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# Centralized Simulated Annealing for Alleviating Vehicular Congestion in Smart Cities

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## Abstract

Vehicular traffic congestion is a serious problem arising in many cities around the world, due to the increasing number of vehicles utilizing roads of a limited capacity. Often the congestion has a considerable influence on the travel time, travel distance, fuel consumption and air pollution. This paper proposes a novel dynamic centralized simulated annealing based approach for finding optimal vehicle routes using a VIKOR type of cost function. Five attributes: the average travel speed of the traffic, vehicles density, roads width, road traffic signals and the roads' length are utilized by the proposed approach to

find the optimal paths. The average travel speed and vehicles density values can be obtained from the sensors deployed in smart cities and communicated to vehicles and roadside communication units via vehicular ad hoc networks. The performance of the proposed algorithm is compared with four other algorithms, over two test scenarios: Birmingham and Turin city centres. These show the proposed method improves traffic efficiency in the presence of congestion by an overall average of 24.05%, 48.88% and 36.89% in terms of travel time, fuel con-

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sumption and  $CO_2$  emission, respectively, for a test scenario from Birmingham city in the UK. Additionally, similar performance patterns are achieved for the a test with data from Turin, Italy.

*Keywords:* Traffic congestion control, Simulated annealing, IoV applications, Multi-attribute decision making.

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## 1. Introduction

### 1.1. Related Works

The increasing number of vehicles on city road networks has resulted in serious road traffic congestion problems which have an effect on the journey travel time, travel cost, fuel consumption and air pollution. The Victoria Transport Policy Institute has reported that the first most common cause of time delay, fuel consumption and wasted money in the United States is vehicle traffic congestion [1]. This has resulted in significant economic and productivity losses. It is predicted that this cost could rise to \$121 billion in 2020 [1], [2]. Therefore, traffic congestion detection and avoidance mechanisms are two of the most pressing issues in Intelligent Transportation Systems (ITSs) [3].

The Internet of Things (IoT) [4], as a promising communication technology, enables various devices such as Wireless Sensor Nodes (WSNs), cell towers, mobile phones, Radio Frequency Identification (RFID) tags and Near Field Communication (NFC) devices to interact and cooperate with each other to attain a common goal [5]. The authors in [6] have suggested a model based on IoT in order to utilize the information and communications technologies which improve the smart city mobility. The framework includes a comprehensive system of the urban information that supports smart cities from sensor-based information collection level to data processing and management, Cloud-based integration of respective systems and services.

The authors in [7] have investigated the utilization of IoT technologies in order to approach particular city infrastructure problems and provide support to traffic operators such as the utilization of traffic sensing tools that includes wifi

25 scanners and magnetic sensors technologies. This would enhance the collection of the traffic information and improve the entire mobility of the smart cities.

The Internet of Vehicles (IoV) is a part of the IoT, that predicts future vehicles as being connected, allowing the sharing of data to enhance traffic comfort and safety. IoV is a promising technology that can offer solutions for providing 30 traffic control systems to monitor road conditions and travel journeys. The authors in [8] have suggested a framework based on IoV in order to support the collection of the local traffic information. This system utilizes a central station selection approach for the data penetration and the optimal traffic information transmission model in order to enhance the efficiency of the data communication in the network. Moreover, the weighted and undirected graph paradigm 35 for IoV networks has been studied. The characteristic of GPS dataset has been analyzed and the network time-invariant has been verified.

The main part of the IoV is the Vehicular Ad hoc NETWORKS (VANETs) that include two main components. Firstly, Vehicle to Vehicle (V2V) communication 40 systems that is On-Board Units (OBUs) installed in the vehicles themselves [9]. Secondly, RoadSide Units (RSUs) or Vehicle to Infrastructure (V2I) systems, consisting of magnetic and induction loop sensors, magnetometers, infrared sensors etc. The authors in [10] have discussed the operation of Vehicular Sensing Networks (VSNs) in a smart city. They have investigated the use of a trust 45 evaluation technique in order to guarantee a reliable and safe communication among drivers in the VANETs environment. This helps to broadcast and combine reliable and valuable traffic data related to smart cities. Moreover, in [10] the significance of an accurate topological construction has been highlighted and they propose a secure selection model of the traffic information to enhance the 50 available network capacity.

The enhancement of data communication of VANETs has been investigated in [11] where the complex network theory has utilized for the analysis and improvement of the data dissemination in VANETs. The complex characteristics of the vehicular network have been analyzed based on some communication parameters for VAENTs environment. Furthermore, the authors have proposed a 55

clustering approach in order to station selection, a traffic allocation optimization model and an information source selection model.

### 1.2. Main contributions

In this work, a new centralized dynamic multi-objective optimization algorithm based on VANETs is presented. It integrates the simulated annealing (SA) algorithm with the VIKOR method [12], [13] as a cost function to formulate an approach called: centralized SA-VIKOR (CSA-VIKOR). The main goal of CSA-VIKOR is to provide the drivers with the optimal paths according to multiple criteria in order to meet the diverse navigation requirements of the drivers. This is achieved via optimization based on a multi-objective cost function. The result of which is that journeys that achieve the minimum Travel Time (TT), minimum Travel Distance (TD), minimum fuel consumption, minimum amount of emissions or a combination of the four.

In a previous work [14], an Improved Simulated Annealing TOPSIS (ISATOP-70 TOPSIS) algorithm is proposed to enhance the mobility in smart cities. ISATOP-SIS is a decentralized method that can only reduce the local traffic congestion, by considering only two attributes (vehicles average speed and road length) in its optimization to provide optimal paths. This work differs in that five attributes have been utilized to form a VIKOR based cost function for use by a CSA algorithm. In addition, the advantage of the centralized algorithm structure is that information about the wider road network can be embedded into the system, unlike the ISATOPSIS method where only local traffic data is available. This means vehicles are re-routed sooner, meaning they are less likely to reach the congestion in the first place.

80 According to [13], a comparative analysis has revealed that VIKOR and TOPSIS methods use different normalizations and aggregating functions for ranking. The VIKOR method presents ranking preferences based on the their “closeness” to the ideal solution and introduces a compromise solution with an advantage rate. In comparison, the main idea of the TOPSIS method is that 85 the selected preference should have the farthest Euclidean distance from the

negative ideal solution and the shortest Euclidean distance from the positive ideal solution. The TOPSIS method proposes two source solutions but it does not regard the relative importance of the distances from these solutions [13]. In addition, the CSA-VIKOR utilizes data relating to the entire road network, unlike the ISATOPSIS method where only local traffic data is available.

The main contributions of this paper are:

1. A new centralized traffic congestion alleviation approach called CSA-  
VIKOR is proposed. This algorithm provides optimal routes that reduce  
the traffic congestion problem in smart cities, reducing global travel times,  
fuel consumptions and  $CO_2$  emissions. CSA-VIKOR has the ability to es-  
cape from local minima or maxima and move toward a solution that is  
close from the global optima. This is because it allows transition to a  
worse solutions under certain conditions.
2. CSA-VIKOR is a centralized approach and can react to dynamic route  
optimization problem by aggregating real-time data from VANETs and  
effectively estimate alternative routes for the drivers. The advantage of  
the centralized algorithm structure in this case is that information about  
the wider road network can be embedded into the system. This differs  
to the work in [14], where only the local traffic information is used to  
optimize the route of each vehicle, reducing the potential improvement in  
travel time etc.
3. CSA-VIKOR can optimize vehicle paths based on multiple criteria by in-  
troducing a multi-attribute decision making (MADM) methodology called  
VIKOR method, allowing numerous criteria to be considered when opti-  
mizing routes for the vehicles.

The remainder of the paper is organized as follows: in Section 2 a literature review of related works is presented. in Section 3, details of the CSA-VIKOR algorithm are given. In Section 4, a performance evaluation is provided. Finally, conclusions are drawn in Section 5.

## 115 2. Related Works

The area of ITSs is considered as one of the most important applications for the VANETs [15]. Recently, researchers have shown an increased interest in developing efficient solutions for improving mobility in ITS [16]. One challenging task encountered in this area is finding the optimal navigation route within a  
120 reasonable period of time.

The vehicle path planning problem has been investigated by numerous studies using a variety of algorithms. For example, the Dijkstra and  $A^*$  algorithms have been used in [17–21]. The ant colony, genetic algorithm, hybrid heuristic and dynamic traffic assignment (DTA) methods have been used in [22–25]. Un-  
125 fortunately, most of these studies did not consider the use of real time data to decrease the likelihood of congestion forming or they have no knowledge about the traffic state for use in re-routing vehicles to avoid the congestion.

In [26], a Multiple Attribute Decision Making (MADM) method called Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is pre-  
130 sented. This mechanism assumes that both vehicles and RSUs are equipped with the VANETs to get the real-time traffic information and estimate the optimal route by using the TOPSIS method. However, the algorithm’s performance is similar in some extent to the Dijkstra’s algorithm [17] and it can only provide partially optimal results, which leads to the transfer of the congestion to other  
135 roads.

Route planning methods that consider real-time traffic information from VANETs have also been considered [27–30]. In [27] an Ant-based Vehicle Congestion Avoidance System (AVCAS) has been proposed. This system combines the predicted average travel speed with the segmentation of a city map to identify and alleviate the congestion. Then it uses the dynamic Dijkstra’s algorithm  
140 to find different shortest paths to re-route the vehicles. In [28] and [29], two approaches have proposed to reduce the vehicular traffic congestion in smart cities. The first one is a centralized and the second one is a decentralized framework. Both solutions rely on re-routing based on the Dijkstra’s algorithm or on

145 the  $A^*$  algorithm to prevent congestion and improve traffic conditions. In [30]  
A Distributed Vehicular Traffic Re-Routing System for Congestion Avoidance  
(DIVERT) has been proposed. The  $K$  shortest path method have been utilized  
by the DIVERT to re-route the vehicles and avoid the congestion. However,  
congestions in these methods are transferred to the new routes as the algorithm  
150 only selects the shortest travel distance when re-routing vehicles.

