedules with Budget Constraints*. https://doi.org/10.3141/1991-03

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & Delgado López-Cózar, E. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Journal of Informetrics*, *12*(4), 1160–1177. https://doi.org/10.1016/J.JOI.2018.09.002

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & López-Cózar, E. D. (n.d.). *Google Scholar, Web of Science, and Scopus: a systematic comparison of citations in 252 subject categories*. https://doi.org/10.31235/OSF.IO/42NKM

Miller, J. (2008). Vehicle-to-vehicle-to-infrastructure (V2V2I) intelligent transportation system architecture. *IEEE Intelligent Vehicles Symposium, Proceedings*, 715–720. https://doi.org/10.1109/IVS.2008.4621301

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*, *339*(7716), 332–336. https://doi.org/10.1136/BMJ.B2535

Morbidi, F., Ojeda, L. L., Canudas De Wit, C., & Bellicot, I. (2014). A new robust approach for highway traffic density estimation. *2014 European Control Conference, ECC 2014*, 2575–2580. https://doi.org/10.1109/ECC.2014.6862333

Mubarkoot, M., & Altmann, J. (2021). *Software Compliance in different Industries: A Systematic Literature Review*.

Munawer, M. E. (2018). Human health and environmental impacts of coal combustion and post-combustion wastes. In *Journal of Sustainable Mining* (Vol. 17, Issue 2, pp. 87–96). Central Mining Institute in Katowice. https://doi.org/10.1016/j.jsm.2017.12.007

Oxford University. (2021a). *congestion noun - Definition, pictures, pronunciation and usage notes | Oxford Advanced Learner's Dictionary at OxfordLearnersDictionaries.com*. https://www.oxfordlearnersdictionaries.com/definition/english/congestion

Oxford University. (2021b). *traffic_1 noun - Definition, pictures, pronunciation and usage notes | Oxford Advanced Learner's Dictionary at OxfordLearnersDictionaries.com*. https://www.oxfordlearnersdictionaries.com/definition/english/traffic_1?q=traffic

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021a). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*. https://doi.org/10.1136/BMJ.N71

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021b). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *PLOS Medicine*, *18*(3), e1003583. https://doi.org/10.1371/JOURNAL.PMED.1003583

Prins, A. A. M., Costas, R., van Leeuwen, T. N., & Wouters, P. F. (2016). Using Google Scholar in research evaluation of humanities and social science programs: A comparison with Web of Science data. *Research Evaluation*, *25*(3), 264–270. https://doi.org/10.1093/RESEVAL/RVV049

Qi, S., & Cheng, S. (2018). China's national emissions trading scheme: integrating cap, coverage and allocation. *Climate Policy*, *18*(sup1), 45–59. https://doi.org/10.1080/14693062.2017.1415198

Rakha, H., & Ding, Y. (2003). Impact of Stops on Vehicle Fuel Consumption and Emissions. *Journal of Transportation Engineering*, *129*(1), 23–32. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:1(23)

Ring, M. J., Lindner, D., Cross, E. F., & Schlesinger, M. E. (2012). Causes of the Global Warming Observed since the 19th Century. *Atmospheric and Climate Sciences*, *02*(04), 401–415. https://doi.org/10.4236/ACS.2012.24035

Rohitratana, J., & Altmann, J. (2012). Impact of pricing schemes on a market for Software-as-a-Service and perpetual software. *Future Generation Computer Systems*, *28*(8), 1328–1339. https://doi.org/10.1016/J.FUTURE.2012.03.019

Rubinstein, S. F. S. and G. J. B. and X.-F. X. and Z. B. (2012). *Real-Time Adaptive Traffic Signal Control for Urban Road Networks: The East Liberty Pilot Test - The Robotics Institute Carnegie Mellon University*. Tech. Report, CMU-RI-TR-12-20, Robotics Institute, Carnegie Mellon University. https://www.ri.cmu.edu/publications/real-time-adaptive-traffic-signal-control-for-urban-road-networks-the-east-liberty-pilot-test/

Saaty, T. L. (2001). *Fundamentals of the Analytic Hierarchy Process*. 15–35. https://doi.org/10.1007/978-94-015-9799-9_2

Salazar-Cabrera, R., Pachón de la Cruz, Á., & Madrid Molina, J. M. (2020). Sustainable transit vehicle tracking service, using intelligent transportation system services and emerging communication technologies: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(6), 729–747. https://doi.org/10.1016/J.JTTE.2020.07.003

