

Review Article

A Comprehensive Review on Traffic Control Modeling for Obtaining Sustainable Objectives in a Freeway Traffic Environment

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Traffic control strategy plays a significant role in obtaining sustainable objectives because it not only improves traffic mobility but also enhances traffic management systems. It has been developed and applied by the research community in recent years and still offers various challenges and issues that may require the attention of researchers and engineers. Recent technological developments toward connected and automated vehicles are beneficial for improving traffic safety and achieving sustainable goals. There is a need to develop a survey on traffic control techniques, which could provide the recent developments in the traffic control strategy and could be useful in obtaining sustainable goals. This survey presents a comprehensive investigation of traffic control techniques by carefully reviewing existing methods from a new perspective and reviews various traffic control strategies that play an important role in achieving sustainable objectives. First, we present traffic control modeling techniques that provide a robust solution to obtain reasonable traffic and sustainable mobilities. These techniques could be helpful for enhancing the traffic flow in a freeway traffic environment. Then, we discuss traffic control strategies that could be helpful for researchers and practitioners to design a robust freeway traffic controller. Second, we present a comprehensive review of recent state-of-the-art methods on the vehicle design control strategy, which is followed by the traffic control design strategy. They aim to reduce traffic emissions and energy consumption by a vehicle. Finally, we present the open research challenges and outline some recommendations which could be beneficial for obtaining sustainable goals in traffic systems and help researchers understand various technical aspects in the deployment of traffic control systems.

1. Introduction

Nowadays, environmental pollution caused by transportation systems has received significant attention from the research community [1, 2]. Significant increase in population and economic expansion of developing economies are considered the main reasons for causing air pollution and increase in energy demand [3]. A report of the Ministry of Ecology and Environment of China revealed that traffic emission becomes a major source of air pollution and could cause disease [4]. It is considered as one of the main reasons for causing premature deaths [5], in which most of them are caused by prolonged exposure to substances such as carbon dioxide (CO₂) and nitrogen oxide (NO_x).

According to US Energy Information Administration, the automobile industry consumes 55% of the total fuels in the world [6]. These statistics could increase in the next couple of decades because of the increasing number of vehicles on the road. Therefore, more attention has brought the issue of traffic emissions and sustainability to the ecological and environmental committee of many countries worldwide.

Recently, the sustainability issue has been addressed in various aspects of human activities [7, 8]. Obtaining the sustainability objectives is a complex task, which requires intensive requirements to be fulfilled in order to accomplish that goal. The development of sustainable cities is one of the listed objectives identified during the meeting of the United

Nations held in 2017. It needs to accomplish as a part of achieving the sustainable goal of the 2030 Agenda [9]. To accomplish the 2030 Agenda, the road transportation systems need to adopt social equity and safer traffic mobility by reducing air pollution and providing environmentally friendly vehicle movement.

Sustainable transportation systems have changed the people lives using improved technologies. The main concept of using traffic control that covers the sustainability mobility in all aspects involves protecting the environment and improving the economic and social development [10]. The aim of sustainable transport is to improve the transportation system and enhance the people lives by providing them better services in terms of access to each facility. Various issues related to sustainability in transportation have been investigated by the research community for last couple of decades [1, 2].

Achieving cleaner and sustainable transportation could significantly reduce traffic accidents and congestions. In particular, traffic accidents are the main reason for causing nonrecurrent traffic congestion and also cause serious and fatal injuries. A road safety report by the World Health Organization indicates that 1.35 million people died in road and traffic accidents every year [11]. Also, it reveals that road accidents lead to cause the death of younger people aged between 15 and 29 years. Therefore, traffic accidents are considered a critical issue, which may lead to cause serious health issues and also affect the country's economy. The fatality rate can reduce by taking precautionary measures on both vehicles and roads. The rapid increase in traffic flow could significantly lead to an increase in traffic congestion, which could increase vehicle traveling times and less reliability of traffic systems handling by drivers. However, it is not possible to modify the existing algorithms to increase the traffic flow. In this regard, a need for robust traffic control and management system arises, which can effectively use the existing road conditions without being required to employ the substantial traffic infrastructure and also can perform a comprehensive analysis on the impact caused by system challenges such as traffic management and security system [12].

The traffic control methods are getting the continuous attention of transport researchers and practitioners. It aims to improve road safety by significantly reducing traffic congestions and accidents causing severe injuries. It also provides cleaner and sustainable transportation by reducing traffic emissions. In recent years, various traffic control strategies addressing sustainable issues have been studied [10, 13, 14]. These studies could be useful for nurturing traffic control methods and strategies for the freeway traffic environment and could be applied to improve traffic safety and to reduce environmental impacts. The traffic control strategy aims to reduce traffic congestion caused by various incidents in the freeway traffic environment. The development of the traffic mobility system in terms of passengers and freight has significantly contributed to the economic prosperity of the country. However, it can lead to traffic congestion and worsening of traffic mobility, such as causing frequent traffic congestion, long queues on the road, an increase in travel time, and road rage incidents. Frequent

traffic congestion causes frustration to drivers who realize that one has spent numerous amount of time to arrive at their destinations, which could be used to perform other useful activities [15, 16].

Traffic congestion is further classified into recurrent and nonrecurrent traffic congestion. Nonrecurrent congestion events are usually caused by the traffic accident, signal malfunctioning, and other events that disrupt normal traffic flow and result in the reduction of traffic capacity on the road [17]. Recurrent and nonrecurrent traffic congestion events produce a severe rise in traffic volumes on the road. The intensive use of fossil fuels and numerous number of vehicles on the road are the main reasons for the emission of harmful substances [10]. These types of traffic congestion show numerous amounts of demerits which are influenced by an increase in traffic volume. It is caused by the usage of nonrenewable energy and the large number of vehicles on the road. It is widely evident that vehicular traffic contributes significantly to increase traffic emission and fuel consumption, among which some substances such as carbon dioxide, carbon monoxide, volatile organic compound, nitrogen oxide, and particulate matter contribute to traffic emission. Some of these substances dissipate into the environment, leading to air pollution and smog which affect sustainability. Also, these types of pollutants could cause severe health issues such as respiratory and cardiovascular diseases [18]. Therefore, the effect of these factors needs to be reduced in order to achieve cleaner, healthier, and sustainable transport [19]. Regardless of the rapid technological development in recent years, another issue is that traffic emissions caused by the usage of fossil fuels are still increasing due to a large number of vehicles on the road [20]. Therefore, limiting vehicle emissions is necessary for the sustainable smart city. Although significant achievements in technology development reduce a large amount of vehicle emissions and fuel consumption [21] in recent years, some fossil fuels are still needed to be in the standard range, which can be achieved by using the cleaning technology for reducing traffic pollutants.

The major part of the freeway traffic environment cannot meet the current mobility demands, which resulted in more road users, a large queue on the road, increasing traffic emissions, large road bottlenecks, and raises security issues as well. Design and development of safety models remain a more focused issue for researchers of Communication Engineering background. Since the traffic accidents cause nonrecurrent congestion, one or more lane congestion leads to reduced capacity, and the deceleration is caused by observing accidents or drivers participating in rescue operations [22]. Therefore, there is a need to improve existing traffic control models and transform them into a new perspective to achieve sustainable goals. Also, incorporating an effective road network could be beneficial for reducing traffic accidents and congestions, thereby reducing the amount of fuel consumptions.

A couple of surveys have been presented for addressing traffic control and strategies with sustainable issues [10, 13] in 2019, and there have been significant developments in

traffic control strategies. To the best of our knowledge, there is no comprehensive survey on traffic control and modeling for obtaining sustainable transportation. Pasquale et al. [10] launched a survey on traffic control strategies with various sustainability and traffic control issues for the freeway traffic environment. They discussed the traffic control strategies in terms of objectives of sustainable issues for the freeway traffic environment. They comprehensively discussed the traffic emission and safety models and highlighted various research challenges. Othman et al. [13] presented a survey on traffic modeling and control strategies for providing a sustainable environment. The authors reviewed the existing traffic modeling techniques to determine the traffic emission and amount of energy consumption. They also reviewed issues related to transportation and traffic control strategies in order to implement them in the urban traffic environment. Then, they outlined the challenges and future directions of the eco-traffic management system.

A rapid increase in the number of vehicles on the road often leads to cause traffic incident and congestion, which resulted in significant increase in traffic emission and amount of fuel consumption [23]. In the recent years, several works have been proposed on the traffic control algorithms for the freeway traffic environment. However, the numerous amounts of vehicles on the road daily often need a higher traffic mobilities, improved road structure, and an enhanced traffic management system. Thus, a new set of traffic control strategies should be introduced which aims to achieve aforementioned objectives and to minimize the amount of traffic emission and fuel consumptions and so on.

The traffic control strategies play an important role in obtaining sustainable goals because they not only improve the traffic mobility but also enhance traffic management systems. In this paper, we carry out a comprehensive review of published works that provide different solutions for the traffic control system. The purpose of this survey is to elucidate the roadmap for those who want to do research in the traffic control and strategy in a freeway environment. This survey not only comprehensively discusses the traffic control modeling techniques but also discusses traffic control strategies. We classify the traffic control modeling techniques into three categories such as traffic flow models, traffic emission and fuel consumption models, and safety models. These techniques could be helpful for enhancing the traffic flow under a freeway traffic environment. We comprehensively discuss about traffic control strategies in the freeway traffic environment. These strategies provide useful information that could be beneficial for enhancing urban traffic and safety management system. We then we present a comprehensive review of recent state-of-the-art methods on the vehicle design control strategy and traffic control design strategy. In the end, we outline open research challenges and recommend traffic control strategies for achieving sustainable goals. By comparing with previous surveys, we summarize the contribution of this paper as follows.