In [31], the authors have proposed a centralized real-time path planning  
based on hybrid VANET where the real-time data have been collected using  
V2V, V2I and cellular systems. Then these data have been sent to the vehicular  
traffic server to be processed and evaluated. Once an accident or a congestion  
155 has happened the vehicular traffic server is responsible of finding an optimal  
alternative route by using the stochastic Lyapunov optimization method. How-  
ever, this approach suffer from high delay time because it collects the real-time  
data from different communication systems and processes it at one place to  
find the optimal alternative path of the drivers. Additionally, the vehicular  
160 congestion in this approach is only considered when an accident has occurred.

An optimization solution has been proposed in [32] with the aim of determin-  
ing a system-optimal traffic scattering that improves the traffic flow and ensures  
that the shortest path for the drivers is not increased past a given threshold.  
In this paper, a road network is provided with an Origin-Destination (OD) ma-  
165 trix. Additionally, the edge travel time is provided and the resulting models are  
linear. However, this work has not considered the real-time data and dynamic  
re-routing of vehicles when unpredicted traffic congestion has happened.

In recent works [33], [34], optimization models have been proposed in order  
to minimize the effects of vehicular emissions, i.e. the pollution routing problem  
170 (PRP). In the first work [33], the main goal is to calculate a set of paths with  
speeds over each edge of the paths at the same time in order to reduce the  
total amount of emissions, fuel consumption and environmental cost. The PRP  
has been formulated as a mixed-integer convex programming problem based  
on disjunctive convex programming and solved by using the branch-and-cut  
175 algorithm.



In the second work [34], the eco-system optimal dynamic traffic assignment (ESODTA) system has been proposed in order to determine optimal eco-routing or green paths to reduce the total vehicular emission. The ESODTA system has been formulated by using the simplified queuing model (SQM). An expanded  
180 space-time network is constructed and a bottleneck discharge rate is introduced as an additional variable. The problem is solved by a Lagrangian relaxation-based algorithm.

However, these works have not utilized any real-time data obtained from the VANETs via wireless access for vehicular environment (WAVE) protocols.  
185 Hence, when an unpredicted congestion happens due to an accident the methods from [33] and [34] can not be applied to re-route the vehicles in order to avoid the congestion. Additionally, in [33] and [34] a dynamic multi-objective optimization method is not considered and hence the method cannot find a trade off between different attributes to determine the optimal routes.

### 190 3. Framework description

V2V and V2I communication systems are the two main components in the VANETs. Both V2V and V2I communication systems can efficiently support the ITS applications by collecting the real-time traffic information such as position, speed, direction and an accident information [35]. As a result, these data can  
195 be utilized for traffic management, path planning and vehicle localization.

Here, it is assumed that both systems utilize Central Access Messages (CAMs) or beacon messages [36]. CAMs are broadcast packets sent periodically between V2V or V2I communication systems that focus on monitoring traffic and congestion alleviation [37]. Figure 1 illustrates the V2V and V2I systems. Individual  
200 RSUs monitor their assigned segment of the road network and have an overview of the average speeds and the density of vehicles on the roads. This information can then be communicated between RSUs, allowing them to have an overview of the state of the road network as a whole. As a result this allows them to select the optimal path to route vehicles to their destinations. The remainder of this

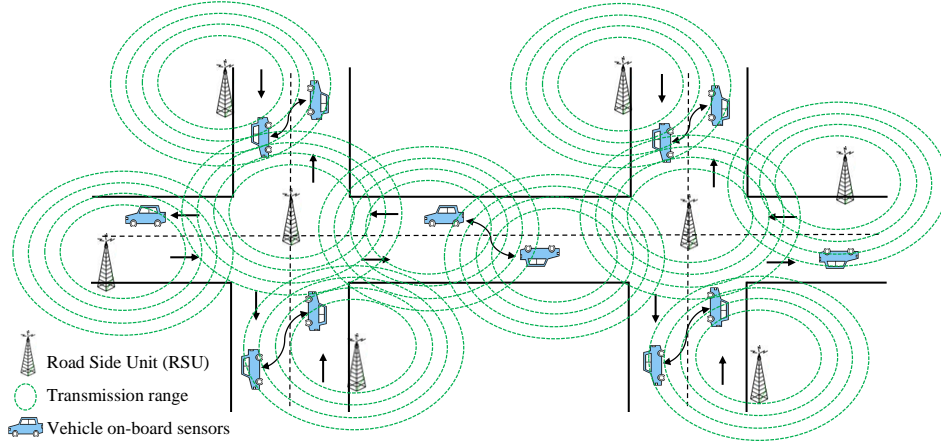


Figure 1: IoV road network infrastructure

205 section describes the proposed framework by specifying the real-time data collecting methodology, the road network model and the CSA-VIKOR algorithm.

### 3.1. Real-Time Data Collecting Methodology:

The proposed protocol relies on periodic messages for data dissemination. Each periodic message that is sent by a vehicle to the RSU monitoring its  
 210 current location contains  $\{roadID, averagespeed, position, density, route, V_f\}$ . Here, the *roadID* gives the ID of the road where the vehicle is, *average speed* gives the vehicle's speed on the road, *position* indicates the current location of the vehicle, *density* is the number of vehicle per unit distance on a road, *route* represents the route along which the vehicle is travelling and  $V_f$  gives the speed  
 215 limit of the road.

The RSU also sends periodic messages to other RSUs within its transmission range. Each RSU holds a road matrix  $A$ , which contains the average speeds, vehicle densities, road lengths, road widths and the number of traffic signals. The current average speeds are found from the speed measurements over the  
 220 previous 5 seconds (one measurement a second). The density of the vehicles on a given segment of road is found using (5), which is given below. Reset parameters (roads length, roads width and number of traffic signals) are uploaded to

the RSU during the off-line phase. Once new data is received by a RSU, the avoidance mechanism is triggered, in which congested roads are specified based  
 225 on the Greenshield's traffic flow theory [38].

The speed ratio is defined to numerically represent the traffic state of a road as follows:

$$V_r = \frac{V_i}{V_f}. \quad (1)$$

Here,  $V_r$  is the speed ratio,  $V_i$  is the current average speed on the road and  $V_f$  is the speed limit of the road.

According to Greenshield's model [38], a linear relationship exists between speed and density, which has the following form:

$$V_r = 1 - D_r, \quad (2)$$

where  $D_r$  represents the density ratio and can be calculated as follows:

$$D_r = \frac{d_i}{d_j}. \quad (3)$$

In (3)  $d_i$  is the current density of vehicles on the road and  $d_j$  is the maximum jam density, which is computed as follows:

$$d_j = K \frac{L_i}{Avg_L}. \quad (4)$$

Note,  $K$  is the number of lanes on the road,  $L_i$  is the road length and  $Avg_L$  is the average vehicle length plus the minimum gap between two vehicles. This  
 230 work assumes  $Avg_L$  is 6.2m, as is done in [39] and [40].

From (2) and (3)  $d_i$  can be calculated as:

$$d_i = d_j(1 - V_r) \quad (5)$$

and the following can be deduced (see Figure 2) [41]:

1. The road is under severe traffic congestion and the traffic density approaches  $d_j$  when the speed ratio  $V_r$  approaches zero.
- 235 2. The road is under free flow speed and the traffic density is low when  $V_r$  approaches 1.

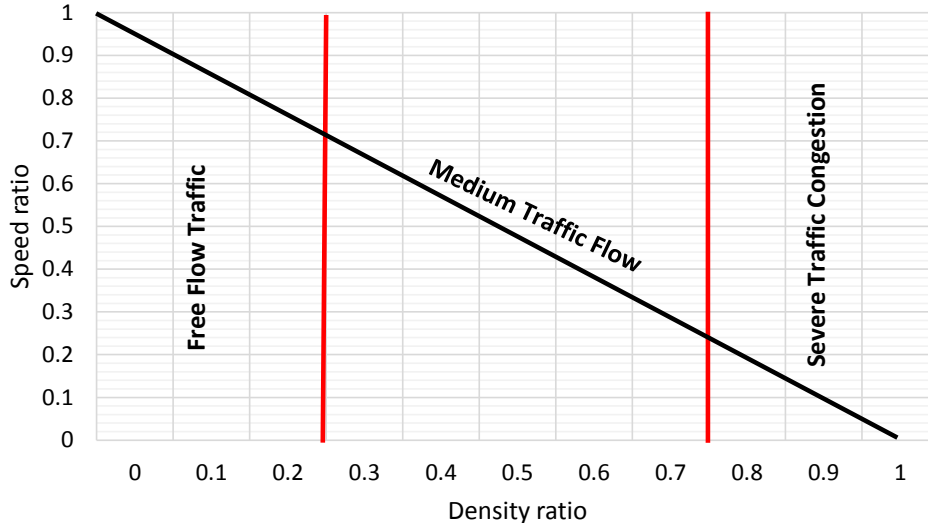


Figure 2: Traffic density-speed relationship [41]

As a result, the speed ratio can be used rather than the density ratio to numerically represent the traffic state. According to Figure 2, when the  $V_r$  is very low the traffic density will be very high and the road will be under severe traffic congestion. The proposed algorithm aims to improve traffic efficiency by detecting and avoiding congestion. Traffic congestion is detected when the speed ratio  $V_r \leq 0.5$ . This value has been chosen in order to avoid the severe congestion which is highlighted in Figure 2 when the speed ratio  $V_r$  become less than 0.5 that means the traffic density increased on the road segments and the congestion will be severe.