Sassykova, L. R., Aubakirov, Y. A., Sendilvelan, S., Tashmukhambetova, Z. K., Faizullaeva, M. F., Bhaskar, K., Batyrbayeva, A. A., Ryskaliyeva, R. G., Tyussyupova, B. B., Zhakupova, A. A., & Sarybayev, M. A. (2019). The Main Components of Vehicle Exhaust Gases and Their Effective Catalytic Neutralization. *Oriental Journal of Chemistry*, *35*(1), 110–127. https://doi.org/10.13005/ojc/350112

Schadschneider, A., Chowdhury, D., & Nishinari, K. (2011). Stochastic Transport in Complex Systems. *Stochastic Transport in Complex Systems*. https://doi.org/10.1016/C2009-0-16900-3

Schwab, K. (2015). Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution. *VDI NACHRICHTEN*, *4*(1), 6.

Shatnawi, I., Yi, P., & Khliefat, I. (2018). Automated intersection delay estimation using the input–output principle and turning movement data. *International Journal of Transportation Science and Technology*, *7*(2), 137–150. https://doi.org/10.1016/J.IJTST.2018.04.001

Statista. (2022). *Motorcycles - Worldwide | Statista Market Forecast*. https://www.statista.com/outlook/mmo/motorcycles/worldwide

Tarko, A. P., Perez-Cartagena, R. I., & Tarko, A. P. (2019). Variability of Peak Hour Factor at Intersections. *Https://Doi.Org/10.1177/0361198105192000115*, *1920*(1), 125–130. https://doi.org/10.1177/0361198105192000115

Tišljarić, L., Erdelić, T., & Carić, T. (2018). Analysis of intersection queue lengths and level of service using GPS data. *Proceedings Elmar - International Symposium Electronics in Marine*, *2018-September*, 43–46. https://doi.org/10.23919/ELMAR.2018.8534668

Tomtom. (2019). *Traffic Index Traffic Index results*. 23.

Towoju, O. A., & Ishola, F. A. (2020). A case for the internal combustion engine powered vehicle. *Energy Reports*, *6*, 315–321. https://doi.org/10.1016/j.egyr.2019.11.082

Types of Traffic Flow. (n.d.). Retrieved December 19, 2020, from https://www.webpages.uidaho.edu/niatt_labmanual/chapters/trafficflowtheory/theoryandconcepts/TypesOfTrafficFlow.htm

United States Department of Transportation. (2022). *Traffic Signal Timing Manual: Chapter 3 - Office of Operations*. https://ops.fhwa.dot.gov/publications/fhwahop08024/chapter3.htm

Urrútia, G., & Bonfill, X. (2010). Declaración PRISMA: una propuesta para mejorar la publicación de revisiones sistemáticas y metaanálisis. *Medicina Clínica*, *135*(11), 507–511. https://doi.org/10.1016/J.MEDCLI.2010.01.015

US EPA, O. (n.d.-a). *Fast Facts on Transportation Greenhouse Gas Emissions*. Retrieved October 25, 2020, from https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

US EPA, O. (n.d.-b). *Overview of Greenhouse Gases*. Retrieved December 12, 2020, from https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, *169*(1), 1–29. https://doi.org/10.1016/J.EJOR.2004.04.028

Watson, A. Y., Bates, R. R., & Kennedy, D. (1988). *Automotive Emissions*. https://www.ncbi.nlm.nih.gov/books/NBK218144/

Yepes-Nuñez, J. J., Urrútia, G., Romero-García, M., & Alonso-Fernández, S. (2021). Declaración PRISMA 2020: una guía actualizada para la publicación de revisiones sistemáticas. *Revista Española de Cardiología*, *74*(9), 790–799. https://doi.org/10.1016/J.RECESP.2021.06.016