The contributions of the proposed survey are the following:

- (i) We present a comprehensive review of different traffic control modeling techniques that helps to provide a reliable solution for obtaining reasonable traffic and sustainable mobilities. Moreover, these techniques could be useful for improving traffic flow in the freeway traffic environment.
- (ii) We discuss various traffic control strategies that help researchers and practitioners to design a robust traffic controller. Moreover, it provides useful traffic information that could improve the traffic flow and enhance the overall performance of the traffic management system.
- (iii) We comprehensively discuss the recent state-of-the-art techniques on the vehicle design control strategy and traffic control design strategy. Adoption of these strategies could be helpful in reducing the amount of energy consumption required by a vehicle.
- (iv) We discuss open research challenges that help researchers to tackle issues while designing a traffic control system. Then, we recommend some control strategies for obtaining sustainable objectives in traffic systems.
- (v) In sum, the proposed survey fills the gap of existing surveys by presenting a comprehensive discussion on traffic control modeling techniques and traffic control strategies, which can be helpful for researchers and practitioners to choose the best research direction for their future work.

The rest of this survey is organized as follows. Section 2 presents the traffic control modeling which consists of traffic flow models, traffic emission and fuel consumptions models, and safety models. These models could perform better for real-time applications and provide accurate estimation of traffic flow and dynamics. Section 3 presents different traffic control strategies in freeway traffic environment. Section 4 discusses the vehicle control design strategy for reducing traffic emission and consumptions, whereas Section 5 discusses traffic control design strategies. Section 6 presents various research challenges and recommendations for the traffic control system. Finally, Section 7 concludes the study.

2. Traffic Control Modeling

Identifying traffic control measures indicates a robust solution, which produces a better measure to obtain reasonable traffic and sustainable mobilities. Various types of control actions have been used to regulate traffic flow in different traffic environments [24]. Ramp management is considered a main issue when applied to traffic lights at on and off-ramps [25], mainstream control, lane-changing warnings, incident notifications, route guidance at intersections, etc. The traffic control modeling techniques are further classified as traffic flow models, traffic emission and fuel consumption models, and safety models as shown in Figure 1.

A traffic control modeling framework is useful to develop various control measures and needs to define in terms of traffic flow description and urban sustainability-related

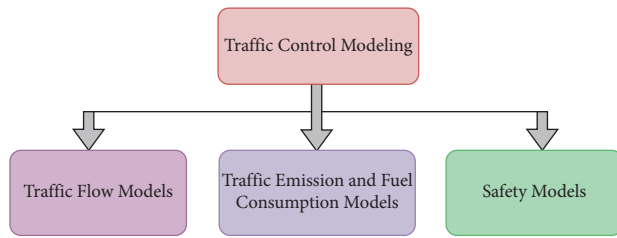


FIGURE 1: Methods of traffic control modeling.

issues. Figure 1 shows the block diagram of freeway traffic control methods such as traffic flow models and traffic safety models. The traffic control mechanism could perform better in terms of real-time applications and provide accurate estimations of traffic flow and dynamics. Note that traffic safety relies on characteristics and features of traffic flow. It can be obtained from various traffic models and require more input information to design and develop a robust traffic safety system.

Most of the various safety models analyze the crash risk based on the road features, weather conditions, etc. The validation and calibration of the safety models remain a critical issue because it requires the collection of a large amount of traffic data over a long period on the freeway traffic environment due to the occurrence of rare events leading to cause traffic incidents. Therefore, the researchers of Communication Engineering and Technology areas should focus on choosing the optimum traffic modeling, which provides accurate estimation and detection of events while maintaining the system computationally efficient.

2.1. Traffic Flow Modeling Technique. In this section, we will discuss the traffic state flow model schemes. Traffic flow (TF) models highlight the dynamic behavior of real traffic systems by developing mathematical relationships. In an intelligent traffic management system, traffic flow prediction could be used for traffic planning, improving traffic and road safeties, and simulating specific control measures [10]. Lighthill and Whitham [26] proposed a wide range of traffic flow using different fields of application. Traffic models can be classified based on different criteria [27, 28]. Figure 2 shows the block diagram of the classification of traffic flow models, which consists of different traffic models such as microscopic, macroscopic, and mesoscopic traffic models.

The main traffic flow classification is further classified as microscopic, macroscopic, and mesoscopic models [28, 29]. These models are distinguished from each other with respect to their detailed levels.

2.1.1. Microscopic Traffic Models. Microscopic models are the computer-based modeling system, which represents the behavior of each vehicle and its drivers in a road network [30, 31]. It depends on different number of generated vehicles, defined network routing, and evaluated vehicle behavior. Due to these variations, it is important to run the model several times to obtain the desired results. Microscopic models are very accurate and usually run on

simulation platforms. However, those can be computationally expensive when applied for control operations [10].

2.1.2. Macroscopic Traffic Models. The macroscopic traffic flow models are the mathematical models and represent traffic dynamics such as traffic density and flow and traffic stream. These models are obtained by combining microscopic traffic flow models and converting the entity characteristics to compare system characteristics [30]. Macroscopic models provide flexible calibration and are less computationally expensive and cheaper than microscopic models [10].

The macroscopic model is further categorized into continuous and discrete traffic models. Discrete traffic models are commonly used in the traffic network. The discrete macroscopic model can be further divided according to the number of state variables accommodated [10]. The first-order macroscopic traffic flow models are the simplest and use dynamics of aggregate vehicles that represent the traffic volume [27]. The commonly used first-order discrete model is named as cell transmission model (CTM). Over the last decades, it has been commonly used by the research community [32, 33]. The CTM model is nonlinear model, which is commonly used for controlling applications [34, 35].

The second-order macroscopic traffic flow model is considered as two dynamic equations, in which the first one represents the density and the second one represents the mean of vehicle speed [36]. A METANET is one of the most reliable techniques for a discrete second-order model [37]. It is a nonlinear model, which is used for controlling applications. However, it is more complex and computationally expensive than the CTM method. In particular, first-order and second-order models are extended to represent the heterogeneous features of traffic flow, which then subsequently lead to multiclass traffic model [10]. They discriminate the user categories according to vehicle types such as a car, truck, and bus and allow the description of some relevant features that cannot be captured by single-class model vehicles.

Recently, various types of multiclass discrete first-order models have been proposed, in which Roncoli et al. [38] introduced the first-order multilane macroscopic model traffic flow for motorway traffic environment. They used the CTM to extend traffic dynamics and considered different traffic scenarios such as changing lanes and traffic flow to compute lateral and longitudinal traffic flows. The result shows that the proposed method obtained a better accuracy on the real-time traffic data. Liu et al. [39] integrated bus class vehicles into the CTM. They applied the BUS-CTM on the road links to determine comprehensive network information. The results obtained from numerical simulations shows that the proposed method obtained reliable performance as compared with other traditional CTM models. Qian et al. [40] proposed a macroscopic heterogeneous traffic flow model to control traffic mobility. They considered the various vehicle classes, which follow homogenous car-following behaviors and vehicle attributes. Boyles and

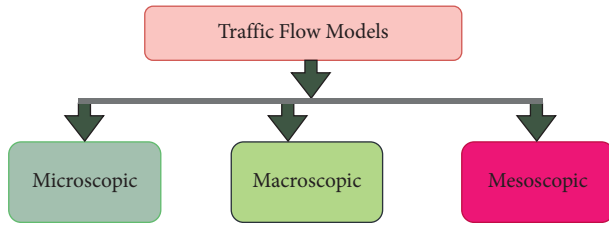


FIGURE 2: Traffic flow models.

Boyles [41] modeled the arbitrary shared road situation using the CTM model. The proposed model relies on variation in traffic capacity and backward speed wave in terms of each class proportions within each cell. The result shows that the proposed method obtained a better performance when the proportion of autonomous vehicles is higher.

Several methods have been proposed for discrete multiclass second-order models. Deo et al. [42] extended the METANET into heterogeneous traffic flow by defining features and class of each vehicle. Liu et al. [43] proposed a multiclass METANET model. It is an extended version of the single macroscopic traffic flow model of METANET. They used a predictive control technique for online traffic control. The results obtained from the simulation show that the proposed method obtained better performance than the single-class METANET model. Pasquale et al. [44] proposed a multiclass control technique for freeway traffic networks. They combined ramp metering and route guidance to reduce a large amount of emissions time. The simulation results revealed that the proposed method implements a better control framework for different vehicle types.

2.1.3. Mesoscopic Traffic Models. The mesoscopic traffic models provide an intermediate detail and describe vehicle flow in terms of probability distributions. It includes cluster models and gas kinetic models.

Traffic models are usually associated with continuous and discrete models. The continuous models represent space and time, and system dynamics are represented with differential equations. On the other hand, in discrete traffic models, space and time are discretized and differential equations can be used to obtain system dynamics. The discrete model is usually used for real-time control scheme in the freeway traffic network. In recent years, researchers from communication and technology background focuses on continuous microscopic models, which is used for controlling the traffic flow system.

2.2. Traffic Safety Modeling Technique. In recent years, several safety models have been proposed, aiming to design traffic safety systems that could provide traffic and road safety. Design and development of safety models remain a more focused issue for researchers of Communication Engineering background due to traffic accidents causing nonrecurrent congestion, one or more lane congestion leading to reduced

capacity, and the deceleration caused by observing accidents or drivers participating in rescue operations [22].