### 3.2. Road Network Model:

Suppose the network map consists of a set of intersections (Nodes)  $N$  and a set of edges  $E = \{e_1, e_2, \dots, e_i\}$  connected between the nodes. Then the road network can be modeled as a directed graph  $G = (N, E)$ . Suppose each intersection on the map contains  $n$  roads or alternatives, each of them having  $j$  routing metrics or attribute values and a weight vector which represents the importance (weight) of the attributes. The road network matrix  $A$  can be

formulated as follows:

$$A = \begin{bmatrix} r_1(a_1) & r_2(a_1) & r_3(a_1) & \dots & r_m(a_1) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_1(a_n) & r_2(a_n) & r_3(a_n) & \dots & r_m(a_n) \\ w_1 & w_2 & w_3 & \dots & w_m \end{bmatrix} \quad (6)$$

where  $r_j(a_i)$  represents the value of  $j^{th}$  routing metric ( $r_j$  attribute) for the  $i^{th}$  road ( $a_i$  alternative) for  $i = 1, 2, \dots, n$  and  $j = 1, 2, \dots, m$ . In this work  $m=5$  attributes are used, which are  $C_L, C_S, C_D, C_W, C_{TS}$ . Each of these attributes  
250 (or performance measures) are defined in the list given below. The weights  $w = \{w_j \mid j = 1, 2, \dots, m\}$  represents the relative importance of the attributes being considered, which can be found as detailed in Section 3.5.

The five attributes (or performance measures) that are considered in the proposed optimization strategy are:

- 255 1. Road Length,  $C_L = \{f_j(a_i) \mid i = 1, 2, \dots, n; \quad j = 1\}$ , which is given as a normalized length in a directed graph  $G$  for each alternative in the matrix  $\hat{A}$ .
- 260 2. Average Speed,  $C_S = \{f_j(a_i) \mid i = 1, 2, \dots, n; \quad j = 2\}$ , which gives the normalized average velocities. The average velocities are found by aggregating the velocities of the vehicles (for the previous 5 seconds) entering the roads in  $\hat{A}$  at a given time.
3. Density of vehicles on the road,  $C_D = \{f_j(a_i) \mid i = 1, 2, \dots, n; \quad j = 3\}$ , which is given as a normalized density in  $\hat{A}$  and calculated using (5).
- 265 4. The road width,  $C_W = \{f_j(a_i) \mid i = 1, 2, \dots, n; \quad j = 4\}$ , which represents the number of lanes on the road in  $\hat{A}$ .
5. The set  $C_{TS} = \{f_j(a_i) \mid i = 1, 2, \dots, n; \quad j = 5\}$ , which represents the normalized number of crossing or signals on each of the roads in  $\hat{A}$ .

Here, as the units of each attribute are different (e.g.  $C_L$  is measured in meters, while  $C_S$  is measured in meters/second), processing all values for every routing metric into a comparability sequence is necessary. This is achieved as

follows:

$$f_j(a_i) = \frac{r_j(a_i)}{\sqrt{\sum_{i=1}^n (r_j(a_i))^2}} \text{ where } i = 1, 2, \dots, n; j = 1, 2, \dots, m, \quad (7)$$

where  $f_j(a_i) \in [0, 1]$  is the normalized value of  $j^{th}$  routing metric for the  $i^{th}$  road for  $i = 1, 2, \dots, n$  and  $j = 1, 2, \dots, m$ . The normalized road matrix  $\hat{A}$  can be constructed as follow:

$$\hat{A} = \begin{bmatrix} f_1(a_1) & f_2(a_1) & f_3(a_1) & \dots & f_m(a_1) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_1(a_n) & f_2(a_n) & f_3(a_n) & \dots & f_m(a_n) \\ w_1 & w_2 & w_3 & \dots & w_m \end{bmatrix}. \quad (8)$$

### 3.3. A Centralized Simulated Annealing VIKOR (CSA-VIKOR) Algorithm:

SA is a probabilistic method proposed by [42] that was originally inspired  
 270 by the operation of annealing in metallurgy. The main idea of SA is to accept  
 worse solutions under certain conditions in order to escape from local minima  
 or maxima and move toward the global optima. The algorithm starts with an  
 initial solution that is randomly generated. Each iteration then produces a new  
 random solution based on the previous solution. A new solution which has a  
 275 better cost (this is a measure of how suitable a solution is, see Section 3.4 for  
 further details) is accepted. However, a solution with a worse cost than the  
 previous solution is only accepted with a set transition probability.

This section presents a dynamic path planning method based on SA with a  
 VIKOR cost function. The proposed approach is as follows:

- 280 • Off-line phase of route calculation: The SA algorithm starts with an off-  
 line path computation, in which  $C = \{c_1, c_2, c_3, \dots, c_l\}$  represents a set of  
 vehicles. Every  $c_l$  in  $C$  has a set of routes, that can take it from it's origin  
 to its destination, that is generated from the normalized matrix  $\hat{A}$ . Every  
 road  $a_i$  in the normalized road matrix  $\hat{A}$  has a cost function constructed  
 285 using the VIKOR method [12], [13]. Each route for vehicle  $c_l$  consists of a

varying number of roads between the vehicles origin and destination. The cost function of each route is then given as sum of the costs associated with the individual road segments making up the route. The SA algorithm is outlined in Algorithm 1, where  $U_c$  means the current solution or an initial possible route. This initial path is generated randomly from the road matrix  $\hat{A}$  as shown in Figure 3.

The temperature  $T$  is a random variable, which is fairly decreased with time and controlled by  $\alpha$  which is a cooling rate factor. When the temperature parameter has a very high value, a new path  $U_n$  is calculated randomly from each intersection road matrix  $\hat{A}$ . The cost of the new path,  $C(U_n)$ , is then compared to the cost of the previous path,  $C(U_c)$ . When it is resolved to be a good solution by the superiority test (step 7 in Algorithm 1) the new solution or route is accepted. When the new cost is greater than or equal to the previous cost, the new route can still be accepted with a given transition probability ( $P_t$  in Algorithm 1). This expands the search space and helps to avoid local optimal solutions. When  $T$  approaches  $T_m$ , the path with the minimum cost value has a high probability of being accepted.

The path  $U_n$  in step number 7 of Algorithm 1 is constructed based on previous path  $U_c$  as follows:

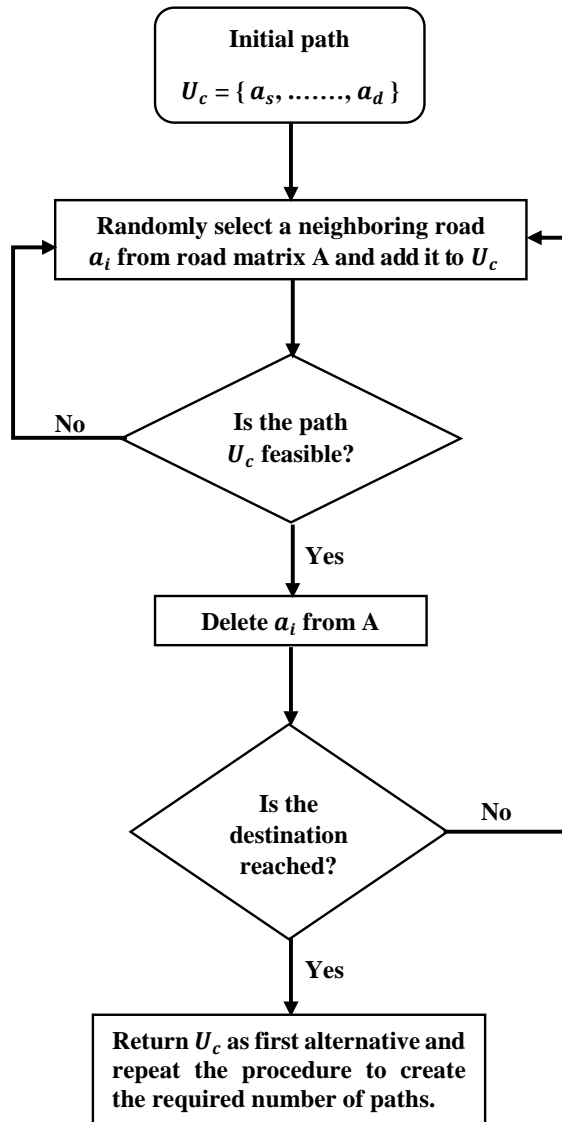


Figure 3: The procedure for generating a random initial path [14]



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**Algorithm 1** Simulated Annealing Algorithm

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- 1:  $U_c = U_{c_0}$  current solution
  - 2:  $T = T_0$  an initial temperature
  - 3:  $\alpha =$  cooling rate
  - 4:  $T_m$  is the minimum temperature
  - 5:  $B_s =$  the best solution
  - 6:  $B_s \leftarrow U_c$
  - 7: **While**  $T > T_m$ :  
Generate a random neighboring solution  $U_n$  from  $\hat{A}$   
**If**  $C(U_n) < C(U_c)$  then  
Move to  $U_n$   
Accept change  $B_s \leftarrow U_n$   
**Else If**  $C(U_n) \geq C(U_c)$  then  
Calculate  $\Delta E = C(U_c) - C(U_n)$   
Move to  $U_n$  with transition probability  
 $P_t = 1/(1 + \exp(-\Delta E/T))$   
**End**  
 $T = \alpha T$   
**End**
  - 8: Return  $B_s$
- 