Zaharia, C., & Clenci, A. (2013). *RESEARCHES ON THE IMPACT OF*

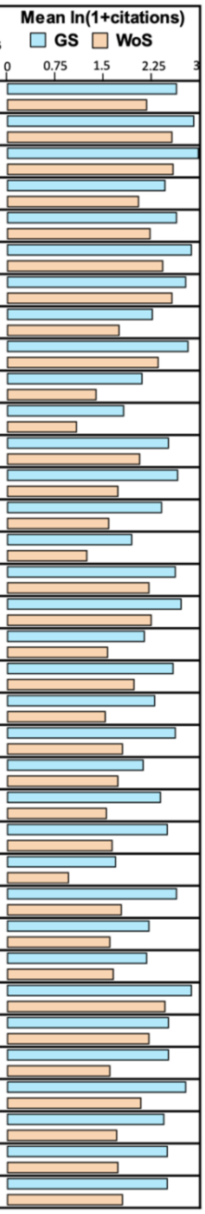
HYPERMILLING TECHNIQUES AND FUEL SAVING DEVICES IN ORDER TO REDUCE POLLUTION IN URBAN AREAS. *39*(3).

Appendix

Appendix 1: Spearman Coefficient Correlation GS– WoS

[1] Spearman Coefficient Correlation GS– WoS

Category (NOWT)	N	*r*	Mean ratio of citation counts GS/WoS
Agriculture and Food Science	24,176	.97	1.74
Astronomy and Astrophysics	16,090	.96	1.60
Basic Life Sciences	134,045	**.98**	1.58
Basic Medical Sciences	23,183	.96	1.76
Biological Sciences	62,094	.97	1.90
Biomedical Sciences	118,817	**.98**	1.72
Chemistry and Chemical Engineering	129,481	**.98**	**1.30**
Civil Engineering and Construction	5,145	.95	1.87
Clinical Medicine	223,309	.97	1.82
Computer Sciences	61,199	.86	3.21
Creative Arts, Culture and Music	1,145	.84	2.80
Earth Sciences and Technology	46,536	.95	1.99
Economics and Business	28,550	.93	3.30
Educational Sciences	13,227	.92	2.92
Electrical Engineering and Telecommunication	68,462	.83	3.18
Energy Science and Technology	19,242	.95	1.86
Environmental Sciences and Technology	64,791	.97	1.86
General and Industrial Engineering	10,757	.92	2.37
Health Sciences	28,371	.95	2.11
History, Philosophy and Religion	5,062	.90	3.15
Information and Communication Sciences	6,214	.94	2.87
Instruments and Instrumentation	6,167	.95	1.74
Language and Linguistics	3,149	.90	3.12
Law and Criminology	4,348	.90	3.37
Literature	368	**.78**	**4.02**
Management and Planning	18,477	.94	2.83
Mathematics	17,187	.91	2.65
Mechanical Engineering and Aerospace	17,006	.91	2.24
Multidisciplinary Journals	44,299	**.98**	1.63
Physics and Materials Science	144,010	.97	1.52
Political Science and Public Administration	8,118	.90	3.22
Psychology	32,875	.95	2.50
Social and Behavioral Sciences, Interdisciplinary	7,001	.93	2.77
Sociology and Anthropology	11,504	.93	2.82
Statistical Sciences	12,955	.92	3.16

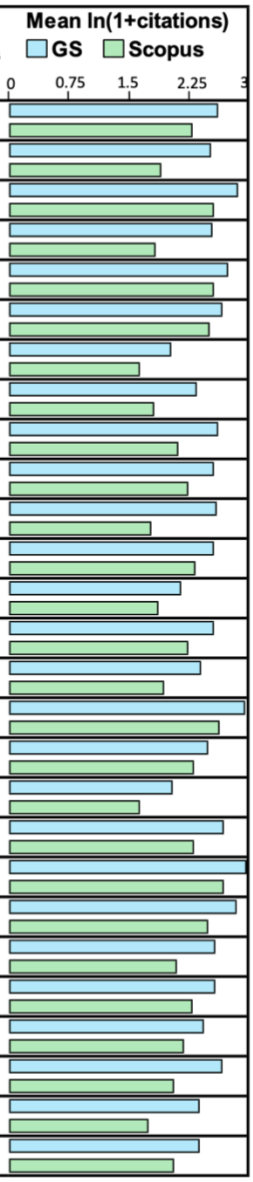


Source: Martín-Martín et al. (2018).