Recently, various studies focused on the statistical analysis of historical crash data associated. In order to determine specific traffic accident conditions and other factors that lead to cause an incident, such as road structure, driver behavior, and environmental factors [45], Lord et al. [46] examined the correlation between traffic safety levels and traffic conditions in a freeway traffic environment. They discussed the relationship between crashes and traffic data of the Canadian site such as traffic flow and density. Potts et al. [47] first proposed the relationship between traffic safety densities. In Ref. [48], Pasquale et al. introduced a risk indicator that can estimate number of crashes in a freeway traffic environment and within specific time limits. As revealed in Ref [48], the index can be added as an objective in the cost function of the control problem. A number of crashes are obtained by combining the two terms, which are related to on-ramps and mainstream. The ramp control may lead to forming a large queue length, which could increase the crashing vehicles at on-ramps sites [10].

Yeo et al. [49] introduced a method to examine the relationship between traffic states and crashes in the freeway traffic environment. First, they discussed different traffic states according to their characteristics and patterns and the states of each freeway network. Then, they integrated the crash data with the traffic states based on upstream and downstream traffic. The proposed method was tested on a 32-mile section of the California I-880 dataset. The result shows that the proposed method obtained a better crash involvement in different traffic states. Chang and Xiang [50] studied the analysis of the possibility of the crash as a function of traffic flow. Golob et al. [51] examined different types of safety level on the freeway traffic environment. They obtained the data from single loop detectors and used them for monitoring different traffic conditions. The proposed method examined over 1700 accidents on the freeway of Orange County, California. Lee et al. [52] performed a study on the characteristics of traffic flow which results in crashes (crash precursors) in the freeway traffic environment. They used data obtained from 38 loop detectors of the Expressway in Toronto to examine the crash precursors. The results show that the potential of crash analysis can be determined based on the precursors collected from real-time data. Pasquale et al. [48] derived the risk indication parameter which is mainly used for traffic control applications. The authors defined the nonlinear optimal control problem, which aims to estimate the number of incidents and crashes. They developed the global safety index, which aims to identify number of incident and crashes in terms of the existing traffic state in the freeway traffic environment. The proposed index implemented the performance indication which is used to evaluate the traffic delay and queue length. The proposed traffic control strategy is considered as the nonlinear control problem with the control variables. These problems could be solved by employing a gradient-based algorithm. The proposed model leads to cause long queue length on both on-ramps and off-ramps and increases the risk of crashes.

2.3. Traffic Emission and Fuel Consumption Models. The traffic emission and vehicle pollution caused by the fossil fuel dispersion in the environment are the main reasons for increasing vehicular traffic. There is a need for an algorithm to determine the traffic emission caused by traffic flow. The traffic emission and the fuel consumption models are regarded as the main issue for developing a sustainable smart city. These models significantly reduce traffic emission by quantifying the pollution into the air and the rate of consumption in terms of different traffic situations such as traffic flow, vehicle speed, and acceleration. These parameters can be obtained by placing the loop detectors on the road network and simulated data generated from different traffic flow models [36, 53].

Generally, traffic emission and fuel consumption rely on the operating conditions of the vehicle configuration and the driver's attitude towards driving and their decision to pass through the signalized intersection [54]. Also, it depends on the acceleration, deceleration, and vehicle speed. Traffic emission not only focuses on the vehicle dynamics but also relies on the adopted fuel, mechanical features, and characteristics of the vehicle. Also, environmental factors such as temperature and humidity affect the sustainability. Recently, several methods have been proposed that aim to make a sustainable smart city by estimating traffic emissions caused by vehicles and amount of fuel consumption. As indicated by Treiber and Kesting [53], the traffic emission model generates local emission in terms of quantified kilograms. In order to make traffic emission model, the researchers rely on the model using descriptive power for meeting their application requirements. For example, several types of microscopic models are commonly used for offline evaluation, while the macroscopic models are generally used for controlling traffic applications because those comprehensively analyze the traffic management system with an efficient computational framework.

COPERT is the most common method of the macroscopic emission model which is used for traffic control at the freeway traffic environment [55, 56]. The COPERT model computes the local emission factors with different range of pollution along with various kinds of vehicles and associates with different average speed emission models. It is distinguished from the traffic emission model based on the traffic control technology, that is, embedded on-board vehicle. Also, the COPERT model provides a better estimation of different traffic conditions with less computational time. Thus, it is considered as a more robust and suitable modeling approach for online control schemes.

Recently, various traffic control approaches have been employed to overcome the limitation of the COPERT model such as the macroscopic form of microscopic emission models so that the VERSIT+ and VT-micro models could be extended to macroscopic case and are called as VT-macro [57] and macroscopic VERSIT+ [58]. These regression-based models use the relationship between speed and acceleration and achieved them using a linear-based regression model [10]. These kinds of models are different from COPERT by considering acceleration effects to obtain an accurate traffic emission. The VT-macro and the

macroscopic VERSIT+ could be used as single and multi-classes based on the traffic control system and traffic model.

In Ref. [57], Zegeye et al. introduced a macroscopic framework for solving traffic control issues. They integrated the macroscopic and microscopic emission models with each other. Then, they demonstrated the proposed framework by considering METANET and VT-macro models. Second, they identified the error produced by the VT-macro model in comparison with the original VT-macro model. Finally, they assessed the performance of the proposed method by analyzing the error introduced by the VT-macro model and determining the computational time of the Dutch A12 highway. The aim of the VERSIT+ macroscopic model is identified by limited parameters with the simple computational method. Therefore, it could be implemented in online traffic control schemes. The VERSIT+ macroscopic model in the multiclass domain computes the traffic emission factors in terms of mainstream traffic flow and assesses them from entering on-ramps and off-ramps based on the average vehicle speed and acceleration. These parameters are aggregated based on the vehicle class. Pasquale et al. [59] introduced a two-class macroscopic emission model to overcome the traffic pollution generated on the freeway. They employed a two-class embedded local traffic controller that relies on a ramp metering model to minimize traffic emission and congestion. The simulation result shows that the proposed model obtained a better reduction in traffic emission.

Recently, a few dispersion models have been proposed to overcome traffic emissions, which aim to enhance the sustainable smart city. In this regard, Buckland and Middleton [60] introduced a dispersion model which could identify high-level complexity by considering different environments, such as atmospheric obstacles. To develop robust traffic control strategies for obtaining sustainable objectives, the traffic dispersion model could be formulated as highlighted in Ref. [61]. In Ref. [61], Csikós et al. proposed a dynamic model for dispersing highway traffic emissions. They developed an integrated model with a Gaussian plume model which is transformed into a discrete time and space. This discrete model is computationally efficient and produces a better output when applied to traffic control systems and leads to transformation into a sustainable smart city. Zegeye et al. [62] introduced a model-based traffic control system for controlling vehicle speed limits and reducing road traffic emission at freeway. They aimed to reduce emission dispersion levels by considering a nearby public area on the freeway, travel times, and the wind speed direction. The simulation result reveals that the proposed system obtained a better dispersion of traffic emissions.

3. Traffic Control Strategies in Freeway

In recent years, traffic control for the freeway traffic environment embarks a great deal of attention from the researcher of communication and technology background. The related existing schemes can be further categorized as traffic modeling, control mechanism, and sustainable control strategy types. These techniques play an important role for designing freeway traffic controllers and provide relevant

TABLE 1: Summary of the research works on the traffic control strategy.

Reference	Year	Features/objectives	Control strategy	Control method	Emission	Sustainability issue
Pasquale et al. [44]	2017	Introduced a multiclass based traffic control method that combines two control strategies	✓	✓	✓	✓
Ferrara et al. [58]	2017	Introduced a control system to regulate traffic flow in the freeway traffic network.	✓	✓	✓	✓
Zegeye et al. [63]	2012	Introduced a predictive traffic controller using parameter control policies	✓		✓	✓
Groot et al. [64]	2013	They investigated an integrated METANET freeway and the VT-macro emission models.	✓		✓	✓
Csikós et al. [65]	2018	They discussed methods for reducing jam waves.	✓	✓		✓
Liu et al. [66]	2017	They added endpoint on the multiclass traffic flow to identify the behavior of traffic pattern.	✓		✓	✓
Wang et al. [67]	2016	Estimate different traffic conditions.	✓	✓		
Ahn and Rakha [68]	2013	Examined the impacts of using eco-routing system strategies.	✓	✓	✓	✓
Abdel-Aty et al. [69]	2006	Discussed various speed limit strategies mechanism for improving safety.	✓	✓		✓
Sheikh et al. [70]	2020	They introduced an incident detection technique using the V2I model.	✓	✓		✓
Yu and Abdel-Aty [71]	2014	Examined the feasibility of using VSL	✓	✓		✓
Pasquale et al. [72]	2014	They proposed a two-class traffic control strategy	✓	✓	✓	✓
Li et al. [73]	2014	Used a generic model to solve the optimization problem	✓	✓		✓
Groot et al. [74]	2015	Employed Stackelberg game to reduce traffic congestion.	✓		✓	✓
Pasquale et al. [75]	2015	Employed a multiclass ramp metering technique to reduce traffic emission.	✓	✓	✓	✓

information to improve sustainability in the urban traffic system. Table 1 shows the research works on traffic control strategies.

3.1. Modeling Framework Classification. In freeway traffic control, different types of models can be used for investigating freeway traffic control strategies. These models are considered as a subset of model-based control techniques and can be effectively used for simulating and validating different traffic scenarios.