1. Consider a current route  $U_c = \{a_s, a_1, \dots, a_i, a_{i+1}, \dots, a_{l-1}, a_l, a_d\}$  where  $a_s$  is the road segment the vehicle starts on,  $a_d$  is the destination segment and  $a_i$  means the  $i$ -th road segment.
2. The procedure for generating a random neighboring solution or randomly perturbed route (see Figure 4) consists of the following three steps.
  - (a) Two roads  $a_i$  and  $a_l$  are chosen randomly in the route  $U_c$  as a source and destination, respectively.
  - (b) Generate a random route between  $a_i$  and  $a_l$ .
  - (c) The route  $U_c = \{a_s, a_1, \dots, a_i, a_{i+1}, \dots, a_{l-1}, a_l,$

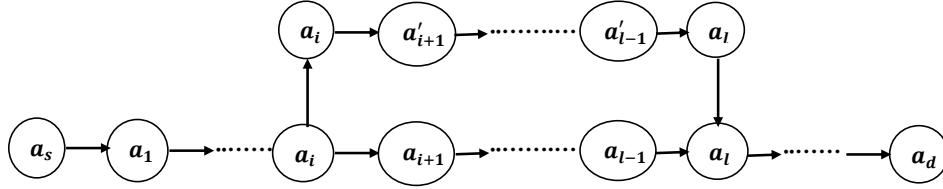


Figure 4: How to construct a new path  $U_n$  based on an initial path  $U_c$  [14]

$a_d\}$  is substitute by  $(a_i, a'_{i+1}, \dots, a'_{l-1}, a_l)$  to generate a new route  $U_n = \{a_s, a_1, \dots, a_i, a'_{i+1}, \dots, a'_{l-1}, a_l, a_d\}$ .

3. Test the continuity of the new route.
4. Repeat steps 2-3 if the route is not feasible. Otherwise, continue with SA as in Algorithm 1 and compare the cost of the new route to the previous route.

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- On-line phase of route calculation: In this phase, the vehicles start driving through the city with the route created by the off-line path calculation. Once the congestion is detected, the on-line phase is triggered automatically to determine an alternative route as follows: Once new data becomes available, the RSU updates the road costs  $RC_k = \{roadId, averagespeed, position, density, V_f\}$ . Based on this data the road matrix  $\hat{A}$  for the RSU is updated. Then the RSU will identify congested roads in  $\hat{A}$  and generates a set of congested roads contained in the matrix  $CR$ . Hereafter, once vehicle  $v_k$  approaches an intersection it will send a query message that contains  $msgQ_k = \{roadId, position, route\}$  to the RSU. This RSU will then evaluate the route for vehicle  $c_l$ . If the evaluation shows that the route will bypass a congested road, then  $c_l$  will keep traveling using the current path. Otherwise, the CSA-VIKOR at the RSU will be activated and reloaded with an updated search space. The alternative route will then be computed and transmitted to the vehicle. This allows the vehicle to then continue towards its destination, avoiding the congestion that has formed. Algorithm 2 shows the procedure of the congestion avoidance us-

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**Algorithm 2** Congestion avoidance using CSA-VIKOR approach

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1: **Input:**  
     $C$  set of vehicles in the network,  $G$  Network graph, Beacon messages between RSUs and vehicles,  $A$  road matrix with different attributes

2: **Output:**  
    A new optimal route that avoids the congested roads

3: **At each RSU:**  
    **For** road  $\in G$  do  
        Calculate the average vehicle speeds  
        Calculate the average vehicle density  
        Update matrix  $A$  (roadID, averagespeed, density)  
        Calculate normalized road matrix  $\hat{A}$   
    **End**

4: **Detect congested roads:**  
    **For** road  $\in \hat{A}$  do  
        Calculate the velocity ratio  $V_r$   
        **If**  $V_r \leq 0.5$  then  
            Add the congested road into matrix  $CR$   
        **End**  
    **End**

5: **Find new route:**  
    **For**  $c_l \in C$  do  
        Extract the vehicle route from beacon messages  
        **For** road  $\in$  vehicle route do  
            **If** road  $\in$  Congested Road Matrix then  
                Exclude the congested road from matrix  $\hat{A}$   
                Get the current coordinate of the vehicles  
                Update road costs  $RC_K$   
                Update matrix  $\hat{A}$  for each RSU by using VIKOR method  
                Calculate new optimal route by using CSA-VIKOR  
                Send the new route to the vehicles;  
            **End**  
        **End**  
    **End**

**End**

---

340 ing CSA-VIKOR. This procedure is repeated every time vehicles approach an intersection and enter the transmission range of a RSU.

### 3.4. VIKOR Cost Function of CSA-VIKOR Algorithm:

In this paper the cost function is implemented using the VIKOR method [12]. VIKOR is an approach for solving multi-criteria optimization problems. It works by ranking solutions and picking the best alternative, by comparing each to the ideal (optimal solution based on conflicting criteria) and worst solution. This ranking is based on Lp-metric given in (9) [13]. This metric is termed the level of regret and is given by:

$$L_{p,i} = \left\{ \sum_{j=1}^m \left[ w_j \frac{(f_j^* - f_j(a_i))}{(f_j^* - f_j^-)} \right]^p \right\}^{\frac{1}{p}}, \quad 1 \leq p \leq \infty, \quad (9)$$

where  $i = 1, 2, \dots, n$  and  $j = 1, 2, \dots, m$ . Here,  $L_{1,i}$  is defined as the maximum group utility ( $S_i$ ), and  $L_{\infty,i}$  is defined as the minimum individual regret of the opponent ( $R_i$ ),  $f_j^*$  and  $f_j^-$  represent the best and the worst values of all 345 attributes, respectively.

The VIKOR method then ranks the alternative solutions as follows:

1. Find that best  $f_j^*$  and the worst  $f_j^-$  values, for each criteria being considered in the optimization.
2. Calculate  $S_i$  and  $R_i$  using:

$$S_i = L_{1,i} = \sum_{j=1}^m w_j \frac{(f_j^* - f_j(a_i))}{(f_j^* - f_j^-)}, \quad (10)$$

$$R_i = L_{\infty,i} = \max_j \left[ w_j \frac{|f_j^* - f_j(a_i)|}{|f_j^* - f_j^-|} \right], \quad (11)$$

where  $w_j$  is the weight of the  $j^{th}$  criterion, expressing the relative importance of criteria. 350

3. Find  $Q_i, i = 1, 2, \dots, n$ , using:

$$Q_i = \alpha \frac{(S_i - S^*)}{(S^- - S^*)} + (1 - \alpha) \frac{(R_i - R^*)}{(R^- - R^*)}. \quad (12)$$

Here  $S^* = \min_i S_i$ ,  $S^- = \max_i S_i$ ,  $R^* = \min_i R_i$ ,  $R^- = \max_i R_i$ , and  $\alpha$  is a weighting term. A value of  $\alpha = 0.5$  is selected to ensure that the compromise solution is stable within a decision making process.

4. The alternative solution can be ranked in descending order based on the values for  $S$ ,  $R$  and  $Q$ . The interested reader can find further details about the VIKOR standard ranking procedure in [12] and [13].

However, in this paper the ranking procedure of VIKOR method has been avoided by using the SA optimization algorithm. The cost function of CSA-VIKOR method has been calculated by adding  $Q$ ,  $S$  and  $R$  of each potential route as in (13) below. The best route is then chosen using the SA procedure in Algorithm 1. Here,  $\mu_i$ ,  $\varphi_i$  and  $\beta_i$  are the weight parameters of functions  $Q_i$ ,  $S_i$  and  $R_i$ , respectively. They are chosen so that  $\mu_i + \varphi_i + \beta_i = 1$  and  $\mu_i, \varphi_i, \beta_i > 0, \forall i \in n$ . The values of  $\mu_i$ ,  $\varphi_i$  and  $\beta_i$  are selected by trial and error to satisfy the system objective and requirement given by:

$$Y_i^* = \mu_i Q_i + \varphi_i S_i + \beta_i R_i \quad Y_i^* \in [0, 1] \quad \forall i = 1, \dots, n. \quad (13)$$

### 3.5. Calculation of Attribute Importance Weights:

The selection of the weights that control the relative importance of each attribute under consideration has an impact on the final solution that is reached. Various methods for making this selection have been previously suggested [43]. In this paper, the Maximizing Deviation (MD) method is used to determine the weight vector  $w = [w_1, w_2, \dots, w_m]$  and to ensure the weight stability intervals of the multiple attributes.

