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# Comprehensive Review and Future Directions in the Analysis and Optimization of Weaving Areas on Urban Arterial Roads

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## Abstract

Weaving sections are small areas with limited lengths along urban main arterial roads, where vehicles merge, diverge, or cross, influencing road capacity, safety, and environmental circumstances. This review synthesizes research into traffic flow analysis and optimization in these sections to bring out efficiency and safety. It begins by considering macroscopic and microscopic models that describe various aspects of vehicular motion, especially how variations in speed, lane changes, bottlenecks, roadway design, traffic density, and driver behavior manifest in weaving areas. The review has indicated conflict prediction models, two-dimensional models of traffic, and advanced forecasting as widespread methodologies in understanding and resolving various challenges of mixed traffic. This will include using VISSIM ["Verkehr In Städten - SIMulationsmodell", which is German for "Traffic in cities - simulation model"] to test flow improvement and congestion reduction strategies. For instance, it considers the environmental impacts an emission increase could have due to lane change. The review reflects with critical insight that future studies should cover the optimization of the weaving length, investigation of reinforcement learning, and synthesis of state-of-the-art technologies along with data-driven models to formulate comprehensive traffic management strategies. The ultimate objective is to achieve efficient, safe, and sustainable urban transport systems.

**Keywords:** Urban Main Arterial Roads, Weaving Areas, Traffic Flow Analysis, Traffic Optimization, VISSIM

## Introduction

### Background and Importance of the Study

Urban main arterial roads carry the major factor of vehicular movement, hence influencing urban transportation. However, the efficiency of these roads is often compromised by weaving areas, where merging and diverging traffic streams create complex traffic dynamics that can lead to congestion and accidents. Some of the factors that determine the operation of urban arterial roads include road design, traffic volume, and external conditions, such as weather and holidays. For example, the speed-flow relationship for urban roads highlights the effects of traffic characteristics—volume and speed—on the general operation and performance of urban traffic systems. This relationship is important to integrated urban planning in that it links some of the primary parameters of the urban model that impact both traffic flow and congestion management [1]. In addition to this, urban arterial roads are also equally causing serious environmental hazards. They are a major source of air and noise pollution that is a great concern for human life in urbanized cities. The street and road network, including arterials, represents the most important source of mobile emissions and provides a substantial fraction of urban pollution [2]. This further emphasizes sustainable urban planning while instituting protectionary measures against these environmental impacts. The efficiency at the level of traffic flow in urban arterial roads is sometimes influenced by exogenous factors; for instance, weather conditions and holidays that might change the patterns of traffic flow as drivers switch travel times, and modes, among others. It is on this premise that predictive models, for instance, the Neural Prophet model, have been used to forecast traffic volumes by incorporating such variables, thus helping in real-time traffic management and reduction of congestion [3]. One important description and management tool for the traffic flow in urban road networks is the Macroscopic Fundamental Diagram (MFD). It aids in the optimization of the distribution of traffic by keeping the flow of the network at an optimal state, which is critical in ensuring effective area traffic control and the management of congestion [4, 5]. Constructing the MFD with the consideration of reliability improves the accuracy of predictions made for traffic flow and optimizes the schemes of signal control as well [5]. Connectivity and accessibility are other important aspects of urban arterial roads. In Indian cities like Hyderabad, the linkage of the road network has been analyzed using various indices to assist in better transportation planning and ensuring the optimal use of already existing infrastructures [6]. This has helped to characterize areas that need improvement and, consequently, guided the application of more effective principles of planning. In brief, primary arterial roads are crucial in traffic flow management and further assist in facilitating urban mobility. They bear influences from a wide range of factors, including but not limited to road architecture, the nature of traffic, environmental impacts, and exogenous conditions. Good management of such roads requires full knowledge of their dynamics through predictive models and connectivity analysis that can enhance the urban transportation system, and this also helps in mitigating environmental impacts. It ensures hereby that the urban arterial road remains efficient and sustainable too [1-7].

Weaving areas are sections of urban main arterial roads where the traffic streams merge, diverge, or cross within a short distance. They form part of the critical segments of the road. The sections are very significant due to their impacts on the flow of traffic, road capacity, safety, and environmental implications. The definition of weaving areas can be deduced from their operational characteristics. These are the sections of roads where vehicles must change lanes to enter or leave the major flow of traffic. This usually leads to turbulence in the main traffic flow. The major source of this turbulence is the process of lane-changing, which, as a result, reduces road capacity and increases vehicle emissions. In a study performed in the Aljouf Region, KSA, this was observed to be true. This study showed that traffic volume, weaving section length, and the percentage of heavy vehicles have a significant effect on both the capacity and the emissions of these sections [8, 9]. The importance of weaving areas is multifarious: they are identified, first of all, as bottlenecks of the urban expressway system and influence the operation efficiency. Further research, however, using cellular automaton models, showed that such lane-allocation strategies could improve operational performance but only if some conditions of traffic prevail; for instance, the flow of traffic and the weaving volume ratio [10]. It is thereby indicative that good management and design of weaving areas may improve the traffic flow and reduce congestion. Besides, weaving areas are likely to cause traffic accidents due to the complex interactions between vehicles. A study from China identified several traffic accident risk factors in weaving sections including driver attributes, weather conditions, and traffic density. It was posited that if traffic flow is big and the weaving ratio is high, certain accidents are likely to occur, among them rear-end and sideswipe accidents [11]. This, therefore, calls for careful design and management to increase safety in these areas. Equally critical is the environmental impact of weaving areas. The increase in lane-changing activity incurs higher emissions, thus contributing to urban air pollution. Through the study in the Aljouf Region, it was found that though the increasing weaving length may increase capacity, by necessity it did not also decrease emissions; hence, there is a trade-off between operational efficiency and environmental impact [8]. Overall, weaving areas play an important role among urban main arterial roads in maintaining safe and efficient traffic flow. Their hallmarks are the type and complexity of the traffic interaction, with variable impacts on the road's capacity, safety, and environmental emissions. There is a need for effective management approaches such as optimized lane allocation and proper design so that these facilities do not pose any threat to users. The argument here is how logical it is to consider operational and environmental conditions while the planning and management of urban weaving sections to make them functional and safe [8, 10, 11].