Several studies have used METANET as a traffic flow model and VT-macro emission model [63]. In Ref. [63], Zegeye et al. introduced a predictive traffic controller using parameter control policies. They adopted different control measures to identify different traffic conditions and features. The proposed model can significantly reduce computational time. Groot et al. [64] investigated an integrated METANET freeway and the VT-macro emission models using the model-based predictive control (MPC) technique. The author proposed a piecewise-affine approximation (PWA) based nonlinear METANET model to control real-time applications. The proposed method obtained a better computational speed by using the cost function values. Csikós et al. [65] proposed a second-order METANET model-based control system to reduce jam waves on the motorway. They designed different controllers that are used to measure predefined control modes. Ferrara et al. [58] introduced a control scheme to regulate traffic flow in

freeway networks. They used the ramp metering technique to identify and reduce traffic congestion. They used the METANET and macroscopic VERSIT+ model to improve the traffic regulations.

The multiclass METANET utilizes the COPERT in order to evaluate the traffic emission model. It combines with the macroscopic model of the multiclass VERSIT+ model [44, 48]. Liu et al. [66] compared extended versions of multiclass METANET, FASTLANE, and multiclass VERSIT+. They added endpoint on these multiclass traffic flows to identify the behavior of traffic pattern. Ahn and Rakha [76] estimated traffic emission and fuel estimation using the data obtained from the probe vehicle. Wang et al. [67] introduced an efficient multiple model particle filter (EMMPF) using the GPS equipped probe vehicle to estimate different traffic conditions such as estimation and detection. Ahn and Rakha [68] proposed the VT-microemission model to determine emission and applied a microscopic model to simulate various traffic dynamics models.

Recently, the microscopic traffic simulation model was used to evaluate different speed limit variations. Lee et al. [77] proposed automatic control strategies that aim to reduce the likelihood of a crash on freeway traffic. They used a microscopic simulation model to simulate different traffic situations using variable speed limits and an integrated crash prediction model. The simulation results demonstrated that the proposed method could minimize 5–17% of crash risk by reducing risky traffic situations. Abdel-Aty et al. [69]

proposed a various speed limit strategies mechanism for improving safety in the freeway traffic environment. The proposed system improved the efficiency of medium to high speed situations on the freeway. Sheikh et al. [70] proposed an improved incident detection method using vehicle-to-infrastructure communication (V2I). First, they developed a connection between the vehicle and roadside unit (RSU). Second, they used a probabilistic approach to obtain traffic information using V2I communication. Third, a hybrid observer is employed to estimate the possible occurrence of traffic incidents [78, 79]. Finally, a V2I communication-based lane-changing speed mechanism was developed to detect traffic incidents and thereby significantly reduce traffic congestion and improve traffic flow. The simulation results revealed that the proposed method obtained a better detection of traffic incidents. Therefore, it significantly reduces crash risks and improves the dissipation of traffic congestion. Yu and Abdel-Aty [71] examined the feasibility of using a variable speed limit (VSL). They used an active traffic management system (ATS) to enhance traffic flow on freeway traffic scenarios. First, they used an extended METANET model to evaluate the VSL effects on traffic flow. Second, a real-time crash risk mechanism is applied to determine the risk associated with that. Finally, an optimizing technique is employed to determined VSL strategies. The simulation results reveal that the proposed system could reduce chances of crash risk and thereby improve traffic flow.

3.2. Classification Based on Control Theory. Traffic classification can be further classified based on control theory for the freeway traffic environment according to the traffic control system and control strategies, and its impacts on developing sustainable traffic systems. Several works have been proposed on control techniques of classification, which used simple control rules to design a robust control algorithm. Pasquale et al. [72] proposed a two-class traffic control strategy. They used different types of vehicles that represent the dynamic model and separate control. They adopted the PIALINEA control strategy to reduce traffic emission and to alleviate traffic congestion. Also, the feedback controller was proposed by Pasquale et al. [80], in which the control mechanism was used to predict and control the traffic classification model.

Additionally, other research works have been proposed that are based on optimization control techniques [48, 71], while Li et al. [73] proposed a generic model, which is used for solving the optimization problem. The application of optimization-based technique in the real-time conditions can be considered as the model predictive control (MPC) technique [62, 64, 65]. Generally, the MPC techniques are computationally expensive for real-time applications [10]. In Ref. [63], Zegeye et al. proposed predictive traffic controller in terms of parameterized control. They employed the MPC technique to control the freeway traffic. The proposed method obtained a significant reduction of computational controller processing. Groot et al. [74] proposed different techniques for extending the Stackelberg game to reduce traffic

congestion. In the proposed system, the traffic authorities can induce drivers to follow the traffic pattern using the Stackelberg game. The proposed mechanism obtained an optimum behavior by considering a heterogeneous driver class. In recent years, some of the previous papers do not use traffic classification control mechanism. However, these methods examined traffic control in terms of various simulation tools used to evaluate issues of urban cities [69, 76]. Also, some methods investigate the effects of speed limits and ramp metering [69, 81].

3.3. Classification Based on the Control Strategy Type.

Selecting and implementing control strategies requires thorough study and investigation to obtain a sustainable traffic control system and its goal. The researchers and practitioners should consider these strategies when designing traffic control models. We can observe from the literature that some control strategies are very effective when it comes to implementing various control strategies such as the ramp metering technique combined with other control methods leads to obtain a sustainable goal. Note that this application could cause long vehicle queues on the ramp which lead to producing emissions and increase the likelihood of traffic incidents and crashes. In this regard, several methods have been proposed which aim to reduce the pollution emission and the possible risk of incidents and crashes at the ramps [48, 58, 66].

Ferrara et al. [58] proposed a congestion and emission reduction scheme for the freeway traffic network using a ramp metering technique. They employed a supervisory based traffic control technique, which receives measurements from the entire network to predict the system performance. The supervisory mechanism takes a decision when the controller needs to change which is followed by a triggered logic. Liu et al. [66] employed a macroscopic traffic flow and emission model to predict traffic networks. The results show that the proposed emission model can improve the performance of traffic control in terms of the total emission. Also, it can reduce large queue lengths as compared to other approaches. Pasquale et al. [48] introduced a control system for reducing traffic congestion and enhancing traffic safety. They developed a safety index that determines the possible number of crashes by considering the function of existing traffic state. The simulation result shows that the proposed index could mitigate traffic congestion and enhance the performance of the traffic management system. These schemes utilized the ramp control strategies and analyzed the risks associated with on-ramp merging areas. Also, they were successfully applied to overcome the traffic emission and incident issues.

Several traffic and emission models are capable of reducing traffic emissions as compared to other traditional methods [58, 76, 82]. Recently, various studies use the combination of variation of speed limits and ramp metering to overcome traffic flow and emission [62, 63, 65]. These approaches produced robust results especially when they were employed for improving the traffic safety and

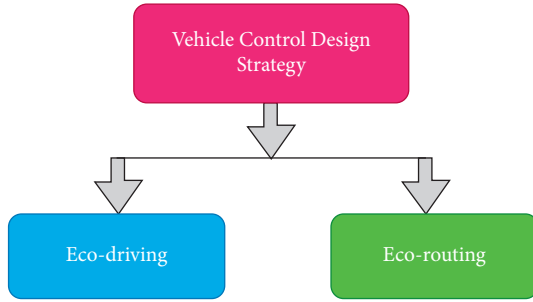


FIGURE 3: Vehicle control design strategy.

management system. The control strategies implemented by these methods significantly reduce the number of traffic incidents and crashes, thereby improving traffic safety. Note that the effectiveness of the different speed limits for reducing traffic incidents and crashes relies on the speed level recommended [71, 77]. We can observe from the literature survey that traffic control techniques are generally used to reduce traffic emissions and minimize the environmental factor influenced by them. These works aimed to reduce the number of traffic incidents in the freeway traffic environment. They could produce better results by obtaining a sufficient safety level.

The aforementioned methods could be extended to a multiclass framework which was assessed and compared with other traditional traffic control methods, which could be used to perform specific control tasks. Pasquale et al. [75] employed a multiclass ramp metering technique to reduce traffic congestion and emission. The proposed method allows heavy vehicles to enter the highway freely without waiting on-ramps. It significantly reduces traffic congestions and emissions by limiting the heavy traffic on-ramps which may be the source of high emissions. Pasquale et al. [44] introduced a multiclass based traffic control method that combines two control strategies. Pasquale et al. aims for reducing traffic congestions and emissions by applying them. They evaluated the control system by predicting the control system in terms of traffic scenarios and by measuring system state. The multiclass control schemes require comprehensive strategies and accurate system modeling as compared to the single-class methods. Also, the traffic safety and management system needs more robust safety models which has the capability of identifying the impact of traffic incidents and crashes on these classes of control system.

The route guidance becomes one of the successful techniques for reducing traffic emissions and crashes in freeway traffic environments and is considered an eco-routing strategy. Such as the environment and energy effects formed by the generated route and the choice of selected route by drivers are analyzed in-depth in [76]. Ahn and Rakha [68] examined the impacts of using eco-routing system strategies. The proposed system investigated various congestion and penetration levels by performing the test on real-time traffic conditions of Cleveland and Columbus, Ohio, USA. This method provides an eco-routing system that could minimize the traffic emission and fuel

consumption which are generally obtained by reducing travel distance.

4. Vehicle Control Design Strategy

This section discusses the vehicle control strategy for reducing traffic emissions and consumption. This goal can be achieved by using an eco-driving system that analyzes and computes a vehicle trajectory, which resulted in reducing traffic emission and energy consumption corresponding to a vehicle route. The eco-routing system is used to plan a route that requires minimum energy and emissions. Recently, a few works have been proposed to discuss the different vehicle control strategies [13, 83], which could reduce traffic emissions are shown in Figure 3. The summary of research works on the vehicle control design strategy is listed in Table 2.