First, the initial values of the weight vector are specified  $w^* = [w_1^*, w_2^*, \dots, w_m^*]$ . According to [44], the weight vector  $w^*$  should be selected to maximize all deviation values (the differences between values of the same attribute) for all the attributes. The weight vector can then be formulated using a non-linear pro-

gramming model:

$$\begin{aligned} \max_{w_j^*} F(w^*) &= \sum_{j=1}^m \sum_{i=1}^n \sum_{z=1}^n w_j^* d(f_j(a_i), f_j(a_z)), \\ \text{subject to} & \sum_{j=1}^m w_j^{*2} = 1, \quad 0 \leq w_j^* \leq 1, \end{aligned} \quad (14)$$

where the distance  $d(f_j(a_i), f_j(a_z))$  between different values belonging to the same attribute is given by:

$$d(f_j(a_i), f_j(a_z)) = (f_j(a_i) - f_j(a_z))^2. \quad (15)$$

To solve (14), let

$$L(w_j^*, \lambda) = \sum_{j=1}^m \sum_{i=1}^n \sum_{z=1}^n w_j^* d(f_j(a_i), f_j(a_z)) + \frac{1}{2} \lambda \left( \sum_{j=1}^m w_j^{*2} - 1 \right) \quad (16)$$

represent the Lagrangian function of the constrained optimization model, where  $\lambda$  is a Lagrange multiplier. The partial derivatives of  $L$  are estimated as

$$\frac{\partial L(w_j^*)}{\partial w_j^*} = \sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z)) + \lambda w_j^* = 0, \quad \text{for } 1 \leq j \leq m \quad (17)$$

and

$$\frac{\partial L(w_j^*)}{\partial \lambda} = \frac{1}{2} \left( \sum_{j=1}^m w_j^{*2} - 1 \right) = 0. \quad (18)$$

From (17), it can be derived that

$$w_j^* = - \frac{\sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z))}{\lambda} \quad \text{for } 1 \leq j \leq m. \quad (19)$$

After substituting (19) into (18), it gives

$$\lambda = - \sqrt{\sum_{j=1}^m \left( \sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z)) \right)^2}. \quad (20)$$

Replacing (20) into (19), it gives

$$w_j^* = \frac{\sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z))}{\sqrt{\sum_{j=1}^m \left( \sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z)) \right)^2}} \quad \text{for } 1 \leq j \leq m. \quad (21)$$

The final  $w_j$  is derived from the normalization of  $w_j^*$  as

$$w_j = \frac{w_j^*}{\sum_{j=1}^m w_j^*} = \frac{\sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z))}{\sum_{j=1}^m \sum_{i=1}^n \sum_{z=1}^n d(f_j(a_i), f_j(a_z))} \text{ for } 1 \leq j \leq m. \quad (22)$$

#### 4. Performance Evaluation

The proposed framework has been tested and evaluated through a vehicular network simulator Veins [45] which integrates the traffic simulator Simulator for Urban Mobility (SUMO) [46] with the network simulator OMNeT++ [47] 375 for Urban Mobility (SUMO) [46] with the network simulator OMNeT++ [47] to manage the mobility of vehicles and the communication between V2V or V2I communication systems. Two realistic maps have been imported from the Open Streets Map (OSM) tool [48] to evaluate and test the proposed method (the scenarios of Birmingham city in U.K. and Turin city in Italy) as shown in 380 Figure 5 and 13.

The proposed algorithm has been implemented for different vehicular environments to optimize the traffic scenario. The CSA-VIKOR has been compared with the Original Dijkstra's Algorithm (ODA), Dynamic Dijkstra's Algorithm (D-DA), Dynamic  $A^*$  (D- $A^*$ ) algorithm, which were implemented as in [19] and 385 the ISA-TOPSIS method which was implemented as in [14]. The simulation of all algorithms has been executed for ten independent Monte Carlo runs and then the average values of the obtained results were recorded. Five different performance measures have been considered in this performance evaluation:

- **Average Travel Time (ATT):** average travel time of all vehicles.
- 390 • **Average Fuel Consumption (AFC):** average fuel consumption taken by vehicles
- **Average  $CO_2$  emission:** average  $CO_2$  emission of all vehicles.
- **Average Travel Distance (ATD):** average travel distance taken by vehicles.

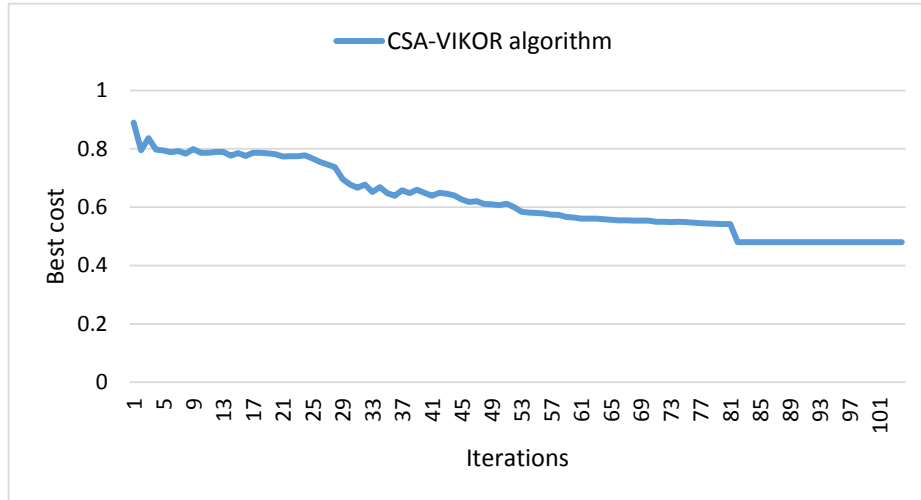


Figure 5: CSA-VIKOR convergence

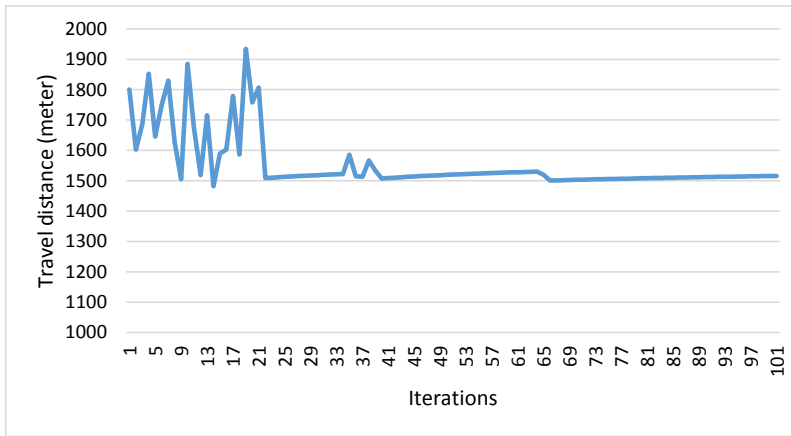
- 395 • **Average Travel Speed (ATS)**: average travel speed of all vehicles.

The EMissions from Traffic (EMIT) model [49], is used to calculate fuel consumption and vehicle emissions. This is done using a statistical model and vehicle speeds and accelerations from the SUMO simulator.

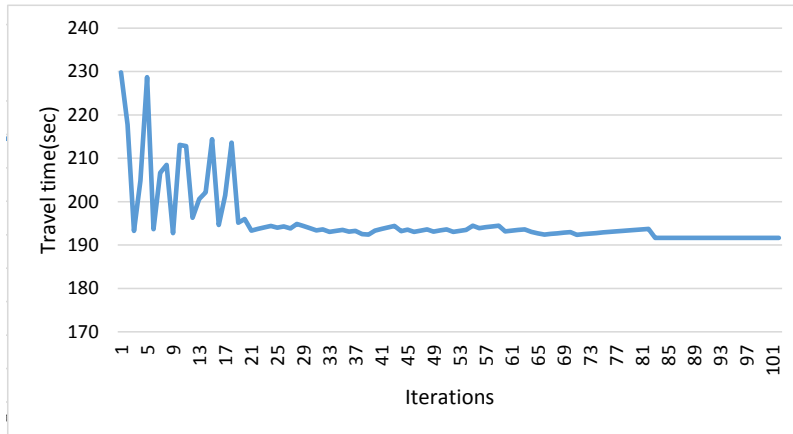
Figure 5 shows the convergence of the CSA-VIKOR approach to the optimal  
 400 cost. It is clear that the CSA-VIKOR continues to search for the solution until reaching convergence, which in this example is after 81 time steps. This algorithm shows a good search ability and finds the solution lading to the optimal route.

Figures 6 a and b show the convergence of the algorithm in terms of the  
 405 travel distance and travel time, respectively. It is obvious that the CSA-VIKOR finds the travel distance and travel time at the same speed from 0 to 81 times. Therefore, we can deduce from Figures 6 a and b that the search speed of the algorithm is good enough to find the solution.





(a)



(b)

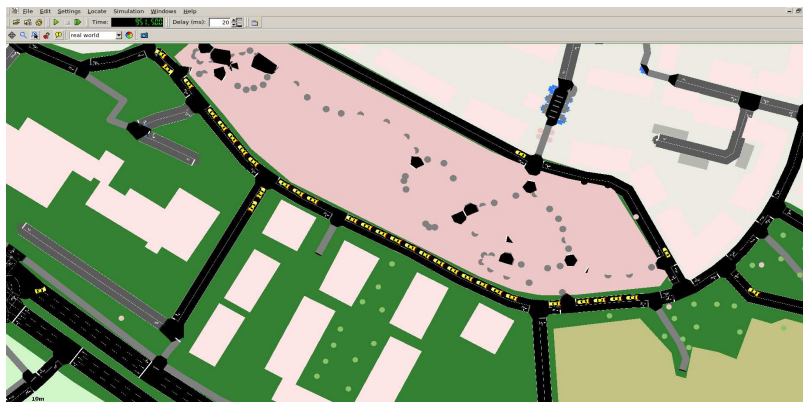
Figure 6: Convergence curves of CSA-VIKOR. (a) Travel distance convergence line; (b) Travel time convergence line.