Weaving areas on urban main arterial roads should be optimized for improved efficiency in traffic flow and safety, considering those sections tend to involve complicated vehicle interactions that will easily lead to congestion and higher accident risks. Merging and diverging places of the vehicle flow are the critical control points in general urban expressways and interchanges. The first measure of optimizing the weaving areas is that it can enhance the operational efficiency of the traffic flow. For instance, the study conducted on channelization and ramp metering with the application of reinforcement learning methods led to evident velocity increases in cars using all the lanes, some even by a factor of 37.03% [12]. It could be judged that strategic means of control were beneficial in the relief of congestion and the improvement of traffic flow. In the same direction, mixed traffic flow with the ACC technology implementation results in improved road efficiency through the ability to provide greater speed limits without compromising safety [13]. Safety is another aspect that is highly optimized for weaving sections. Such a high degree of interaction typically requires a complex way of controlling sections, which produces a higher risk of crashes within these areas. It has been reported that weaving length, lane continuity, and the number of lanes are important factors in safety performance optimization [14]. As an example, the increase in the width of the inside shoulder is associated with a decrease in crash occurrences elucidating the importance of the geometric design on safety optimization. Further, models for conflict prediction based on TTC-ML (Time-to-Collision-Machine Learning) could be applied to locate risks of collision effectively and to develop appropriate schemes for the control of traffic [15]. The spatial distribution of risks in weaving areas is a matter of prime concern. For instance, smaller weaving lengths have been found to, in general, concentrate risks, particularly to outer lanes, which can imply higher probabilities of accidents [16]. This therefore brings to light that the issue of determining the extent of weaving and how flow should be organized must be given much serious thought. The give-and-take of the traffic flow would provide a better safety performance. The other nature controlling the safety and operation of the weaving areas is driver behavior. For instance, driving styles categorized as aggressive or conservative change weaving area dynamics concerning traffic speed and safety aspects [17]. Knowledge of such behaviors would be very useful in the elaboration of specific control strategies for driver subpopulations and therefore essentially enhance overall safety.

In short, the optimization of weaving areas within the limits of urban main arterial roads is a vital contributor to the overall efficiency and safety of traffic. The approach utilizes strategic methods of control, integration of technology, geometric design considerations, and how driver behavior is understood. Proper attention paid to these factors reduces congestion and accident risks substantially; hence, the effectiveness and safety of urban transportation systems can be realized with high efficiency. With the incorporation of state-of-the-art technologies and data-driven models, the development in designing effective optimization strategies ensures that the weaving areas positively contribute to the general performance of the urban road network.

### *Objectives of the Review*

- **Synthesize Existing Research:** The focus of the review is majorly centralized on the existing research and pulling together different propositions for analyzing and optimizing weaving areas within the urban main roads. By combining different studies and articles, the review shall have achieved a comprehensive understanding of the current state of knowledge within the field.
- **Identify Key Methodologies:** Another key objective is to identify and evaluate methodologies used for the analysis and optimization of weaving areas. This includes the examination of theoretical models and empirical methods that apply to this context, stating the methodology’s strengths and limitations.

- **Highlight Key Findings:** The review is meant to highlight key findings from past research especially how they affect performance in the weaving areas, the effectiveness of different optimization strategies, and the role of technologies like VISSIM to traffic analysis.
- **Uncover Research Gaps:** Finally, by revealing the gaps in the current literature, especially in areas where research is lacking or contradictory, the review is aimed to point towards future studies and opportunities for more detailed exploration and innovation.

### Scope of the Review

This review aims to analyze the existing studies on the design, analysis, and optimization of weaving areas in urban arterial roads. Normally, the weaving segment is considered a critical section that might link a range of streams of traffic, which can always lead to conflicts that reduce efficiency in the flow of traffic. The theoretical basis for this review includes the characteristics of traffic flow, approaches to modelling-like design principles and optimization techniques for an all-rounded introduction. It will be useful to researchers, traffic engineers, and urban planners with the desire for the development of traffic performance and safety in urban weaving areas.

## Traffic Flow Analysis in Weaving Areas

### Theoretical Foundations

Traffic flow in weaving areas is rather complex to analyze, and both macroscopic and microscopic models of traffic flow exist. These are key models for the analysis and prediction of the behavior of traffic, in particular sections where the lanes are merging and diverging. The macroscopic models outline the traffic flow by relating the traffic density with the flow across a network. The Macroscopic Fundamental Diagram (MFD) is critical because it allows one to estimate the average flow and density of traffic. It is, therefore, a very important tool in understanding large-scale traffic dynamics. This approach becomes especially useful in applications for urban traffic management and planning since it can be used to assess traffic conditions and apply control measures to optimize flow, hence reducing congestion [18, 19].

In weaving sections, the macroscopic approach can be coupled with microscopic models that capture influences of variables like vehicle speed, acceleration, deceleration, and lane-changing activity. The importance of microscopic models is clear when the objective is the understand the detailed dynamics of the traffic flow, especially in complex scenarios where passengers travel in vehicles with blending traffic [20]. It explains how the behaviour of individual vehicles gets added up to form overall traffic patterns; hence, the microscopic approach is needed in designing efficient traffic management strategies in weaving areas.

A combination of macroscopic and microscopic models is needed to understand thoroughly the structure of the traffic stream in weaving areas. While macroscopic models provide a general perception of traffic, microscopic models help to give a much deeper insight into the interactions of vehicles. This helps to predict accurate traffic and new ideas evolved for proper measures to improve the flow and increase safety. In-depth analysis would be enhanced by the use of simulating tools like VISSIM in the incorporation of different alternate scenarios and interventions in a controlled environment to diagnose the causes of traffic congestion and evaluate the effectiveness of different traffic management strategies [21, 22].

In conclusion, the theoretical development of traffic flow in weaving areas stands on the integration of approaches between macroscopic and microscopic theories. Considering MFD as a relation expressing the overall traffic flow features, macroscopic models must be complemented by microscopic models to have a fine analysis of vehicle interactions. Combining such models with the utilization of simulation tools is crucial for flow management in weaving sections. This is an integrated approach that will eventually enable transportation planners and policymakers to devise plans to maximize the efficiency, safety, and sustainability of vehicular traffic in the most complex traffic environments.