Appendix 2: Spearman Coefficient Correlation GS - Scopus

[2] Spearman Coefficient Correlation GS - Scopus

Category (ASJC)	N	*r*	Mean ratio of citation counts GS/Scopus
Agricultural and Biological Sciences	109,423	.98	1.45
Arts and Humanities	21,698	.95	2.19
Biochemistry, Genetics and Molecular Biology	216,180	**.99**	1.43
Business, Management and Accounting	40,539	.94	2.43
Chemical Engineering	56,569	**.99**	1.27
Chemistry	118,885	**.99**	**1.23**
Computer Science	135,932	.94	1.72
Decision Sciences	13,557	.94	2.04
Dentistry	3,933	.97	1.78
Earth and Planetary Sciences	52,356	.97	1.49
Economics, Econometrics and Finance	22,273	**.93**	**2.83**
Energy	31,166	.98	1.35
Engineering	146,545	.96	1.49
Environmental Science	66,212	.98	1.50
Health Professions	12,309	.96	1.79
Immunology and Microbiology	50,615	**.99**	1.44
Materials Science	108,794	.98	1.27
Mathematics	66,239	.94	1.78
Medicine	361,217	.97	1.56
Multidisciplinary	18,851	**.99**	1.43
Neuroscience	46,462	.98	1.55
Nursing	19,431	.96	1.80
Pharmacology, Toxicology and Pharmaceutics	38,377	.98	1.42
Physics and Astronomy	126,820	.97	1.42
Psychology	42,037	.96	2.09
Social Sciences	81,542	.94	2.22
Veterinary	4,550	.98	1.47



Source: Martín-Martín et al. (2018).

Appendix 3: PRISMA 2020 Checklist

[3] PRISMA Checklist

TITLE		
Title	1	Identify the report as a systematic review.
ABSTRACT		
Abstract	2	See the PRISMA 2020 for Abstracts checklist.
INTRODUCTION		
Rationale	3	Describe the rationale for the review in the context of existing knowledge.
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.
METHODS		
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.

	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.
RESULTS		
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.

Study characteristics	17	Cite each included study and present its characteristics.
Risk of bias in studies	18	Present assessments of risk of bias for each included study.
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.
	20c	Present results of all investigations of possible causes of heterogeneity among study results.
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.
DISCUSSION		
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.
	23b	Discuss any limitations of the evidence included in the review.
	23c	Discuss any limitations of the review processes used.
	23d	Discuss implications of the results for practice, policy, and future research.
OTHER INFORMATION		
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.

	24c	Describe and explain any amendments to information provided at registration or in the protocol.
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.
Competing interests	26	Declare any competing interests of review authors.
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.

Source: Page et al. (2021a).

Appendix 4: AHP Expert Questionary

[4] Expert Questionnaire

In this questionnaire, the following information was to be obtained: The weight of each criterion will be quantified with respect to the fundamental objective of improving traffic flows at intersections with optimal implementation of STL/ITS technologies as an element of the traffic infrastructure under budget constraints. To achieve this, the first stage of the questionary will compare the AHP objective with the three dimensions in layer one (Equation 1).

In the second stage the second- criteria layer (Intersection Delays, Stopped Delays, Travel Time, Deceleration Delays, Queue Length, Construction Costs, Maintenance Costs, Operation Costs, Fuel Consumption, Co2 Emissions, Construction Congestion Costs) will be compared with the third-alternatives layer (Bluetooth Detection, Radar Detection, Inductive Loop Sensors, Video Vehicle Detection, Magnetic Sensors, Acoustic Sensors, Background Extraction, Foreground Extraction, Aerial Images, Smartphone-based, GPS-based).

Comparing these with each other is necessary to choose the one that is most important and quantify by how much more. Next, the criteria that belong to each of the corresponding fundamental criteria are compared in pairs and the expert has to choose the most important criterion and quantify how much more this is. Finally, the three STLS will be evaluated for each criterion.

An AHP evaluation is also suggested for further research with the STL system architectures, frameworks, algorithms, and simulators.

Comparison of first level criteria

1. Which of the following first-layer criterion is most important with respect to the others for a STL system under budget constraints?
   - C1P: Performance | C2C: Costs
   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ()

2. Which of the following first-layer criterion is the most important with respect to the others for a STLS under budget constraints?
   - C1P: Performance | C3E: Emissions
   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ()

3. Which of the following first-layer criterion is the most important with respect to the others for a STLS under budget constraints?
   - C2C: Costs | C3E: Emissions
   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )
   -

B.1 Comparison of the second level: Performance Criteria

1. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
   - C1P.1 Intersection Delays | C1P.2 Stopped Delays
   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

2. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.1 Intersection Delays | C1P.3 Travel Time
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )
    -
3. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.1 Intersection Delays | C1P.4 Deceleration Delays
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

4. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.1 Intersection Delays | C1P.5 Queue Length
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

5. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.2 Stopped Delays | C1P.3 Travel Time
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

6. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.2 Stopped Delays | C1P.4 Deceleration Delays
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

7. Which of the following second-layer performance criterion is the most

important with respect to the others for a STLS under budget constraints?