#### 4.1. Birmingham City Scenario

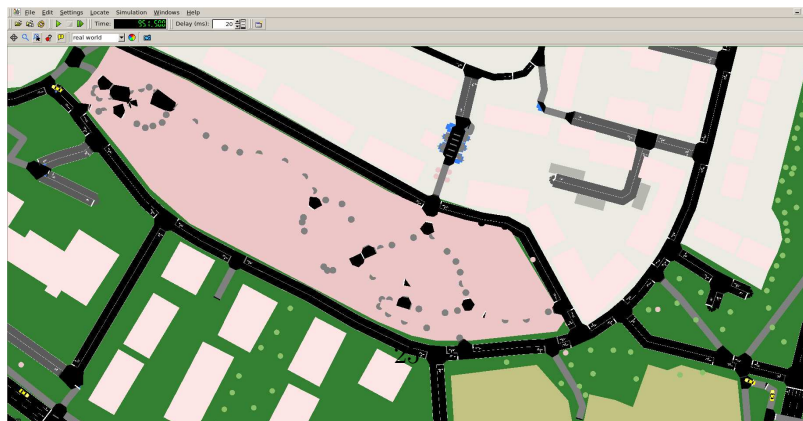
410 In this Scenario, a realistic map scenario for Birmingham city centre has been imported from OSM tool into SUMO simulator. The area under consideration is shown in Figure 7. Figure 8a then shows a selected region where congestion forms if no dynamic re-routing is used when congestion is detected. When the proposed method is used this congestion is then avoided as shown in Figure 8b.



Figure 7: Birmingham city centre Map that is imported into SUMO



(a)



(b)

Figure 8: The traffic flow of vehicles with ODA and CSA-VIKOR. (a) The traffic flow with ODA approach; (b) Traffic flow using CSA-VIKOR approach.

Table 1: Simulation parameters as configured in the SUMO implementation of Birmingham scenario

<b>Simulation parameters</b>	<b>Value</b>
<b>Map dimension</b>	3.5 km×2.5 km
<b>Maximum allowed speed</b>	32 m/s
<b>Simulation time</b>	1000 s
<b>MAC/PHY</b>	IEEE 802.11p
<b>Max. transmission range</b>	600 m
<b>Number of vehicles</b>	100-1000
<i>T</i> <b>off-line</b>	100 °C
$\alpha$ <b>off-line</b>	0.998
<i>T</i> <b>on-line</b>	35 °C
$\alpha$ <b>on-line</b>	0.992
$\mu_i$	0.55
$\varphi_i$	0.225
$\beta_i$	0.225
<b>Number of simulation runs</b>	10 times
<b>Confidence Level</b>	95%

415 Table 1 shows the parameters that have been used in the simulation, where the vehicles speed have been chosen by the designer using U.K. road laws as a guide. The SA parameters ( $T$  and  $\alpha$ ) have been selected to give a suitable trade-off between computation time and amount of optimization. The other parameters have been chosen based on the OSM and Veins specification.

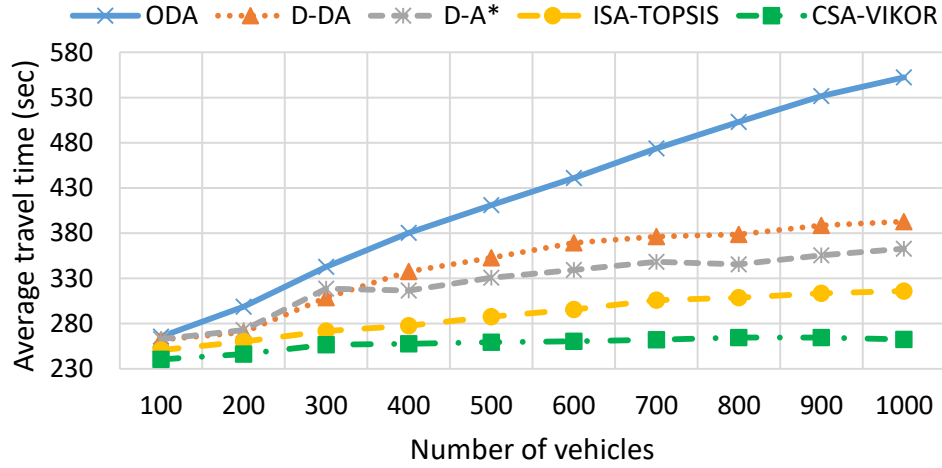


Figure 9: Average travel time

4.1.1. Average Travel Time

Figure 9 depicts the average travel time obtained by the five methods. It is clear that the average travel time has a direct relationship with the number of vehicles. As is expected, the average travel time increases as the number of vehicles increases. This is because the more vehicles there are on the roads, the greater the probability of traffic jams forming (as well as them being longer due to the increased number of vehicles), resulting in larger average travel times. This is illustrated by the results shown for ODA in Figure 9.

The D-DA and D-A\* algorithm obtain travel times that are more constant and lower than those of the ODA. This is due to the re-routing mechanism when the congestion is detected. The ATT of D-DA is slightly better than the D-A\* algorithm for low numbers of vehicles. However, when the number of vehicles starts increasing, the ATT of the D-A\* algorithm becomes much better compared with the D-DA. This is due to the fact that the D-DA selects the shortest route for all vehicles and due to the low number of vehicles in the sparse vehicle example, it does not move the congestion to another area. In contrast, in a dense vehicle scenario re-routing, many vehicles to the route with the shortest path will move the congestion from one area to another one.

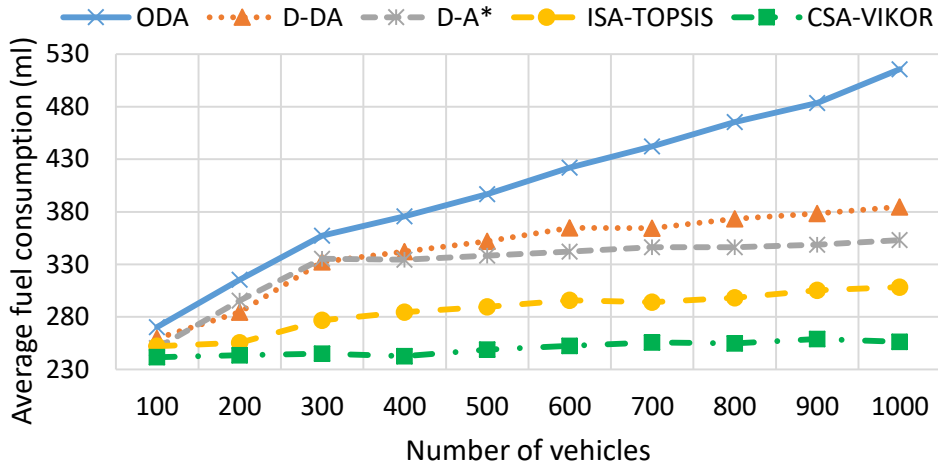


Figure 10: Average fuel consumption

It is clear that the CSA-VIKOR algorithm has significantly improved the average travel time as compared to the ODA, D-DA, D-A\* and ISA-TOPSIS, respectively. The reason is that the CSA-VIKOR algorithm routes the vehicles through the less congested path by using the MADM VIKOR method to consider more attributes (density of cars on the road, the traffic light at the roads and width of the roads) in its cost function. Additionally, the centralized approach CSA-VIKOR helps the RSUs to update most of the roads in the road matrix, giving an overview of almost all the roads on the map. The ISA-TOPSIS is seen to have better ATT as compared with the ODA, D-DA and D-A\* algorithms. This is because the ISA-TOPSIS utilizes the real-time information in its cost function. However, its performance is still relatively lower than the CSA-VIKOR algorithm. The reason is that the ISA-TOPSIS only has a local overview of roads on the map.

#### 4.1.2. Average Fuel Consumption

Figure 10 illustrates the AFC obtained from all algorithms. It can be seen that the impact of taking the longest and shortest route on the traffic efficiency and the fuel consumption. The D-A\* algorithm selects the longest free flow route that helps to distribute the vehicle and decrease the congestion. However,

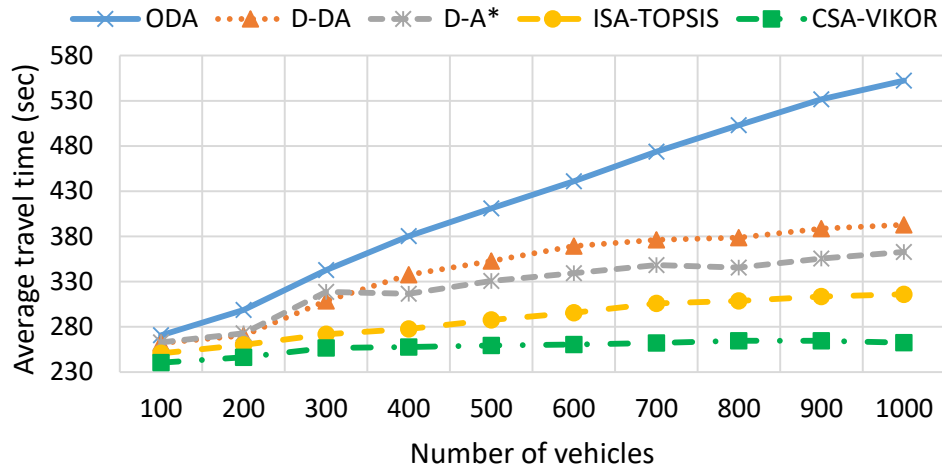


Figure 11: Average  $CO_2$  emission

that leads to driving for long distances which in turn leads to the consumption of more fuel by the engine. On the other hand, in dense scenarios choosing the shortest path by ODA and D-DA leads to the generation of severe traffic congestion which in turn leads to the consumption of more fuel due to the higher numbers of vehicles waiting in the queues.