### *Traffic Flow Characteristics*

The weaving areas are always one of the difficult zones in any traffic interface; several traffic streams merge into one at these areas and diverge out, hence this causes different traffic characteristics such as the existence of speed differentials, lane-changing, and bottleneck formation characteristics that are highly dependent on road design, traffic density, and driver behaviors. Speed dynamics play an essential role in the weaving sections, and as mentioned by Wei et al., considerable traffic dissipation, in the speed limit zones leading to the formation of bottlenecks, is a possibility. This study indicated that smaller maximum speeds and longer areas under speed limit zones cause a reduction in the traffic flow and average vehicle speed; therefore, much is needed in speed management to restore road capacity and safety, especially where speed differentials can create more congestion [23]. Lane changing also introduces the effects of weaving sections where vehicles must change lanes to merge into or to leave the mainline traffic stream, which might cause an interruption in the flow of traffic. While studies on lane-changing in weaving sections are lacking, the model of Böhme et al. regarding traffic flow with stochastic velocity functions has shown that random driver behaviors, including lane-changing, result in higher traffic densities and higher flow variabilities [24]. It has been shown that this contributes to bottlenecks, which tend to form in weaving sections attributed to the converging flows. Furthermore, the study by Wei et al. indicates that speed limit zones may be a bottleneck for platoons of similar conditions found in weaving areas [23]; this effectively demonstrates, through the help of VISSIM simulation, that effective measures can be taken in dynamic traffic simulation studies to identify and reduce bottlenecks arising from congestion for such complex scenarios arising in weaving areas [21]. Intelligent transportation systems (ITS), such as those detailed in articles by Xu et al. and Alkarim et al., and advanced traffic flow prediction models provide solutions to these bizarre traffic characteristics. Such systems use machine learning and deep learning algorithms in predicting traffic patterns and optimizing flow; therefore, at weaving areas, bottlenecks could be reduced and overall traffic efficiency improved [25, 26].

In other words, traffic flow characteristics within weaving sections are diversified by speed, have complex lane-changing behavior, and are ruled by things such as speed limits, driver behavior, and road design, making the bottleneck highly frequent. Advanced modelling and simulation techniques, together with intelligent traffic management systems, provide a few of the very promising approaches to knowledge and management of such challenges in a way that betters traffic flows and safety in weaving sections. Connecting these technologies, as Mayar et al. believe, will easily make traffic systems more resilient and efficient [27].

### *Existing Analytical Models*

The analysis of traffic flow in weaving areas is complex because of the vehicle interactions in both the lateral and the longitudinal directions. This challenge has been solved through the development of different models, each with some strengths and limitations. One of the ways to analyze the flow of traffic in weaving areas is to use conflict prediction models, as discussed in the research study by Ouyang et al. This analysis focuses on weaving sections between intersections whose close spacing results in strong traffic conflicts. Negative binomial regression models are used in this study for predicting conflicts and identifying influential factors, which include lane markings as well as diverging and merging section lengths. The results seem to imply that any facility design that is deliberately made to minimize conflicts might therefore increase conflicts, demonstrating how challenging it is to put in place an appropriate and effective traffic management scheme for these areas [28]. On the other hand, Matcha et al. present a review of the two-dimensional (2D) traffic models which account for lateral and longitudinal vehicle behaviors. Such models are quite important when conditions of mixed traffic are being considered. Traditional one-dimensional car models turn out to be inappropriate in the conditions of mixed traffic. These 2D models captured vehicle heterogeneity and continuous lateral maneuvers, leading to a clearer improvement in understanding the vehicular traffic dynamics in the weaving areas. However, the review also presented the limitations and research gaps in these models to capture the complexity consequent upon mixed traffic flows [29]. Another perspective is offered by Naser, who reviews speed-flow relationships in traffic studies. These models are fundamental in highway capacity planning and evaluation, including weaving sections. Understanding how the speed and flow relate would help design a much more effective traffic system, but this review does not make explicit reference to weaving areas [30]. Advanced forecasting models, like the attention-based deep learning model proposed by Zhou et al., provide another way to analyze traffic flow. It uses the spatial and channel attention mechanisms to serve key areas and channels, enhancing the accuracy of traffic flow prediction. Such models, although essentially designed for forecasting, can also be applied to analyze traffic flow in weaving areas by determining the critical congested and conflicting contact points [31]. In this respect, the systematic review provided by Rydzewski and Czarnul focuses on models of traffic optimization, most of them concerning microsimulations and macro simulations in urban traffic management. Those tools could be applied to the weaving areas in such a way as to optimize the flux of traffic, avoiding congestion. The work also points out that there is a time for innovative solutions besides gaps in research in view, such as a lack of simulations at a real-world scale, which would allow modelling a weaving area with truthfulness [32]. Finally, some other related approaches to spatiotemporal analysis and graph convolution methods are followed by Liao et al. and Wang et al. in an attempt to perceive the dynamics of traffic flow. These two research studies delved into the required spatiotemporal characteristics that may analyze the complex interaction taking place in weaving areas. Drawing from ride-hailing trajectories and polycentric information about the functional network of regions in urban settings, such studies inform on traffic patterns and copies of areas that can be intervened with. [33, 34].

Various models exist that analyze the weaving area traffic flow, which ranges from conflict prediction and 2D traffic models to advanced forecasting and simulation techniques; each has unique insight and tools for understanding and managing traffic in such complex environments. However, each of these models points to the need for further research in overcoming the limitations of each model and integrating them into comprehensive traffic management strategies.