4.1. Vehicle Eco-Driving. Eco-driving is a modern and efficient style of driving that reduces fuel consumption and improves traffic safety. It computes and analyzes the initial vehicle trajectories to process for embedded algorithms. The parameter values are used to forecast road structure, traffic flow, and congestions, and various limitations such as vehicle trip time and maximum vehicle speed. Some of the limitations rely on the driver's attitude towards driving, such as driving a vehicle while traffic signal lights are flashing [83].

In eco-driving, the ego-connected vehicle can cooperate with other vehicles on the road. For instance, a group of vehicles (platooning) that travel together closely and safely at high speed. The aim of using the eco-driving mechanism is to reduce fuel consumption and aerodynamics drag, and when the eco-driving uses a multivehicle scenario, the information processing is more complex as compared to the single-vehicle.

Let us assume the vehicle vector at time step function tt as $q(t) = [m(t), v(t)]^T$, where m represents the vehicle position along the specific route and v denotes the speed of vehicle. The aim of the eco-driving is to evaluate each time step t input vector $z(t) = [H_{em}(t), H_{en}(t)]^T$, where H_{em} and H_{en} represent the traction force and mechanical brake force, respectively. The input vector $z(t)$ has an ability to significantly reduce traffic emission or energy consumption by the vehicle [13].

The optimization problems of eco-driving are represented as follows [84]:

$$\min_{z_0, \dots, z_{m-1}} \sum_{t=0}^{m-1} g(q(t), z(t)). \quad (1)$$

Reference [13] indicated that the vehicle state at time step at $t + 1$ function can be written as follows:

$$f(q(t), z(t)) = \left(\begin{array}{c} m(t), \vartheta v(t) \\ v(t) + \frac{\vartheta(H_{em}(t) - H_{en}(t) - H_{re}(t))}{M} \end{array} \right), \quad (2)$$

TABLE 2: Summary of the vehicle control design strategy.

Reference	Year	Technique	Features/objectives	Performance	Application
Sciarreta et al. [84]	2015		Considering different road conditions, such as online and offline for real-time analysis and estimation.	Reduces traffic emission and fuel consumption.	Sustainable smart city.
Ozatay et al. [85]	2014		Reducing energy consumption based on the velocity optimization problem.	Significantly reduces energy consumption.	Sustainable smart city.
Dib et al. [86]	2012		Employing performance metrics to determine the energy efficiency based on intelligent eco-driving methods.	Helps in obtaining better energy efficiency.	Sustainable smart city.
Hellström et al. [87]	2009		Minimizing trip and fuel consumption using the on-board optimization controller.	Reduces amount of fuel consumption.	Sustainable smart city.
Dimitrakopoulos and Demestichas [88]	2010		Notifying the driver about traffic light cycles prior to arriving at signal intersection.	Provides a better traffic light cycles notification at signal intersection.	ITS.
Ozatay et al. [89]	2014		Considering traffic lights as stop signs to optimize the speed trajectory.	Better optimization of the vehicle speed trajectory.	ITS.
Maher and Vahidi [90]	2012	Eco-driving	Using a signal phase and timing information to obtain vehicle energy consumption.	Obtains a better energy efficiency and less computational time.	Sustainable smart city.
Sun et al. [91]	2018		Investigating speed planning when CVs communicate with traffic lights.	Improves traffic flow and significantly reduces traffic congestion.	ITS.
Miyatake et al. [92]	2011		A method for eco-driving based on dynamic programming by considering traffic signal on the road.	Reduces traffic congestion and enhance traffic flow.	Sustainable smart city/ITS.
HomChaudhuri et al. [93]	2017		Control using the decentralized strategy for each vehicle that forms its own strategy based on the neighboring vehicle.	Enhances traffic management system in terms of reducing traffic congestion and lane-changing warning.	ITS.
De Nunzio et al. [94]	2016		Solving the nonconvex control problem using a suboptimal strategy.	Enhances traffic flow with less computational time.	Sustainable smart city/ITS.
Zhang and Cassandras [95]	2018		Introducing a control strategy method to reduce energy consumption based on the maximum throughput criteria.	Significantly reduces amount of energy consumption.	Sustainable smart city.
Boriboonsomsin et al. [96]	2012		Using the eco-routing navigation system to determine the route between trip origins and destinations.	Improves the vehicle navigation system.	ITS.
Ericsson et al. [97]	2006		Using eco-routing to identify and classify the road networks in various different groups based on the GPS device.	Reduce substantial amount of fuel consumption.	Sustainable smart city/ITS.
Liu [98]	2015	Eco-routing	Integrate a microscopic vehicle emission model into the Markov decision process to solve signalized traffic issues.	Improve traffic flow at signalized intersection.	Sustainable smart city.
De Nunzio et al. [99]	2017		A real-time searching algorithm which could provide drivers with different sets of solutions.	Reduces traffic congestion and improves vehicle traveling time.	Sustainable smart city.
Kluge et al. [100]	2013		Solved a time-dependent eco-routing using the Dijkstras algorithm.	Efficient energy consumption in all road networks.	Sustainable smart city/ITS.
Nannicini et al. [101]	2012		To overcome vehicle traveling time and distance	Significantly reduces the complexity of route planning.	ITS.

where $H_{re}(t)$ denotes the resistance force caused by driving vehicle.

The problem associated with eco-driving is the traction force H_{em} and mechanical brake force H_{en} . These forces are directly applied to the input and are compatible with autonomous and connected vehicles in terms of vehicle position and directions (longitudinal and lateral). Note that

eco-driving creates various issues for human drivers to return the speed profile that vehicle users can follow [13].

Sciarreta et al. [84] introduced several methods to overcome eco-driving control problems. They aim to reduce traffic emissions caused by transportation energy. Sciarreta et al. considered all the road conditions (online and offline) for real-time analysis and estimation. Recently,

various methods have been proposed for energy efficiency and offline optimization. Ozatay et al. [85] provided a solution for reducing energy consumption based on a velocity optimization problem. They incorporated the road conditions (road structure and grade) with an optimization problem and generated a vehicle speed trajectory corresponding to a given vehicle route. They tested the performance of the proposed system in terms of various problems and compared it with a dynamic programming solution. The results show that the proposed method generates a better vehicle trajectory for about 10% as compared to the cruise speed control method. Dib et al. [86] introduced an evaluation approach for energy of the electrical vehicle. They used the performance metrics to determine the energy efficiency by using intelligent eco-driving methods.

Additionally, a few works for providing online solutions have been presented in the recent past years [87]. Hellström et al. [87] introduced a method for minimizing trip and fuel consumption. They used an on-board optimization controller by considering the road slope and a GPS device to obtain the road geometry and its conditions. They performed the experiments using a heavy truck in the freeway traffic environment. The results show that the proposed method could significantly reduce the fuel consumption in an eco-driving vehicle.

In an urban traffic environment, eco-driving is complex and challenging due to nonlinear traffic flow. At traffic signal intersection, it is very difficult to know the traffic lights before arriving at the intersection due to phase duration that depends on amount of traffic flow on the street. As stated by Demestichas [88], intelligent transportation systems and urban traffic management systems could reduce these issues and notify the driver about traffic light cycles before arriving at the signal intersection. Ozatay et al. [89] proposed a method for optimizing the vehicle speed trajectory. They considered traffic lights as stop signs to optimize the speed trajectory. The driver can send the traffic information to the cloud. Then, the cloud server generates the routes and collects the corresponding traffic information, (i.e., the number of vehicles at traffic signal intersection). Finally, they solved the optimization problem based on these information using a dynamic programming method. The proposed system uses a speed advisory system, in which the driver has the choice not to follow the generated velocity produced by the algorithm when the traffic light is green.

Note that the irregularity and uncertainty of traffic light cycles at signal intersection remains a challenging issue. In this regard, Maher and Vahidi [90] presented a planning algorithm for predicting optimal velocity. The proposed method uses a signal phase and timing information to obtain vehicle energy consumption. They considered the case with no prior phase knowledge or timing indicates an unaware driver and provides minimum energy required for a vehicle. The proposed prediction model is evaluated by considering average time data and real-time data. The results obtained from the numerical simulation show that the proposed method obtained efficient energy. Sun et al. [91] examined the speed planning issues when connected vehicles (CVs)

communicate with traffic lights. They considered the eco-driving problem as a data-driven optimization problem. Second, they defined the duration of red light as a random variable and performed an analysis on the amount of time required by a vehicle passing through the traffic signal intersection.

Several methods have been proposed to overcome the eco-driving issues [92–94]. In Ref. [92], Miyatake et al. presented a method for eco-driving based on dynamic programming. They evaluated the effectiveness of the proposed method by considering the road with a traffic signal in the simulation network and obtained a better performance. HomChaudhuri et al. [93] developed a model predictive control method for connected vehicles in the urban traffic environment. The control system consists of a decentralized strategy for every vehicle since its form owns a strategy based on the neighboring vehicle. The experimental results show that the proposed control method is computationally effective. De Nunzio et al. [94] proposed a method for consuming less energy while a vehicle travels through the signal intersection. The proposed method solves the nonconvex control problem using a suboptimal strategy. After retrieving convexity, they solved the optimization problem using a given route to determine the vehicle crossing time at each signal intersection. The proposed method produces a better result which could be used for online verification and obtained a lower computational processing time.