Despite the D-DA, D-A\* and ISA-TOPSIS algorithms having lower fuel consumption than ODA, their traffic efficiency is lower compared with the efficiency of the CSA-VIKOR algorithms. This is due to the shorter waiting time, better average speeds and an optimal path that is selected based on different navigation criteria by this algorithm. Additionally, both the ISA-TOPSIS and CSA-VIKOR pay attention to the congestion by using the real-time data from VANETs that helps to re-route the vehicles by selecting the optimal paths and avoiding the traffic jams. However, CSA-VIKOR shows better performance as compared to the ISA-TOPSIS. This is due to the fact that the ISA-TOPSIS can only avoid the local traffic congestion because it only updates a few roads in the vehicle transmission range.

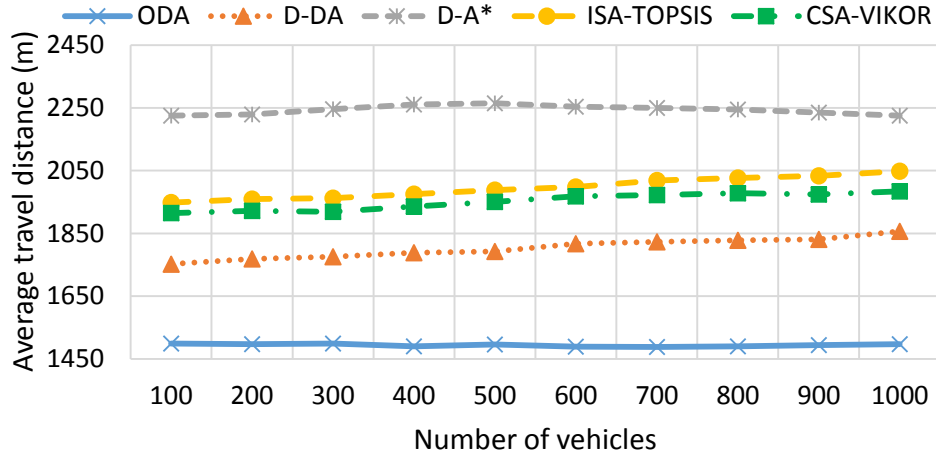


Figure 12: Average travel distance

#### 4.1.3. Average $CO_2$ Emissions

Figure 11 shows the  $CO_2$  emissions result obtained by the five algorithms. The results of  $CO_2$  emissions are directly related to the results of fuel consumption. The longer the travel distance, the larger the waiting time, the more fuel that is consumed by the engine, the more  $CO_2$  emissions there are. For large vehicle numbers and when there is congestion, there are longer waiting times on the roads, increasing the fuel consumption and  $CO_2$  emissions.

It is clear from Figure 11 that CSA-VIKOR has the lowest average  $CO_2$  emissions compared with the other algorithms. This is due to it gives the best average travel speeds by finding the optimal paths. The ISA-TOPSIS comes in the second place in terms of  $CO_2$  emissions. Both D-DA and ODA have the worst  $CO_2$  emissions due to a large amount of fuel being consumed by the vehicle on the routes being optimized by these methods.

#### 4.1.4. Average Travel Distance

Figure 12 depicts the average travel length result for all of the algorithms. The D- $A^*$  has a larger average travel distance than ODA, D-DA, ISA-TOPSIS and CSA-VIKOR. This is due to the fact that D- $A^*$  chooses the routes with the longest travel distance (with the maximum average speed limit) but it has the

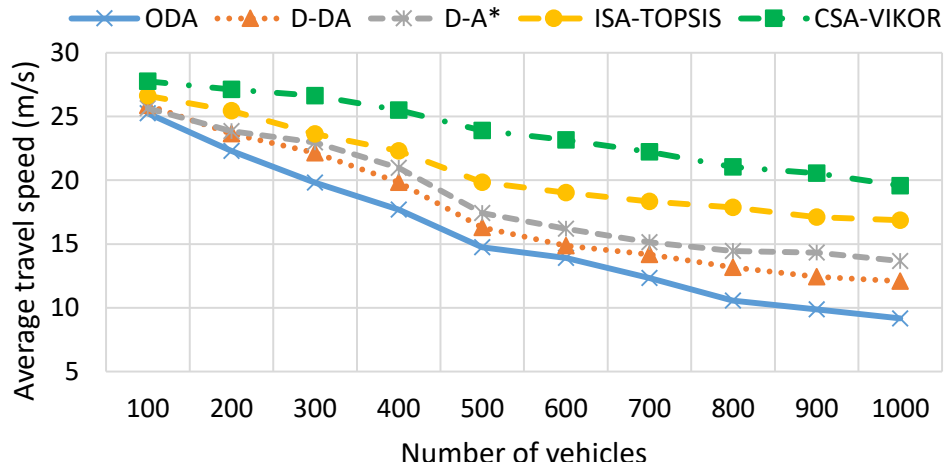


Figure 13: Average travel speed.

490 minimum travel time and distributes the vehicles on them to avoid generating further congestion.

It can also be seen that both ISA-TOPSIS and CSA-VIKOR can find a compromise by minimizing effectively the travel time, fuel consumption and  $CO_2$  emissions due to their ability to consider multiple pieces of traffic information. 495 However, this reduction leads to a slight increase in the travel distance compared to ODA and D-DA. This is a knock on effect of ISA-TOPSIS and CSA-VIKOR using real-time traffic information to re-route vehicles to avoid congestion that forms on the shorter routes.

The D-DA has slightly increased the travel distance as compared to ODA. 500 This is because the vehicles are already on the shortest paths (as are the ones routed using ODA) and are then given an alternative route when congestion is detected. However, this has not aided the drivers in avoiding the congestion because it re-routes the vehicles with the shortest path and that leads to transfer the congestion from one area to another. The ODA has a constant travel distance as compared to the other algorithms, as there is no re-routing in this case. 505 Note, this distance is fixed and is not affected by whether congestion occurs or not.



#### 4.1.5. Average Travel Speed

Figure 13 speeds the average travel speed obtained by all of the algorithms. CSA-VIKOR has recorded the best average travel speed compared to the other methods for all vehicle numbers considered. This is due to the congestion avoidance method and providing the vehicles with the best alternative paths. Additionally, it is a centralized approach that gives drivers a comprehensive overview for almost all of roads on the map.

The CSA-VIKOR has recorded the best performance in terms of average travel speeds. This is because this optimization method can avoid the traffic congestion by using the traffic information for the wider region and considering five attributes in its optimization that it is not possible for the ODA, D-DA and D-A\* algorithms. The ISA-TOPSIS has better performance in terms of ATS as compared with the ODA, D-DA and D-A\* algorithms. However, this method can only improve the local traffic congestion by utilizing the local traffic information.

Despite the D-DA and D-A\* having better performance compared to ODA, they have a relatively poor performance when compared to the proposed solution. This is because they avoid the congested roads by re-routing all vehicles along an alternative route based on a single attribute. Therefore, the congestion is transferred to the new routes. The ODA has the worst average travel speed. This due to a large number of vehicles being stuck in traffic congestion, due to there not being a re-routing mechanism. We can see the impact of travel speed on the traffic efficiency especially the fuel consumption and  $CO_2$  as in Figures 10 and 11, respectively.

#### 4.1.6. Average CPU Time

Figure 14 illustrates the average CPU time that has been estimated by combining the transmission time of real-time data with the elapsed time to find a new path and re-route vehicles to avoid congested roads. It is clear from Figure 14 that the ODA, D-DA and D-A\* require less CPU time as compared to ISA-TOPSIS and CSA-VIOKR algorithms. However, that has not really

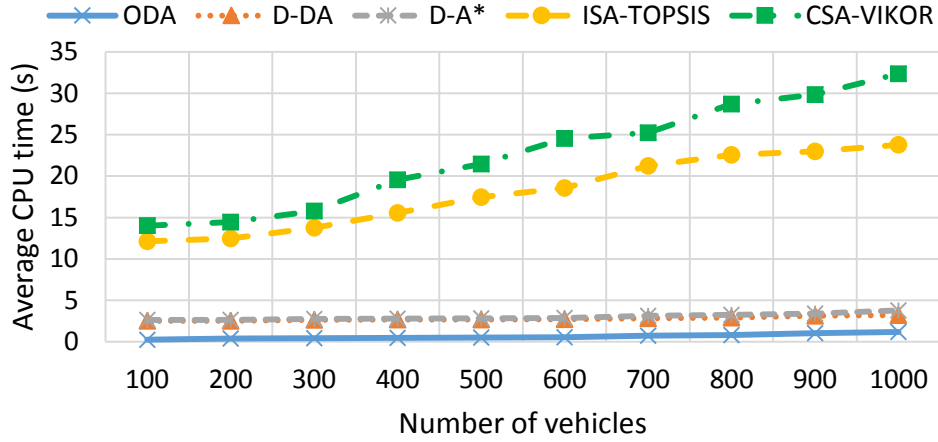


Figure 14: Average CPU time

helped the driver to avoid the congestion because they re-route drivers with the shortest path or longest free flow path to escape from the congestion and that leads to moving the congestion from one street to another one. ISA-TOPSIS has better CPU time as compared to CSA-VIKOR. This is due to the search of an alternative route has been done independently in each vehicle rather than waiting for all traffic states to be communicated by the RSUs. However, this only helps the driver to escape from the local traffic congestion. CSA-VIKOR has the largest CPU time because the optimization has been done centrally in each RSU to find the optimal path for all drivers. This helps to decrease the global travel time, fuel consumption as well as  $CO_2$  emissions of all drivers.