### *Simulation Tools*

In the analysis of traffic flow in weaving sections on urban arterial roads, several simulation tools are commonly used to model and assess the dynamics of traffic. These tools help to understand the complex interactions involved in weaving sections, which are critical areas where streams of traffic flow both merge and diverge, resulting in congestion and increasing accident risks. One of the applied simulation tools is mostly VISSIM-a microscopic traffic simulation software. VISSIM is particularly noted to have been connected with studies on the level of service (LOS) in weaving sections of urban roads. For example, a study used VISSIM to simulate traffic conditions at two-sided weaving sections and compared them with results obtained using the Highway Capacity Manual (HCM) methodology. The study concluded the similar LOS and density results between VISSIM and HCM at some volume-to-capacity (V/C) ratios, but observed they are significantly different in higher V/C ratios, evidencing the sensitivity and accuracy with which this tool can approach complex dynamics in weaving sections [35]. Another of the prominent tools is SUMO (Simulation of Urban Mobility) an open-source, highly portable, microscopic, and continuous traffic simulation package aimed at simulating the road network on a large scale. SUMO has been used for several urban traffic studies, among them, those focused on air quality and traffic flow modelling. For instance, SUMO was applied in the city of Zaragoza to simulate flows of traffic and to foresee levels of air pollution, proving its utility for integrating traffic and environmental modelling [36]. Although it is mainly used for wider traffic flow and pollution studies, SUMO’s capabilities could still be developed further for analysis of specific road segments—such as weaving sections—by utilizing in detail the vehicle movement simulations from this tool. Generally, microsimulation tools are known to do very well in modelling individual vehicle movements and interactions, thus giving a quite dynamic approach toward traffic analysis. They will become crucial in the evaluation of infrastructural interventions and traffic management strategies, as portrayed in a study carried out in Catania, Italy, where a microsimulation assessment was made on the impact of different traffic regulation strategies on LOS and emissions [37]. It will be apposite at this stage to highlight that while VISSIM and SUMO represent tools commonly in use among freight planners, other simulation systems exist in the form of DynasTIM. Precisely, DynasTIM is designed to carry out real-time online simulation and optimization of dynamic traffic flows, particularly in urban networks. It has been applied in the Futian Central Business District of Shenzhen, China, for the optimization of traffic signal timings, reducing travel delays, thus showing its capability in dealing with complex urban traffic scenarios [38].

In summary, the two most widely spread simulation tools applied to analyze traffic flow in urban arterial road weaving sections are VISSIM and SUMO. The full capability of traffic modelling and optimization is available in these and another package, such as DynasTIM, so that proper traffic management and planning can be conducted in cities. Individually, each tool is designed with close differences in the features and strengths that fit the needs of specific aspects of traffic analysis, from detailed vehicle interactions to broader network-level assessments.

## Design and Operational Aspects of Weaving Areas

### Design Principles and Guidelines

Weaving sections represent one of the most important interchange sections, where traffic merging and diverging must be fashioned for safety and efficiency. Among the basic dimensioning criteria in this area are such aspects as lane width, weaving length, and location of entry and exit. The lane width is very important in weaving sections because it is a very critical factor as it greatly influences how comfortably vehicles will be able to change lanes and merge into traffic. Wider lanes encourage greater vehicle holding capacity and reduce collision incidents, as they provide more space for maneuvering [14]. Design Element: Length of Weave Section Generally, a longer weave section is preferred because it is capable of providing more time and space for vehicles to complete intended movements safely, thus reducing the risk of an accident. Other studies have also indicated that the crash rate can be effectively reduced by increasing the length of weaving sections, specifically when the average daily traffic is greater than 10,000 [14]. Over the decades, with the accumulation of works, the HCM has also been revised, and weaving length has been emphasized, together with lane-changing rates in the most recent version of the HCM [39]. Entry and exit points should be located to avoid congestion and allow free flow of traffic. The distance between entry and exit points should be such that the vehicle can have a lane change within it without affecting the normal flow of traffic; otherwise, it may affect the normal flow of traffic and may create congestion, leading to the possible occurrence of accidents [40]. Furthermore, the design should also consider the interleaving length and the interlacing ratio. Unreasonable parameters can cause the accumulation of traffic flows and reduce the capacity of the road [40]. Additionally, the configuration of weaving sections reduces conflicts by using an auxiliary lane that connects the on-ramp to an off-ramp and is an important factor in managing the traffic flow at an on-ramp [14]. Within these conflict areas, the complexity of vehicle interactions creates even operational problems outside the state of flow, and the necessity for good design and analysis procedures in such settings is brought into clear focus. The establishment and exercise of performance matrices and analysis models, such as those considered in the PATH Task Order 6304, yields tools for more readily conducting the assessment of the effectiveness of different design and operational strategies in different conditions in a given corridor of interest [41]. In essence, the design of weave areas has to take into consideration the compromise between capacity, safety, and operational efficiency related to the specific characteristics of the site and the expected traffic volumes and patterns.

### *Impact of Design on Traffic Performance*

The design of weaving areas in highways and urban roads greatly influences the performance and safety of traffic. Several research works have been conducted on geometric and operational features within a weaving environment that exerts an influence on such performance, thereby offering valuable insights into effective design strategies. First, the geometric design of weaving sections, including lane length and width, goes a long way in influencing the safety and performance of traffic. For instance, the work of Mallipaddi and Anderson has pinpointed the length of the weaving section, the number of lanes, and the width of inside and outside shoulders as the most influential factor in crash rates in type A weaving sections. For example, they found that increasing the width of the inside shoulder may decrease total crashes since wider provides more space for maneuvering, hence higher safety [14]. Similarly, Liao et al. found that the risk has been concentrated on particular sections of short weaving areas, particularly at the 3/4 section and exit of the outer lane, with design adjustments in these areas mitigating risks [42]. In addition to design factors, there are operational factors such as traffic densities and weaving ratios that affect safety. Mao et al. identified that the high traffic density and weaving ratios increase the occurrence of accidents at this location, especially rear-end and side-swipe incidents [11]. This implies that traffic flow and density control using ramp metering or other mitigation measures may help in improving safety, as also recommended by Mallipaddi and Anderson [14]. Driver behavior is another critical factor affecting weaving area safety. Zhanji et al. reported that aggressive drivers normally have a higher speed and more sudden lane changes, which have a high likelihood of leading to accidents. This paper supports the conclusion that it is possible to use driver behavior knowledge in the control strategy design process to achieve safety improvements [17]. Simulation models like FWASIM (Freeway Weaving Areas Microsimulation Model) by Alkubaisi are very useful in evaluating the traffic performance in weaving areas. Such models allow for the analysis of driver and vehicle behaviour in different configurations and provide information related to the design and operational strategies' effectiveness [43]. Similarly, Ouyang et al. used conflict prediction models in assessing the safety of inter-tunnel weaving sections. They found that some lane markings—purposely designed and located to reduce conflicts—had excesses over their expectations, which increased those conflicts, generating a need for validation with actual data [28].