In order to improve the traffic safety and avoid traffic incident and crashes, Zhang and Cassandras [95] introduced a control strategy method. It aimed to reduce energy consumption based on the maximum throughput criteria. First, they highlighted the problem between controlling connected vehicles (CVs) and nonCVs traveling on the road to reduce energy consumptions. The simulation results demonstrated that the proposed method significantly reduces energy consumption by increasing penetration rates of CVs on the road. The problem associated with eco-driving algorithms is that they need an accurate traffic condition such as number of traffic flow, road strategy, and safety conditions. These traffic conditions could be obtained by various equipment that are placed on the road such as electronic sensors, loop detectors, and a macroscopic traffic model. Obtaining parameter values from these equipment remain a challenging issue due to uncertainty and difficulty to predict driver's decision-making for selecting the traffic route and to analyze the safety margin for pedestrians.

Autonomous and connected vehicles provide a significant reduction in traffic consumption since they can accurately receive information and guidance from eco-driving algorithms [102]. When connected vehicles form a platoon and communicate with each other, they can reduce energy consumption along a given traffic route at which the platoons were formed even if they have different traveling destinations [103].

4.2. Vehicle Eco-Routing. The eco-routing plays a significant role for planning and determining the energy-efficient route.

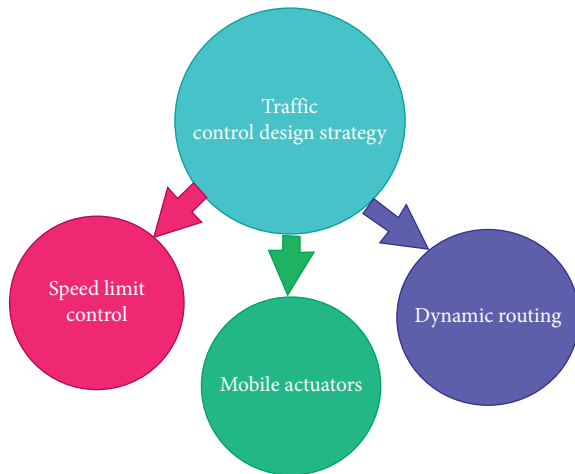


FIGURE 4: Traffic control design strategy.

It determines an optimum route based on users requirements, road maps, and structures such as traffic flow, traffic speed, and fuel consumptions. [83]. The g function is connected to each link that the traffic emission of a vehicle travels on a link of that route. Generally, the g function depends on time function t since traffic network conditions change rapidly, and the function g depends on the link when we apply static eco-routing algorithms [13].

Boribonsomsin et al. [96] introduced an eco-routing navigation system using real-time traffic information. They determine the route between trip origins to destinations using the eco-routing algorithm. Then they used a dynamic road database using a fusion algorithm. Second, they evaluated the real-time vehicle trajectories to determine the energy consumption of each link. Ericsson et al. [97] introduced a method for estimation of reducing fuel consumption. They used an eco-routing algorithm that identifies and classifies the road networks in various different groups based on GPS devices. They performed the analysis using a large amount of database of real traffic patterns obtained from the road network. Then, they extracted different routes from the database in order to evaluate the fuel-saving navigation system. Moreover, they determine the model performance during peak and nonpeak traveling hours for the entire day.

Generally, the eco-routing algorithms could only consider the cost of the link associated with the vehicle route. It does not consider vehicle patterns at the signalized intersection. Although this aspect plays an imperative role in reducing traffic emissions or fuel consumption, several methods have been proposed that focus on designing energy consumption at the road intersection. Liu [98] proposed an eco-routing algorithm for solving signalized traffic issues. He integrated a microscopic vehicle emission model into the Markov decision process. High-resolution traffic data consist of vehicle entry and exit status which are used to evaluate the performance of the proposed method. De Nunzio et al. [99] proposed a method for biobjective eco-routing in urban traffic environments. They formulated the routing problem using a weighted sum optimization method. Then, they presented a real-time searching

algorithm, which could provide drivers with different sets of solutions. The simulation results show that these strategies could reduce energy consumption and traveling time.

Kluge et al. [100] introduced used an energy-efficient route in the urban traffic road network. First, they performed an analysis on energy consumption of the road network and then derived the traffic measurement using a mesoscopic traffic model. Then they solved a time-dependent eco-routing using the Dijkstras algorithm. The heuristic searches can be used to determine energy-efficient routes as indicated by Ref. [101]. It has overcome the complexity of route planning caused by the uncertainty of vehicle arrival time at destination using time-dependent graphs [101].

Eco-routing algorithms require a large amount of computational time due to planning of an energy-efficient route. In order to reduce the computational time of an eco-routing algorithm, one can consider reducing vehicle traveling time or minimizing a route distance. Moreover, the computational time can also be reduced by employing a multiobjective eco-routing algorithm, which not only aims to minimize traffic emission but also reduces the vehicle traveling time and distance. In this regard, a few works have been presented, which aim to overcome vehicle traveling time and distance [99, 104].

5. Traffic Control Design Strategy

This section discusses various traffic control design strategies which aim to reduce traffic emissions and energy consumed by a vehicle. We will review different traffic control strategies, which play a significant role in reducing traffic emissions or energy. Such control strategies could be useful for improving traffic flow and traffic management systems in terms of controlling vehicle speed limits, traffic light control, splitting traffic flow at different signal intersections, and using different actuators. The traffic control strategies rely on various actuators, as illustrated in Figure 4. We will comprehensively discuss the various actuators which could be used for implementing traffic control strategies in different traffic environments.

Traffic control strategies aim to minimize traffic emission and energy by implementing different optimization methods. In the past, several algorithms have been proposed which aims to alleviate traffic incident and congestion and to eliminate shock waves using different approaches such as vehicle equalization and homogenization rather than minimizing traffic emission or energy unambiguously [13]. Most of these approaches are designed to reduce the amount of vehicle acceleration, which then subsequently leads to minimizing traffic emission and fuel consumption [105]. Prior to implementing these approaches, one should perform a comprehensive analysis of how much traffic emission or energy could be minimized by applying them. They can also reduce the vehicle speed [106]. Table 3 shows the summary of research works in terms of traffic control design and strategy.

5.1. Speed Limit Control. Speed limit control is used to regulate traffic flow. It aims to minimize traffic emissions

TABLE 3: Summary of work for traffic control design and strategy.

Reference	Paper	Year	Strategy	Features/objectives	Application
[107]	Walraven et al.	2016		Traffic flow optimization based on the reinforcement learning technique.	ITS.
[108]	Hegyi et al.	2008		A framework for limiting speed limit using shock wave theory.	Sustainable smart city/ITS.
[109]	Zu et al.	2018		Reducing vehicle fuel consumption using the COPERT model at the freeway traffic network.	Sustainable smart city.
[63]	Zegeye et al.	2012		A predictive traffic controller to optimize the control law parameters and determine control inputs.	Sustainable smart city/ITS.
[110]	Van den Berg et al.	2007		An MPC method based on optimal control inputs for urban and freeway traffic networks.	ITS.
[111]	Tajali and Hajbabaie	2018	Speed limit control	An MPC approach for examining the variations in traffic demand.	ITS.
[112]	De Nunzio et al.	2014		Reducing energy consumption using a macroscopic steady-state analysis.	Sustainable smart city/ITS.
[113]	Liu and Tate	2004		Determining network effects based on intelligent speed adaption system (ISA).	ITS.
[114]	Panis et al.	2006		Emission model using empirical measurements and the vehicle emission type.	Sustainable smart city.
[115]	Zhu and Ukkusuri	2014		Tackle traffic demand uncertainty using the speed limit control model.	Sustainable smart city/ITS.
[116]	Khondaker and Kattan	2015		An overview and mechanism for controlling speed limits.	ITS.
[117]	Stren et al.	2019		To improve air quality using autonomous vehicles.	Sustainable smart city/ITS.
[118]	Yang and Jin	2014		To control theoretic formulation based on intervehicle communication.	ITS.
[119]	Wu et al.	2018	Mobile Actuators	Stabilize traffic flow using an autonomous vehicle such as string stability and optimal traffic conditions based on frequency domain analysis.	ITS.
[120]	Liu et al.	2019		A country-level evaluation for investigating greenhouse gas emission.	Sustainable smart city.
[121]	Xu et al.	2011		Integrated traffic control based on the MPC.	Sustainable smart city/ITS.
[82]	Luo et al.	2016	Dynamic routing	A route diversion method based on the MPC in terms of multiple objectives.	ITS.
[122]	Wang et al.	2018		Reviewed different techniques used for sustainable transportation system and smart city applications.	Sustainable smart city.

and energy consumption by controlling speed limits. The speed limits relate to different vehicle locations from the entire road network.

Recently, various methods have been proposed, which aim to reduce speed vehicle limits in the freeway traffic environment. A few works were focused on eliminating shock waves instead of reducing traffic emissions and energy. Walraven et al. [107] proposed a traffic flow optimization method based on the reinforcement learning technique. They formulated the traffic flow problem using a Markov decision process. Then, they employed the Q-learning algorithm to detect the maximum driving speed which is allowed on the highway traffic. The simulation results revealed that the proposed method reduced traffic congestion under the heavy traffic environment. Hegyi et al. [108] introduced a method for limiting speed limit using shock wave theory. First, they employed the traffic control algorithm based on shock wave. Then, they controlled the speed limit when the shock wave is considered as solvable.

Additionally, several methods have been proposed which aim to reduce traffic emissions and energy. These methods

employed different optimization techniques, which could significantly reduce vehicle traveling time and control the speed limits. Zu et al. [109] solved a convex optimization problem using a macroscopic traffic control. The authors aimed to reduce vehicle fuel consumption based on the COPERT model in freeway traffic network. Then they formulated a convex optimization problem to produce an efficient energy scenario under a real-time traffic environment. Zegeye et al. [63] introduced a predictive traffic controller using parameter control policies. The proposed control method relies on MPC and state feedback control mechanism. It optimizes the control law parameters that determine the control inputs, which significantly reduces computational complexity. The effectiveness of the proposed control model is validated on the freeway traffic environment.