- C1P.2 Stopped Delays | C1P.5 Queue Length
- How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

8. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.3 Travel Time | C1P.4 Deceleration Delays
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

9. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.3 Travel Time | C1P.5 Queue Length
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

10. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C1P.4 Deceleration Delays | C1P.5 Queue Length
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

B.2. Comparison of the second level: Cost Criteria

1. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C2C.1 Construction Costs | C2C.2 Maintenance Costs
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

2. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C2C.1 Construction Costs | C2C.3 Operation Costs
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

3. Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?
    - C2C.2 Maintenance Costs | C2C.3 Operation Costs
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

B.3 Comparison of second level: Emissions Criteria

Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?

- C3E.1 Fuel Consumption | C3E.2 Co2 Emissions
- How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?

- C3E.1 Fuel Consumption | C3E.3 Construction Congestion Costs
- How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )
-

Which of the following second-layer performance criterion is the most important with respect to the others for a STLS under budget constraints?

- C3E.2 Co2 Emissions| C3E.3 Construction Congestion Costs
- How much? According to the provided Fundamental Satty Scale for

Pairwise Comparisons ( )

Comparison of last layer criteria between specific alternatives:

1. From the point of view of criterion C1P.1 Intersection Delays, which alternative (from A1 to A12) do you think best satisfies the performance criteria?

    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

2. From the point of view of criterion C1P.2 Stopped Delays, which alternative (from A1 to A12) do you think best satisfies the performance criteria?

    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

3. From the point of view of criterion C1P.3 Travel Time, which alternative (from A1 to A12) do you think best satisfies the performance criteria?

    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

4. From the point of view of criterion C1P.4 Deceleration Delays, which alternative (from A1 to A12) do you think best satisfies the performance criteria?

    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

5. From the point of view of criterion C1P.5 Queue Length, which

alternative (from A1 to A12) do you think best satisfies the performance criteria?

- How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

6. From the point of view of criterion C2C.1 Construction Costs, which alternative (from A1 to A12) do you think best satisfies the cost criteria?

   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

7. From the point of view of criterion C2C.2 Maintenance Costs, which alternative (from A1 to A12) do you think best satisfies the cost criteria?

   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

8. From the point of view of criterion C2C.3 Operation Costs, which alternative (from A1 to A12) do you think best satisfies the cost criteria?

   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

9. From the point of view of criterion C3E.1 Fuel Consumption, which alternative (from A1 to A12) do you think best satisfies the emissions criteria?

   - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

10. From the point of view of criterion C3E.2 Co2 Emissions, which

alternative (from A1 to A12) do you think best satisfies the emissions criteria?

- How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

11. From the point of view of criterion C3E.3 Construction Congestion Costs, which alternative (from A1 to A12) do you think best satisfies the emissions criteria?