In general, the research indicates that an integrated weaving area design should consider aspects concerning geometric design, operational factors, and driver behavior. While geometric features provide a basis for intervention, the associated operational strategies toward traffic flow management and consideration for driver interventions are equally important. These strategies can be fine-tuned to the highest levels through the incorporation of simulation models and real-world data to ensure that design intentions manifest as designed in terms of actual traffic performance and safety outcomes. All the findings together inform the development of more effective and safer weaving area designs, obviously designed for improved overall traffic performance and reduced accident risk.

### *Case Studies of Urban Arterial Roads*

In weaving areas of urban arterial roads, innovative designs are critical in many respects, basically to improve the traffic flow, safety, and environmental impacts. Very few recent literature focus on the design issue of these complex sections of urban road networks. In one interesting study, the use of some microsimulation models and the factors considered were very innovative in developing a new approach to analyzing the capacity and emissions factors of urban weaving sections. A study in the KSA Aljouf Region used the VISSIM model to analyze the effects of such weaving section length, volume ratio, and percentage of heavy vehicles on road capacity and emissions. The results indicated that increasing the weaving length increment is an option to increase capacity, but in principle, no emission force reduction. The results have indicated that capacity improvements through weaving area design must be balanced against environmental considerations [8]. Another new design is proposed to apply a cooperative method based on reinforcement learning, wherein channelization and ramp metering are combined. This was applied to experiments on urban expressways and resulted in achieving improvement in vehicle speeds on more than double lanes, with increases of up to 37.03% in some cases. The program outperformed other cooperative approaches, pointing to the potential that it can enhance the traffic safety and efficiency of the weaving area [12]. Risk distribution characteristics were analyzed for the optimization of the flow of traffic in short weaving areas in complex municipal interchanges. For instance, it was identified that risk concentrates on some typical sections of the weaving area, mainly in the outer lane. Based on this understanding of the pattern of the risk, organization methods of traffic can be further modified to achieve a proper equilibrium to diffuse risk, thus lowering the influence at the peak of risk, which in turn results in a betterment of both safety and efficiency [42]. However, there is also a study that considers the influence of differences among individual drivers on the diverging behavior at weaving sections. The drivers are classified in that study and sub-categorized into aggressive, conservative, and normal drivers, where it was shown that the behaviour as a result and the highway-lane changing positions are significantly different. This may therefore pave the way for the development of targeted control strategies in a weaving segment, hence increasing safety [17]. The experiment of two-sided weave areas on urban roads has also ascertained that the existing classic models like the HCM have limitations in fully representing the complexity of urban weave areas. In this regard, simulation models have been utilized in assessing the LOS under different conditions of traffic, which has brought to light discrepancies in the computed results and those obtained by prediction in the HCM. This points out the need for still greater precision in the models, given an effective appraisal and design of the objectives of weaving portions of urban centres [35]. It is thus evident that a need arises for incorporating advanced simulation techniques about cooperative traffic handling strategies and driver behavioural analysis for the effective design of urban weaving areas. The innovative solutions, together with the capacity and safety issues, will make the urban road networks more efficient and sustainable. Future research shall henceforth consider these methods, due to the peculiarities of city environments and multiple behaviors manifested by road users.

## *Optimization Techniques for Weaving Areas*

### *Optimization Objectives*

The major optimization objectives in the weaving areas are maximized efficiency in traffic flow, minimised delay, and reduction in accidents. Weaving sections serve as crucial bottlenecks in an urban expressway system due to the nature that results from the merging and diverging traffic streams; thus, the optimization process within these sections has refocused a lot of attention toward effective management strategies that ought to be considered to enhance the operational efficiency within the system [10]. One of the very significant objectives is the optimization of the capacity of the weaving area, which can be realized through lane allocation. These strategies segregate drivers by destination and allow lane changes only where permitted, thus reducing disturbances between weaving and non-weaving traffic streams with the potential to increase the area’s capacity [10]. In addition, special attention should be given to the optimization of the length of the weaving section because, in general, longer sections will result in smaller inherent collision risks, more space for drivers to make relatively safe lateral changes, and, consequently, both the potential for reducing weaving turbulence and enhancing the flow of traffic [39]. Signal control schemes are also optimized for managing the weaving flow ratio in ways that effectively increase the actual weaving capacity; for instance, by up to 35.71% using an optimized three-phase signal timing scheme [44]. Further, the optimization process would aim for a more equilibrated distribution of the probability of risk occurrence within the areas of better driving conditions; hence, an internal risk equilibrium distribution for urban short-weaving areas [42]. This implies the examination of the design of traffic organization and its improvement that would lead to the reduction in peak value of the area of risk concentration for better safety and fewer accidents [42]. The optimization also considers the geometric situations of the weaving area; for example, to improve the benefits of the lane allocation strategies, consider the impacts of implementation location of isolation facilities[10]. In addition to that, optimization techniques depend on methodologies among which include the HCM; this manual provides a vital guide in the estimation of impacts of lane-changing rates and weaving turbulence to ensure that there is adequate accommodation relative to prescribed traffic volumes of flow and also to achieve desired operating conditions in weaving sections [45]. In essence, weaving area optimization is a multiple approach that integrates traffic flow management, risk distribution, and capacity enhancement strategies in attaining the prime objectives of delay reduction, minimization of accidents, and overall flow improvement in traffic [10, 39, 42, 44].

### *Optimization Approaches*

Optimization techniques at weaving areas are very important to improve traffic flow and safety. Several approaches have been investigated, most notably:

#### Mathematical Optimization Models:

This includes mathematical optimization models such as linear programming and dynamic programming that seek to enhance traffic flow even further by minimizing congestion on the roads or highways and facilitating lane changing. The HCM 2010, for instance, offers a methodology for the analysis of weaving sections, specifically the maximum weaving length and the lane-changing rate, targeting major issues that allow the optimization of traffic flow in these areas [39]. The same linear programming could also be used in finding the optimum lane allocation. It is shown that lane allocation techniques may enhance operational efficiency by around 10% for certain traffic conditions, as was investigated earlier by various studies [10]. On the other hand, dynamic programming can be used to model complex interactions within weaving areas with the characterization of vehicle speed and acceleration that helps to fairly distribute in segments with better driving conditions the probability of risk occurrence [42]. The cellular automaton models have also been used for the simulation of traffic flow in weaving areas to provide optimum lane allocation and assessment of indicators of traffic performance, such as average travel time and speed [10]. These models take into account factors impacting traffic flow, the weaving volume ratio, and the installation of isolation facilities—critical for the optimization of weaving area operations. Cooperative intelligent transport systems to distribute more evenly lane-changing activities have been proposed, in particular, for the freeway weaving segment with a concentration lane-changing problem. The systems work by distributing lane-changing activities more uniformly through optimization algorithms like particle swarm optimization, thus reducing these congestions and improving the traffic flow [46]. This gives an overview of the integration of the management of weaving areas using mathematical models and related techniques for optimization, ensuring that the traffic flows both smoothly and safely. Government traffic engineers use these models to develop weaving sections that are capable of handling higher volumes of traffic efficiently and safely, without negatively impacting speeds or causing accidents [10, 39, 42, 46].