The model predictive control provides numerous opportunities for controlling traffic lights and limiting vehicle speed. It is compatible with different traffic conditions and models which can solve nonconvex optimization problems. Nevertheless, computational complexity could be reduced

effectively while employing MPC for real-time traffic scenarios. Therefore, a parameterized MPC could be useful for applying MPC-based macroscopic traffic flow control without compromising the computational performance [63].

Van den Berg et al. [110] introduced an integrated approach for urban and freeway traffic networks. They employed the MPC method based on optimal control inputs which are obtained from numerical optimization. The simulation results show that the proposed method obtained a better reduction in traffic congestion. Tajali and Hajbabaie [111] proposed an MPC approach to determine the variations in traffic demand. The author designed a mathematical model for dynamic speed harmonization in urban traffic networks to enhance traffic flow. Additionally, a few works focused on reducing traffic emissions and fuel consumption. Additionally, De Nunzio et al. [112] presented a method for reducing traffic energy consumption using a macroscopic steady-state analysis. The authors assess the system behavior using boundary conditions based on the timing of traffic lights, and a traffic control policy by relying on a variation of vehicle speed limits. The effectiveness of the proposed model has demonstrated using a microscopic simulation network.

Liu and Tate [113] presented a method for determining network effects based on the intelligent speed adaption system (ISA). The ISA aims to improve the traffic micro-simulation model to signify the ISA throughout the road network. The effectiveness of the proposed ISA is performed on a real-world traffic network, and it evaluated the impact of traffic congestion and speed distribution. The result shows that the ISA model is more efficient for reducing different traffic conditions. The main limitation of the proposed model is that it requires numerous amounts of traffic data for simulating the ISA on microscopic traffic models, which causes requirement of a large amount of computational time to process the algorithm. Panis et al. [114] introduced a model for traffic emission and speed limits. They developed an emission model based on empirical measurements based on the vehicle emission type. Then the traffic control model obtains the instant speed and acceleration of each vehicle traveling under the road network. They tested the proposed model at Ghentbrugge, Belgium.

The learning-based method has been used to control speed limits. Zhu and Ukkusuri [115] proposed a speed limit control model used for tackling traffic demand uncertainty. First, they developed a link dynamic model which simulates traffic flow propagation to control the speed limits. Second, the author represents the speed limit problem as a Markov decision process (MDP) and was solved in terms of a real traffic control method. A case study on the Sioux Falls network was performed to demonstrate the effectiveness of the proposed model. Also, in Ref. [116], Khondaker and Kattan presented a detailed overview and mechanism for controlling speed limits.

5.2. Mobile Actuators. This section discusses the mobile actuators, which rely on the vehicle's movement and control the traffic around the network. The vehicles which are

controlled by mobile actuators aim to reduce traffic emissions and amount of fuel consumption.

Stren et al. [117] proposed a method for improving air quality using autonomous vehicles. The authors examined the likelihood of reducing vehicle emissions influenced by the whole traffic network. They collected data for velocity and acceleration by conducting various experiments using a single autonomous-capable vehicle to dampen traffic waves with about 21 human-piloted vehicles. Yang and Jin [118] proposed a method for control theoretic formulation based on intervehicle communication. They designed a control variable that aims to follow a subsequent vehicle's speed without changing its average speed. Also, they performed the analysis of a constant independent and three cooperative green driving strategies. Wu et al. [119] proposed a method for stabilizing traffic flow using an autonomous vehicle. They formulated the problem using string stability and optimal traffic conditions based on frequency domain analysis. They determined the traffic stability while implementing safety limitations on the autonomous vehicle.

Liu et al. [120] presented a country-level evaluation for investigating greenhouse gas emissions. The authors examined the various effects of autonomous vehicles which are deployed on greenhouse gas emissions. These effects are vehicle penetration rates by 2050 and the amount of fuel consumption changes.

5.3. Dynamic Routing. This section discusses another approach named dynamic routing, which is used to reduce traffic emission and fuel consumption. It consists of reorganizing the traffic flow over the road network efficiently in terms of controlling split ratios [13]. The controller first analyzes and predicts the optimal routes for different traffic flow directions and communicates with the vehicle users in terms of radio communication devices, message signs, etc. [53].

The dynamic routing problem is regulated system optimization. Xu et al. [121] proposed a model for integrated traffic control based on the MPC. It corresponds to minimizing traffic congestion and the user equilibrium is categorized by a density distribution for all used routes. The author modeled the driver's information using an adaptive Kalman filtering theory. A case study shows that the proposed model could improve traffic efficiency and reduce the cost of the traffic management system. Luo et al. [82] introduced a route diversion method based on the MPC in terms of multiple objectives. The authors used the routes which are provided by the traffic authority. The recommended routes are considered as the control variable. Then they determined the split ratio based on route recommendations in terms of driver compliance rate. The diversion route control uses an MPC model based on a parallel Tabu Search algorithm.

Note that traffic emission and energy cost could also influence the selection of dynamic routing. It aims to select main routes which could significantly reduce traffic emissions and energy consumption. Wang et al. [122] discussed

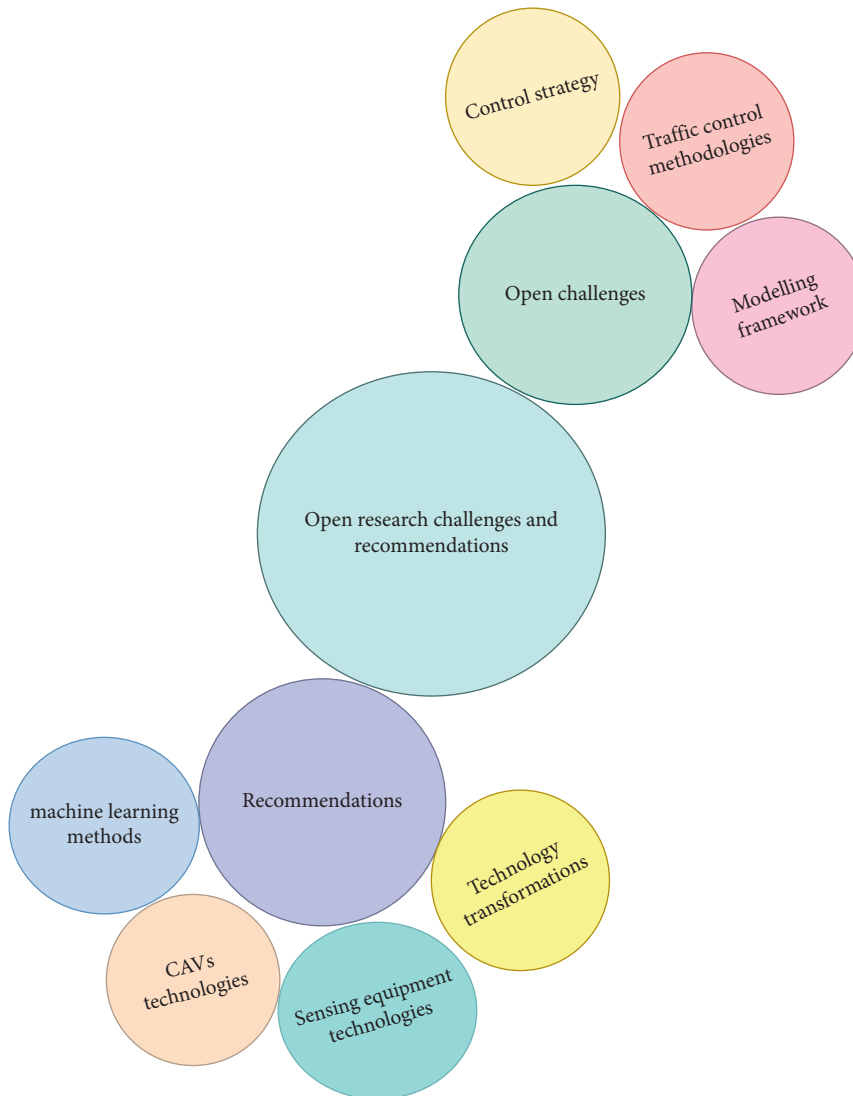


FIGURE 5: Open research challenges and recommendations.

the various dynamic road pricing and reviewed different techniques that are used for the sustainable transportation system and smart city applications.

6. Open Research Challenges and Recommendations

We wrap up our survey by discussing the open research challenges and recommendations as illustrated in Figure 5. They were obtained after reviewing existing techniques on the traffic control modeling. We found that various challenges still exist in traffic control modeling and strategies and require comprehensive research and investigation to design a sophisticated algorithm to test these strategies.

6.1. Open Challenges

6.1.1. Challenges in Traffic Control Methodologies. This section discusses the control methodologies of freeway

traffic management system. The traffic control highlights environmental and traffic safety issues. An improvement in traffic operation remains a complex control problem for the regulation of traffic management systems. In our opinion, researchers should focus on control models based on traffic analysis to design and develop robust traffic control algorithms in order to solve the complexity of the control system and its objectives.

In the past, several works have been presented, which demonstrates that the feedback control strategies and techniques were reliable schemes for reducing traffic emission and enhancing traffic safety [72, 77]. These schemes usually require traffic measurements and then integrate with traffic simulators to assess the performance of calibrated control parameters.