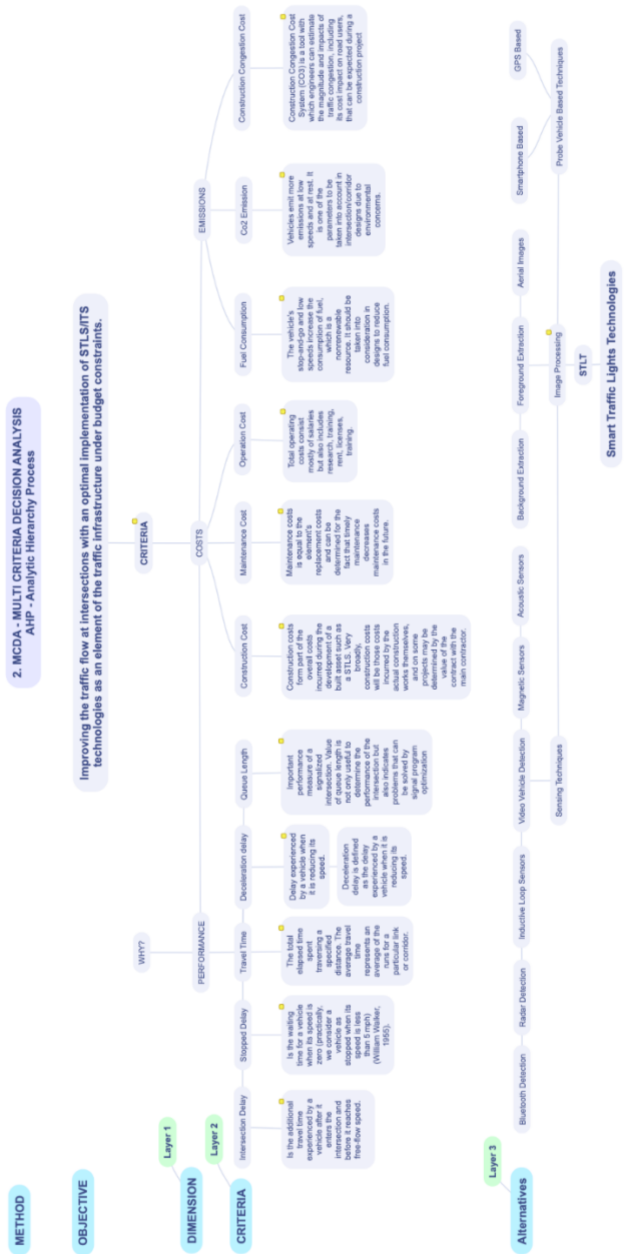
    - How much? According to the provided Fundamental Satty Scale for Pairwise Comparisons ( )

Appendix 5: AHP Electronic Survey Form

[5] Electronic Survey

Appendix 6: AHP Top-Down Hierarchy Model

[6] AHP Top-Down Hierarchy Model



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Abstract (Korean)

기후변화는 전세계적으로 중요한 문제가 되었다. 오염, 특히 유해가스 배출에 의한 세계적인 기온 상승은 생물, 특히 2022 년 기준 7 십억 9 천만명이 넘는 인간의 생존을 위협한다. 이러한 오염 경향은 1 차 산업 혁명으로 거슬러

올라가며 자동차 산업에서 휘발유 첨가제를 도입하면서 전환점에 도달했다. 오늘날 차량 부문은 세계 첫번째 오염원이자 지구 기온 상승과 그에 따른 기후 변화의 주요 원인이다. 과학 전문지는 교통 역학을 분석하고 배출량 증가의 중요한 순간은 차량이 가장 효율적인 연료 소비 속도로 이동해야 하는 교통 혼잡 시간 동안임을 발견했다. 이를 바탕으로 교차로가 차량의 교통수요를 처리할 수 있는 실시간 대응기술이나 장치 부족으로 인한 교통체증의 가장 흔한 원인으로 판단된다. 이와 관련하여 중산층 및 고소득 국가는 교통 관리 시스템의 디지털 전환에 대한 대규모 투자를 통해 차량 교통 혼잡을 줄이기 위해 교통 및 도시 정책으로 인프라를 개선하고 도시를 스마트화하기 위해 여러 현대 기술을 도입하고 있다. 이 문제는 저소득 국가가 인구 요구를 우선하고 예산을 기후변화보다 식량, 주거, 건강, 교육, 안보, 교통에 할당할 때 발생한다. 그래서, 온실가스 오염으로 인한 교통 분야에 연관된 구조적 문제는 계속된다. 이 시나리오에서는 오염이 제거되거나 감소되거나 증가하든, 최종 영향은 세계적인 기온 변화에 달려 있다. 이 이슈를 더 철저하게 조사하기 위해서, 현재의 연구는 두 가지 논점을 제기한다. 첫번째는 "이산화탄소 배출 증가와 교차로에서의 교통 정체가 연관되어 있는가?"이고. 방법론으로서의 체계적인 문헌 검토를 사용했다. 135 건 이상의 문서 스마트 교통신호와 온실가스 배출이. SLR 논문 데이터베이스에서 키워드 추출기가 구현되어 아키텍처, 플랫폼, 프레임워크, 시뮬레이터, 센서, 방법 및 알고리즘을 식별하고 각 항목에서 추출했다. 규화 단어 클라우드 방법을 사용하여, 총 241 개의 서로 관련된 STL 기술을 확인하였고, 2 단계에서 총 135 개의 용어로 감소하였다. 관련 또는 밀접하게 관련된 기술을 조사한 후에는 분류 트리 맵을 사용하여 결과를 27 STL 주요 용어로 제한했다. 연구 질문은 Lu Jie, Watson, Bates 및 Kennedy, Towjua 및 Felix Isholab, Addy Majewski 의 연구에 대한 SLR 식별으로 해결되었습니다; 그들 모두는 교통 체증과 정체 그리고 온실가스 배출 증가율 사이의 상관관계를 확인하기 위해 서로 다른 방법에 동의하고 제공했다. SLR 의 집중적인 기술 설명, 추출 및 정규화를 통해 스마트 신호등 관련 기술, 아키텍처 및 프레임워크를 명확하게 식별할 수 있다.대체 계층 또는 차원을 제공함으로써 AHP 프로세스에서 중요한 단계 중 하나가 되도록 의도된 STL 기술 맵을 생성할 수 있습니다. 두 번째 연구 질문: "STL 시스템 기술의 SLR 식별을 바탕으로 교통 흐름을 개선하고 GHG-Co2 배출량을 줄이는 것을 목표로 예산