### Heuristic and Metaheuristic Approaches:

Weaving area optimization is important to improve traffic flow and safety. For this, various methodologies are being taken into consideration, namely heuristic approaches with the metaheuristic class, particularly the use of genetic algorithms or even particle swarm optimization, since problems are highly complex and are characterized as non-linearity problems, which typically turn up in a traffic system. These methods aim to ensure a good, nearly optimal solution and make the result available fast enough for use in weaving areas where the traffic will keep changing. For instance, genetic algorithms are a suitable method for optimizing lane allocation strategies in which segregation of traffic by destination and minimization of lane-changing conflicts can be emulated through the process of natural selection that iteratively improves solutions [10]. Particle swarm optimization, as a technique bioinspired by the social behavior of birds, can be used in optimizing traffic signal timings and ramp [10]. Studies insisting on parameters like weaving length, traffic flow patterns, lane change behavior, and others are very critical in reducing congestion and enhancing safety; thus, the application of these methods is well supported [14, 39]. For instance, some research has shown that a lengthier weaving segment is associated with lower crash rates, according to which optimization techniques also need to account for the geometric design parameters [14]. In addition, heuristic approaches can be combined quite effectively with more traditional traffic management tools—including variable speed limits and high-occupancy/toll lanes—to achieve notable gains in both traffic flow and safety [10]. It is necessary to develop analytical models of the weaving area dynamics that include such optimization techniques to gain full insight into the process and to enable the design of effective interventions [47]. These models are very promising, but further research is needed for refinement and validation of the effectiveness of such approaches under various traffic conditions since current studies often assume static capacities and do not fully account for variability in traffic demand and driver behavior [10]. In general, heuristic and metaheuristic methods provide a robust framework for weaving area optimization, but the success of their implementations is linked to the real appreciation of the specific characteristics and problems of each site [39].

### Simulation-Based Optimization:

Simulation-based optimization is one of the most powerful approaches to enhancing the efficiency of weaving areas, which are crucial segments in traffic networks where merging and diverging traffic streams intersect. This tool utilizes simulation coupled with optimization algorithms responsive to the complex dynamics and interaction observed across a weaving section. Perhaps the first basic methodology to analyze freeway weaving sections is offered by the HCM 2010, which has been further adapted and developed properly for urban contexts and different traffic conditions according to several studies [8, 39]. The capacity models for these weaving sections, as well as models for environmental impact and their analysis, have been developed using simulation tools to a large extent such as VISSIM, where different traffic scenarios can be simulated to estimate the effects of variables like weaving length, percentage of heavy vehicles, and volume ratio of the traffic streams [8]. These simulations can replicate some of the complex vehicle behaviors occurring in weaving areas, such as lane-changing maneuvers that are of importance to optimization purposes for the reduction of congestion in traffic flow[39]. Optimization algorithms integrated with simulation models like these would find the same optimal strategies about lane allocation, ramp metering, and variable speed limits supposed to be some of the control strategies suggested for controlling weaving areas. For instance, lane allocation strategies have been proven to improve operational efficiency by almost 10% under some specific conditions, such as high traffic flow and medium weaving volume ratio [10]. Furthermore, simulation-based optimization presents an opportunity to assess a series of geometric configurations and traffic management strategies that can shine a light on the best design and operation of weaving sections. The proposed strategy also permits the evaluation of the risk and safety at weaving areas by simulating various traffic characteristics on collision risks and allows the identification of unsafe links [42]. Using simulation-based optimization, researchers can find robust models that optimize not only traffic flow but also safety and reduce environmental impacts, making it a very important tool in the design and management of weaving areas [8]. The integration of simulation tools with optimization algorithms makes for a comprehensive framework for dealing with weaving areas by developing effective solutions that allow tailoring under specific traffic conditions and infrastructure designs.

**Real-Time Optimization:**

Real-time optimization of weaving areas focuses on enhancing the efficiency and safety of complex road sections using dynamic traffic data. One way in which this can be approached is by developing micro-simulation models embedded with real-time data, which will predict and control its traffic flow. These models can be calibrated and validated using field data, as demonstrated in studies where factors like volume ratio and weaving ratio were examined for their interaction with weaving capacity under different conditions [48]. It is important to integrate driver behavior within these models since lane-changing forms a predominant component of the weaving section operations. Knowing the various kinds of lane-changing behaviors by different driver types, such as conservative, normal, and aggressive drivers, can be useful in the design of weaving sections that adapt to real-time traffic conditions [17]. Besides, regression models developed from field data—in this case, average predictions for the number of lane changes—can be adjusted dynamically regarding traffic signals and lane assignments in real time for further optimization of traffic flow [49]. The optimization can also be realized in both the length and width of the weaving section. These dimensions can be changed and adopted by the system through real-time data so that all required weaving maneuvers are accommodated over a longer distance to minimize congestion and enhance the quality of the operation [50]. Further, statistical analyses and rational formulations can be used in an overall process for the analysis and design of weaving sections to frame real-time optimization. Such techniques are those that bring together data from several different sources and apply analytical derivations reflecting practical conditions, hence improving operational quality in weaving sections [47]. Such knowledge of weave section driving behavior, such as the fact that most lane-changing behaviors occur within the first 25% of a weaving section, can inform adjustments to traffic management strategies at weaving sections in real time, ensuring smoother transitions and reduced bottlenecks [17]. Such methods will permit the weaving areas to be optimized in real-time for far-improved traffic flow and safety under prevailing conditions and driver behaviors.