The optimum control strategy relies on the solution of finite horizon problems and receding horizon schemes [48, 71]. Also, the model control predictive (MPC) strategies produce better improvement in different types of control methods [64]. However, the optimization-based

schemes required numerous amounts of computational time to process the real-time application. These schemes could be based on models using an adequate power system, which can resolve the complexity and computational issue of optimization-based schemes. Furthermore, centralized and model-based control schemes use large traffic state measurements on the network, which is considered a critical issue for implementing traffic control schemes for practical applications. The equipment costs and computational efficiency are the main drawbacks of these schemes. To overcome these issues, optimum control schemes can be processed as predictive decentralized control techniques [10]. In Ref [80] and Ref [48], the authors proposed ramp metering schemes, which do not require a large amount of computational time for real-time applications. Also, these can be used to overcome the limitation of feedback schemes.

6.1.2. Challenges in the Modeling Framework. The selection of a modeling framework remains a critical issue, which must be reliable and robust to address and overcome traffic control problems. For instance, the pollution emission and fuel consumption by the vehicles contributes directly to assessing the ability of the control model to estimate and predict traffic flow on the road. In this regard, the first-order macroscopic traffic flow model does not provide satisfactory results and it is not the best choice for traffic control used for reducing traffic emissions [82]. The speed of a vehicle plays an important role to analyze and determine the severity of traffic incidents. Traffic safety models usually correlate with the occurrence of an incident event such as traffic flow volume, road characteristics, and vehicle speed. Consequently, a first-order macroscopic traffic flow model could be adopted to analyze and estimate the crash risk associated with traffic incidents.

The second-order macroscopic traffic flow model provides robust evolution of traffic speed and could be used to significantly reduce traffic emission and also enhance traffic and road safety. In the past years, various studies have been performed by increasing the precision of emission estimation and average acceleration was reduced from the traffic flow models [48, 63, 64, 80]. More specifically, macroscopic simulation tools obtained an accurate analysis of traffic safety and emissions. However, they cannot apply the tools to develop model-based control strategies.

An appropriate selection step should be considered for obtaining detail of the traffic control model. However, these models required more information to process traffic control models. For instance, the microscopic simulation requires parameter settings in terms of vehicle types (bus and public transport), fuel capacity, road structure, and environment conditions (temperature, humidity, and air). In the dispersion model, prior knowledge of traffic evolution is required. It processes the input to the pollution quantity, which is generated by vehicles, and other useful traffic information such as fuel consumption, wind direction, and road structure. Traffic safety models usually rely on the processing of traffic data obtained from loop detectors. The

data processing and description of unusual events caused by incidents are difficult to predict. Therefore, the safety methods correlate with events caused by crashes. These events can be evaluated with different traffic parameters such as traffic flow and traffic density, driver behavior, and weather conditions.

6.1.3. Challenges in the Control Strategy. The fundamental step of the traffic control framework is to select the best type of control strategy that could achieve both safety and sustainable goals, which are discussed in this survey. According to the literature review, it could observe and determine traffic control strategies that are suitable for applying to traffic control objectives. For example, the ramp metering combined with other control techniques can lead to obtaining a better performance and achieving sustainability goals. Note that most of the applications can lead to long queues on the road, thereby increasing the emission and increasing the likelihood of traffic incidents and crashes. Several approaches have been successfully applied for route guidance approaches, which consequently led to reduced crash risk [48, 58, 65]. Also, these schemes have been successfully applied to reduce emissions and fuel consumption. Variation in speed limits is combined with the ramp metering to alleviate the traffic flow and emission [63, 65, 76]. These strategies could be used to improve traffic and road safety by reducing the risky interaction among vehicles.

Reference [71, 77] mentioned that the effectiveness of variation in speed limits remains a critical issue that depends on the accepted speed level of vehicles. Note that we realized that the traffic control issues still exist when the results were obtained from different simulation tools. The traffic control problems aimed to reduce environmental issues in terms of reducing performance indicators and enhancing the safety indicators, which alleviate traffic control problems. Nevertheless, these schemes aim to minimize the number of traffic incidents in freeway traffic environments but not real-time crash analysis.

The aforementioned schemes can be extended into multiclass frameworks and evaluated with traditional traffic control techniques. It allows defining traffic control parameters and types of the vehicle class. Pasquale et al. [75] presented a method for using the multiclass ramp metering technique. They modeled two types of vehicles in a multiclass framework and then they determined the class of each vehicle type. The simulation results demonstrated that the proposed method provides feasible directions of a multiclass framework. Pasquale et al. [44] proposed a multiclass routing control algorithm to provide priorities to determine the specific vehicle classes in a predefined structure. Note that the multiclass traffic control modeling requires more accurate modeling strategies as compared to the single-class control model. Also, multiclass models in terms of safety models have the capability of assessing the impact of each vehicle class based on total incident numbers. This kind of multiclass model required a large amount of data and required them to calibrate.

Most of the multiclass schemes that were covered in this survey aimed to obtain better results in terms of improving traffic safety and reducing traffic congestion and to obtain sustainability in urban cities. The main advantage of applying multiclass schemes is to evaluate whether or not sustainable objectives are considered in the conflict domain. Then, it is necessary to choose reliable cost function parameters in order to obtain better traffic control algorithms by using these objectives against each other. Zegeye et al. [63] introduced a method that could be able to reduce traffic emission by minimizing the total time spent required for emission; however, it could deteriorate traffic flow and introduce conflict objectives. Pasquale et al. [75] investigated on reducing travel times and emissions which considered the nonconflict objectives of sustainability. Then, they implemented the control strategies which aim to significantly reduce traffic congestion and improve traffic flow. In Ref [77], Lee et al.'s scheme demonstrated that the improvement of traffic safety due to variation in speed may lead to an increased vehicle traveling time. However, in Ref. [48], Pasquale indicated that the results obtained from multiramp metering control show that the traffic congestion mitigation infers significant improvements to the vehicle traveling times and traffic and road safety conditions. Nevertheless, it obtained less amount of these objectives used for different solutions and is also considered a competitive behavior.

6.2. Recommendations for Obtaining Sustainability Goals. This section discusses the recommendations which could be used to obtain sustainability goals in the freeway traffic environment. The development of the Internet of vehicle technology and automated technology could be significantly used to improve traffic safety and reduce traffic emissions. These technologies should be adopted to meet the future sustainability goals of the traffic systems.

6.2.1. Technology Transformations. The automotive industry has undergone significant changes in recent past years and is shifting its focus toward electric and automated vehicles since the traffic safety and environmental and sustainability issues are more challenging in traditional vehicles. Nowadays, car manufacturers are producing automated vehicles which are embedded with automated components and comprise of various intelligent features. These features can significantly improve road safety and reduce the amount of fuel consumption and also enhance the overall experience.

6.2.2. Sensing Equipment Technologies. The vehicular technologies such as vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) [70, 123–125] provide a connected environment that enables vehicles to become a direct mode of communication with other vehicles, infrastructure, and network and to perform various control operations, and significantly reduces traffic emission [126]. Recently, several control strategies have been applied in logistic and freight transportation, which employs truck

platooning policies to reduce the significant amount of fuel consumption [127, 128].

6.2.3. Connected and Automated Vehicles Technologies. The connected and autonomous vehicles (CAVs) technologies bring significant improvements to the traffic control and management system, including reducing the possibility of collision risks influenced by driver's negligence. The CAVs could improve self-driving abilities and provide fast and efficient communication between vehicles that reduce vehicle travel time, improve road and traffic safety, reduce traffic emission and energy consumption [129], and provide speed guidance in different traffic environments [130]. The CAV is considered an essential product in intelligent transportation systems (ITS) and consists of various features such as the advanced decision-making system, the recognition model, and the control model [131]. These features could be helpful for drivers to take safe driving decisions while maintaining road safety and reducing the environmental impacts [132].

6.2.4. Machine Learning Methods. Recently, machine learning (ML) approaches have gained significant attention from the research community due to their ability to analyze data which could help to manage large data operations and reduce vehicle emissions and limit fuel consumption. Neural networks, such as wavelet neural networks [133], are widely used ML methods for estimating traffic emission and the amount of fuel consumption required by a vehicle. The reinforcement learning (RF) methods have been applied successfully for reducing traffic congestion and emissions and could be employed based on actuator types.

7. Conclusion

In this survey, a comprehensive investigation of traffic control strategies for the freeway traffic environment has been discussed. We performed a thorough analysis by reviewing the latest papers on traffic control strategies. Such strategies play an important role in obtaining sustainable objectives by reducing traffic emissions, collision risk, and amount of fuel consumption. It is evident from the literature review that traffic control strategies have been deeply discussed in recent years. This indicates that a significant interest is shown by a research community for this research area due to the rapid transformation in electronics and communication devices. Therefore, this transformation encourages the research community or the automobile industry to design and develop a robust traffic control system. We first introduced the traffic control modeling approaches. It provides a better solution for obtaining reasonable traffic and sustainable mobilities. We then comprehensively discussed various control strategies that could be beneficial for researchers in order to design a robust freeway traffic controller. These strategies could enhance the traffic flow and traffic management system and reduce traffic congestion. A comprehensive analysis of existing methods on the

vehicle control design and traffic control design strategies is presented. Adoption of these control strategies could be helpful in reducing the amount of energy consumption required by a vehicle. A detailed discussion on open research challenges and issues for traffic control in the freeway network is covered with the recommendation of obtaining sustainable goals. The proposed survey reveals that there is a need for focused research on the traffic control system that can overcome various safety challenges such as traffic incidents and crashes and also reduce the environmental effects. In short, this survey is well developed to cover traffic control techniques in the freeway traffic environment. It fills the literature gaps of existing surveys and incorporates the recent trends and approaches in traffic control.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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