제약 하에서 교차로(신호등)의 교통 인프라 요소로 구현하기에 가장 적합한 기술은 무엇입니까?" 의사결정자와 정책 입안자가 가장 적합한 것을 결정할 수 있도록 하기 위해 분석 계층 프로세스(AHP)에 기반한 다중 기준 의사결정 분석(MCDA)에 따라 연구되었다.교차로의 차량 정체 관리와 관련된 IR 기술.

1970 년대 토마스 새티 교수가 개발한 AHP 방법론은 전형적으로 계층적이고 서로 자주 대립하는 다수의 선택 기준 또는 변수를 기반으로 많은 대안 중에서 선택하는 데 도움이 되는 다중 기준 결정 과정이다. 선택 기준과 하위 기준을 신중하게 선택하고, 이를 올바르게 정의하며, SLR 기술, 식별 및 분류를 통해 상호 배타적인 문제임을 확인하는 것이 프로세스의 필수 구성 요소 중 하나입니다. 새티 기본 척도는 조사 과정에서 쌍체 비교를 수행하는 데 사용됩니다. 계층 구조는 하향식입니다. 이 방법의 주제는 질적 측면을 양적 측면으로 전환할 수 있는 목표 > 치수(STL 기능, STL 비용 및 교통 배출) > 기준 > 대안, 다양한 대안 간의 비교를 상당히 용이하게 하고 보다 객관적이고 신뢰할 수 있는 결과를 도출한다. 전문가 설문조사 문항을 기반으로 한 AHP 분석에 따르면,기존 신호등 인프라 업그레이드를 위한 STL 기술을 구현하기 위해 비용 차원이 현재 45.79%로 가장 중요한 요소이며, 그 다음이 효율 차원(41.61%)이다.
대안 수준에서는 유도 루프 센서가 23.67% 동의로 GHG 저감과 함께 교차로 고도화 및 교통흐름 개선에 가장 적합한 기술로 파악됐으며 영상차량 감지 15.02%, GPS 기반 기술 13.37% 순으로 나타났다. 본 연구의 목적은 저소득층 정부가 디지털 전환이나 스마트화에 투자하지 못하게 하는 재정적 제약을 해결하는 것이다. 제안은 SLR 을 구현하여 STL 과 관련된 스마트 기술, IoT, AI 의 최첨단 기술을 파악하고 도로 교차로의 트래픽과 GHG 배출량 증가 간의 상관관계 및 과학적 증거를 찾는 것이다. 그러나 이 연구는 과학적 근거를 식별하고 제공하려는 시도 외에도 교통 관리 전문가와 실무자의 관점에서 이러한 기술을 평가함으로써 결과에 대한 높은 수준의 신뢰성을 제공한다. 따라서 의사 결정자와 정책 입안자 모두 현재의 연구를 바탕으로 유도 루프 센서가 교차로의 교통 흐름을 개선하고 신호등에 실시간 정보를 공급하는 최고의 스마트 기술임을 결정할 수 있다, 단기적으로는 높은 비용으로 이해할 수 있지만 장기적으로는 효율성 측면에서 이점이 있는 초기 투자의 높은 비용에도 불구하고.

주요어 : STL, 교통 체증, 교차로, GHG, Co2, 센서.
학 번 : 2020-25828