**Table 1.** Summary of Optimization Techniques for Weaving Areas in Urban Arterial Roads

| Optimization Technique | Strengths | Weaknesses | Applications |
|---|---|---|---|
| Segment-based Lane-changing Control (SLDC) with Ramp Metering (RM) [51] | Improves traffic efficiency and reduces conflicts by coordinating Connected Autonomous Vehicle (CAV) distribution and ramp control. | Effectiveness diminishes when weaving region occupancy is low; and requires high CAV penetration. | Suitable for high-occupancy weaving regions with significant CAV presence. |
| Microsimulation with VISSIM [8] | Provides a detailed analysis of factors affecting capacity and emissions, such as weaving length and heavy vehicle percentage. | Limited by the accuracy of input data and assumptions in simulation models. | Useful for capacity and emissions prediction in urban weaving sections. |
| Lane Allocation Strategy [10] | Enhances operational efficiency by optimizing lane usage based on traffic conditions. | Benefits are contingent on specific traffic flow and geometric conditions and may require physical infrastructure changes. | Effective in scenarios with high traffic flow and specific weaving volume ratios. |
| Integrated Lane Assignment and On-ramp Signal Control [52] | Significantly improves capacity, especially under high weaving volume ratios. | Complexity in implementation due to the need for simultaneous optimization of multiple factors. | Best applied in high-volume weaving segments requiring comprehensive control strategies. |
| Variable Speed Limit Guidance with DQN ( Deep Q-Network) Algorithm [53] | Increases traffic efficiency and safety by dynamically adjusting speed limits. | Requires advanced infrastructure and real-time data processing capabilities. | Applicable in urban expressways with advanced vehicle-infrastructure systems. |
| Vehicle-Infrastructure Cooperative Technology [54] | Reduces dangerous driving behaviors and improves traffic flow by leveraging cooperative systems. | Dependent on the availability and reliability of cooperative technology. | Suitable for modern urban roads with cooperative infrastructure. |
| Heuristic Optimization Methods (e.g., Genetic Algorithm, Harmony Search) [55] | Robust and adaptive to complex traffic conditions; effective in optimizing traffic signal timing. | Performance varies with problem complexity and requires careful parameter tuning. | Ideal for dynamic traffic assignment and congestion pricing in urban networks. |
| Performance Matrix for Weaving Analysis [56] | Provides a comprehensive evaluation of different analysis methods under various conditions. | May not account for all real-world variables; relies on existing data and models. | Useful for selecting the best analysis method for specific weaving scenarios. |

## Challenges and Future Research Directions

### Challenges in Current Research

There are many challenges in the analysis and optimization of weaving areas in urban main arterial roads. One of the basic problems is data limitation. Much of the existing research relies on simulated or controlled data that cannot capture all the complexities of real traffic. It's pretty difficult to acquire high-quality, granular data in urban locations because of the density of traffic, concerns over privacy, and continuous monitoring. Also, most optimization models lose their accuracy because they make simplified assumptions, not including all variables affecting the flow of traffic such as driver behavior, weather conditions, or new events. The other major reason is that these models often fail to predict what happens because they are very rarely validated against empirical data. A very important challenge is scalability, for methods that work quite well in smaller or mid-sized networks do not have almost the same capabilities as more populated cities that bear complex traffic patterns. Finally, the inclusion of new strategies for optimization into the old infrastructure complicates large-scale implementation in densely populated cities.

### Emerging Trends

Among all of these challenges, some emerging trends envision promising directions for the optimization of weaving areas. More and more often, the integration of machine learning (ML) is happening in algorithms used to predict traffic patterns and optimize weaving areas in real time; therefore, adaptive solutions would be provided that respond to changing conditions. In behavioral modelling also, ML lends strength to more accurate models of the traffic flow by understanding driver behavior better. Another important trend is that of the Internet of Things, with devices of the Internet of Things (IoT) connected sensors and vehicles aiding in real-time data collection and improving vehicle-to-infrastructure communication. Improved communication would then allow for more coordinated traffic management, reducing congestion. Again, the development of autonomous vehicles provides an opportunity for more fluent traffic, as they can move more harmoniously and predictably than a human driver. The integration of autonomous vehicles (AVs) with adaptive traffic control systems can be expected to optimize the use of road space and make traffic flow more efficient at weaving areas.

### Suggested Areas for Future Research

Looking ahead, some of the important contributions that future research could make are interdisciplinarity-oriented approaches to collaboration between traffic engineers, urban planners, data scientists, and behavioral psychologists in developing more holistic optimization strategies. In particular, research in human factors will be relevant to driver behavior and how it interacts with the emerging technologies of AVs and smart infrastructure to come up with friendlier and more effective solutions. There is also an urgent requirement for large-scale real-world studies and pilot testing programs that can test optimization strategies across a variety of urban environments. Longitudinal data analysis would allow one to identify the long-term implications of the various strategies adopted and point out possible areas of improvement. Finally, future research should be aimed at developing adaptive models which can be easily scaled across different kinds of urban environments while taking into account the unique characteristics of these areas. In the future, the integration of weaving area optimization into other smart city initiatives will be important from a progressive perspective toward overall traffic management. The application of advanced technologies such as IoT, AI (Artificial intelligence), and digital twins can enhance traffic flow and safety by utilizing real-time data for decision-making and predictive analytics[57, 58]. Moreover, the development of a comprehensive framework that incorporates various smart city dimensions—such as infrastructure, sustainability, and cybersecurity—can address the complexities of urban transportation systems[59, 60]. For instance, employing intelligent transportation systems (ITS) can facilitate better traffic management by analyzing hybrid traffic streams and optimizing routes, thereby reducing congestion and environmental impact[58]. This multidisciplinary approach not only aligns with current trends in smart city research but also addresses critical challenges in urban planning and infrastructure development[60, 61].

## Discussion

### Synthesis of Findings

The integration of analysis, design, and optimization into urban traffic management is a comprehensive task that requires knowledge of many different interlinked aspects. According to Xu et al., the prevention of congestion and improvement in the efficiency of traffic flow in an urban construction project lies in the optimal distance interval between entrance and exit. In this respect, optimal distances as shown in Figure 1 are determined using calculation models according to Equation (1) and simulation tools like VISSIM [62].