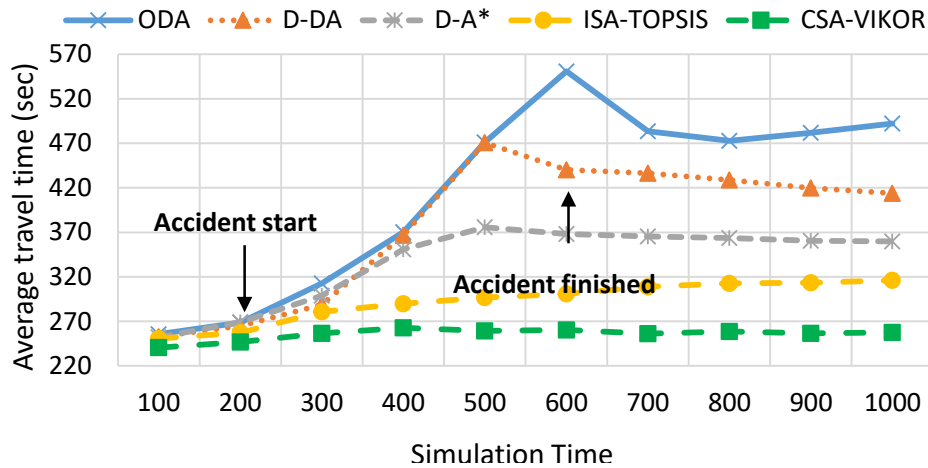


Figure 15: Average travel time of the accident scenario

#### 4.1.7. Average Travel Time of Accident Scenario

Figure 15 represents an accident scenario, which is similar to a scenario considered in [27] in order to evaluate the performance of all of the algorithms in the presence of accidents. In this scenario, 1000 vehicles were involved and 500 vehicles are assigned to the five algorithms, with each algorithm being used to select the route of 100 vehicles. The remaining 500 vehicles are guided randomly to generate accidents and congestion on the some of the main roads in the map of Birmingham being considered. The accident starts after 200 seconds of simulation time and it is cleared after 600 seconds.

As can be seen from Figure 15, all vehicles that are routed through the shortest paths via ODA have a worse travel time as compared to the other algorithms. This is due to the lack of utilizing of real-time data and the lack of a mechanism to avoid the congested roads. The D-DA gives the second worst travel times. This is due to the dynamic re-routing of all of the vehicles to the shortest paths, which leads to the transfer of congestion to other roads. The D-A\* algorithm has a better reaction to the congestion as compared to ODA and D-DA because it routes the vehicles along the roads with the minimum travel times. However, its' performance is still less efficient than compared to ISA-



Figure 16: Turin city centre Map that is imported into SUMO

TOPSIS and CSA-VIKOR. This is due to the efficient reaction and utilization of real-time traffic information and congested roads by ISA-TOPSIS and CSA-VIKOR.

The CSA-VIKOR algorithm has the best performance in the presence of  
570 congestion as it utilizes the real-time data of almost all of the roads on the map while the ISA-TOPSIS can only utilize the local traffic information. This sometimes does not give the driver enough time to avoid the congested area. In addition, the CSA-VIKOR algorithm selected the optimal paths based on two real-time navigation criteria (average speeds and vehicle densities) and three  
575 static criteria (roads length, roads width and a number of traffic signals on the roads). This helps the driver to select the path with the fewer number of vehicles, higher average speeds, larger number of lanes and fewer traffic signals.

#### 4.2. Turin City Scenario

Another realistic map scenario for Turin city centre in Italy has been im-  
580 ported from the OSM tool as shown in Figure 16.

In this Scenario, The parameters for the CSA-VIKOR algorithm are the same as the Birmingham city scenario and are summarized in Table 1 except

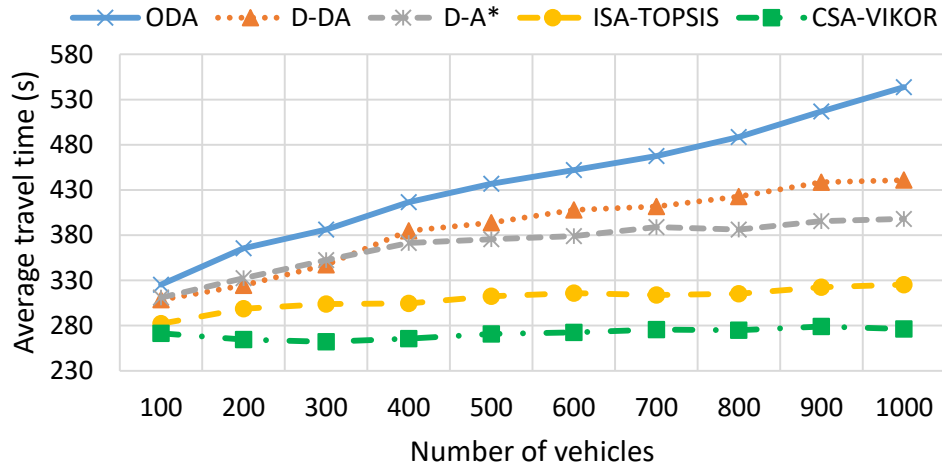


Figure 17: Average travel time

the map size that is 3.8 km×3.2 km and the maximum allowed speed that has been set up to 30 m/s.

585 Figures 17, 18 and 19 show the obtained results of average travel time, average fuel consumption and average travel speed of all of the algorithms being evaluated. They show a similar performance pattern as that has been obtained for the Birmingham city scenario. Moreover, they show that the CSA-VIKOR algorithm still has the best performance as compared to the other algorithms.

590 In conclusion, the relative results of the algorithms have not been changed by changing the city under consideration. However, the absolute values of the average travel times, fuel consumption and travel speed levels have changed due to the difference in the size of roads and ring roads of Turin map used as compared to Birmingham map. The improved performance over the comparison

595 algorithms is due to the fact that real-time traffic information has been used to continuously optimize travel time, travel speed, fuel consumption and  $CO_2$  emissions.

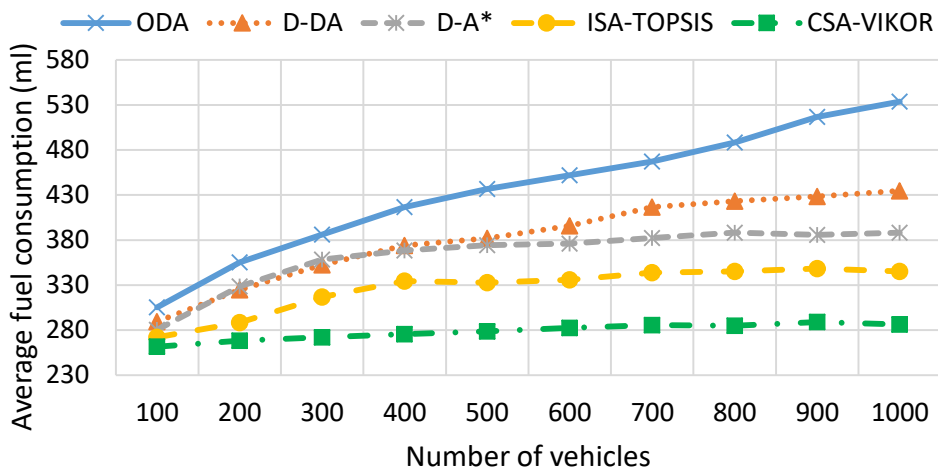


Figure 18: Average fuel consumption

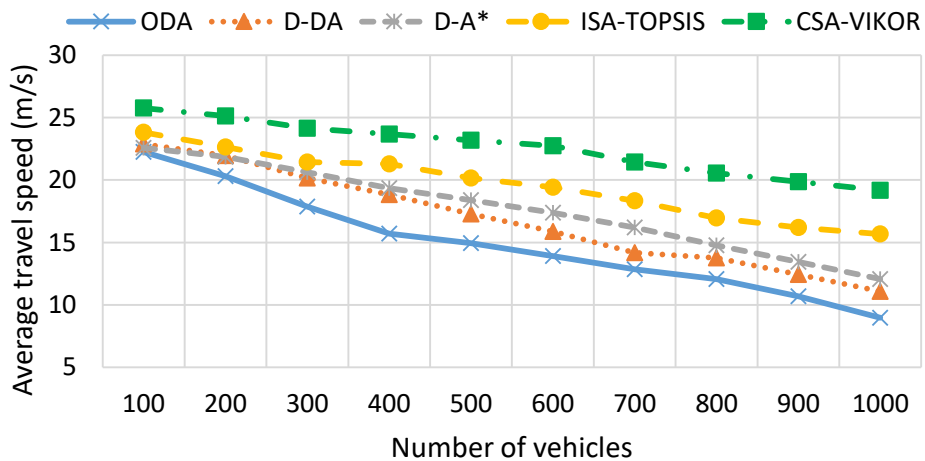


Figure 19: Average travel speed

## 5. Conclusion

As the number of vehicles on road networks increases so does the problem of congestion, making the development of congestion avoidance algorithms an important problem. In this paper, a new congestion alleviation method called a centralized simulated annealing VIKOR (CSA-VIKOR) algorithm has been proposed. The novelty of this work consists of the developed optimization al-

gorithm based on a multi-objective cost function and dynamic route planning.  
605 The proposed method can lead to a reduction in global travel time, fuel consumption and  $CO_2$  emissions. Simulation results from the Birmingham scenario show that the proposed approach has a better performance as compared to the original Dijkstra's algorithm, dynamic Dijkstra's algorithm,  $A^*$  algorithm and an improved simulated annealing TOPSIS algorithm. As reported from the  
610 Birmingham scenario, it is shown that the proposed approach improves traffic efficiency in the presence of congestion by an overall average of 24.05%, 48.88% and 36.89% in terms of travel time, fuel consumption and  $CO_2$  emissions, respectively. Moreover, similar performance patterns were obtained for the Turin-based simulation.

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