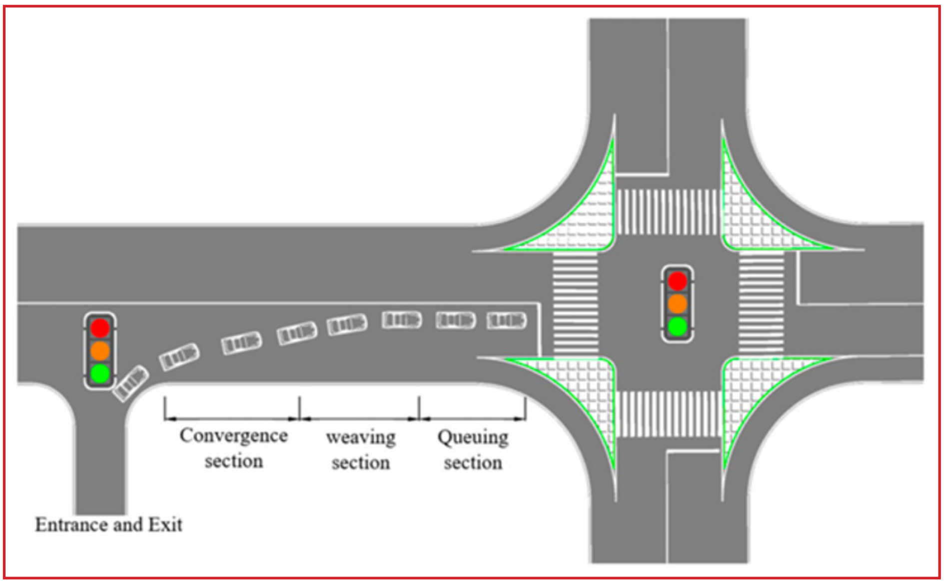


**Figure 1.** Combination of signal control entrances and exits at the upstream distance of the intersection.

$$L = L1 + L2 + L3 \quad (1)$$

- L = Distance model for signal-controlled entrances and exits to adjacent intersections;
- L1 = length of converging section (m);
- L2 = length of weaving section (m);
- L3 = length of queueing section (m);

The important thing that is brought out clearly by this approach is the need for proper design and analysis to achieve efficient operational functioning of junctions and entrances/exits in the management of traffic. In particular, the work by Orieno et al. in AVs and another study on the implications for urban mobility with AVs pinpoint such technologies' potential to transform the current urban scenario. On the other hand, roads could reduce congestion and increase safety with the help of AVs, which may further fundamentally require a rethink of infrastructures within cities and land use. This concerns an urban planning approach where AV technology is married for better land use with reduced needs for parking, hence contributing toward environmental sustainability [63, 64]. In this regard, therefore, the design and optimization of the urban spaces will have to put into consideration the integration of the AVs, of which some sort of forward-looking approach is called for in linking urban planning and traffic management.

### Implications for Urban Traffic Management

These findings have important practical implications for urban planners and traffic engineers. The optimization of distances between entrances and exits, discussed by Xu et al., gives a clear methodology as to how this could improve traffic flow in an urban area by avoiding congestion. This would directly apply to designing efficient traffic systems by urban planners to ensure minimal vehicle queues while the flow is kept as high as possible[62]. The introduction of AVs brings many opportunities as well as challenges to urban traffic management. According to ORIENO et al., with the potential to change traffic dynamics radically by decreasing congestion and increasing safety on roads, autonomous vehicles have huge potential. Indeed, for their successful integration into urban environments, comprehensive policy and industry strategies are required—including standardized safety regulations and incentives for AV adoption[64]. Urban planners will have to bear that in mind while developing an urban landscape for the future with infrastructure that would be adaptable to the then-changing requirements of AV technology. That further promotes urban innovation and traffic management through the integration of smart city technologies as discussed by Lyu et al. Smart technologies could provide an avenue for better acquisition and analysis of data, hence leading to informed decision-making in the improvement and management of traffic [65]. This, therefore, underpins smart city frameworks about urban planning, which responds dynamically to the needs of modern living in cities. In summary, an integration of the results from those studies underscores the interlinkage within the domains of analysis, design, and optimization involved in urban traffic management. Urban planners and traffic engineers can take advantage of data-driven models by embracing a future with AVs and smart city innovations to come up with more efficient, viable, and adaptive urban traffic systems. These are important strategies for tackling modern urban mobility's complex issues and guaranteeing the long-term sustainability of the urban environment.

## Conclusions

### Summary of Key Points

This study rigorously examined optimization strategies to enhance the operational performance of weaving sections on urban arterial roads. These sections, defined by their merging and diverging traffic flows, pose significant challenges in balancing traffic efficiency, safety, and environmental sustainability. A detailed evaluation of various optimization strategies—ranging from lane allocation and geometric design improvements to traffic control interventions—revealed a hybrid approach combining reinforcement learning-based channelization with ramp metering as the most effective solution. This integrated methodology demonstrated notable improvements in traffic flow efficiency, evidenced by increased average speeds and reduced delays, while maintaining safety benchmarks. The research also highlighted the critical role of lane allocation in mitigating turbulence within weaving sections and boosting capacity, particularly under high traffic density and weaving volume conditions. Simulation emerged as an essential tool, providing insights into the effectiveness of proposed strategies and enabling refinements in key parameters such as weaving section lengths and lane configurations. Notably, VISSIM simulations illustrated the influence of driver behavior variability and underscored the potential benefits of extending weaving lengths with careful calibration to balance capacity gains and environmental impacts.

### Final Thoughts

The findings of this research emphasize the importance of simulation-driven, data-centric approaches in optimizing weaving sections on urban arterial roads. By leveraging advanced methodologies and tools, this study provides a robust framework to guide urban planners and traffic engineers toward achieving enhanced operational efficiency, improved safety, and sustainable outcomes. However, the proposed framework requires further field validation and exploration of emerging technologies such as connected autonomous vehicles (CAVs) and intelligent transportation systems (ITS). Integrating these innovations has the potential to significantly expand the scalability of traffic management solutions while contributing to safer, more efficient, and environmentally sustainable urban mobility systems.

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## Conflicts of Interest

The authors declare no competing interest.

## Author Contributions

**Bakhtiar Tahir Tofiq Al barznji:** conceptualization, methodology, data curation, writing- original draft preparation. **Hirsh M. Majid:** methodology, writing- original draft preparation, writing- reviewing and editing, supervision.

## Data Availability Statement

The data used to support the findings of this study are included within the article.

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