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RESEARCH ARTICLE

Multi-Class Vehicle Segregation for Enhanced Safety and Efficiency of Mixed Traffic Networks

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ABSTRACT The heterogeneity of vehicle types and their lane-free movement are the unique characteristics of mixed traffic conditions. Modelling and controlling such a traffic system is challenging. Towards this, to overcome the adverse effects of heterogeneity, segregation of traffic based on vehicle type is the viable solution proposed in this study. Two mathematical formulations are developed for multi-class segregation problems to identify a vehicle type or a combination of vehicle types to be segregated from the remaining traffic to enhance efficiency and safety in mixed-traffic networks. The corresponding objectives are related to minimising the total system travel time and network crash risk. The developed models were evaluated using a real-world mixed traffic network case study and it was observed that the total system travel time savings were 10% compared to the case of conventional traffic assignment. Sensitivity analysis shows that the segregation patterns are repeatable across compositions, demands, and parameter values. Based on the observations, a heuristic solution is proposed for the multi-class vehicle segregation problem. The heuristic solution involves routing different vehicle types in the network, and the evaluation results showed that the heuristic method could provide a good trade-off solution with respect to efficiency and safety. Considering the extreme point solutions of the two single-objective formulations, the total system travel time value is 11% higher than the single objective case of travel time and the total crash risk is 90% higher than the single objective case of crash risk. The findings in this paper are expected to improve the modelling and traffic assignment strategies for mixed traffic networks by addressing their unique characteristics.

INDEX TERMS Crash risk, mixed traffic network, multi-class vehicle segregation, traffic composition, travel time.

I. INTRODUCTION

Mixed traffic composition in developing countries comprises vehicles with varying types, sizes, engine power, manoeuvrability, etc. that include motorised two-wheelers, three-wheelers, four-wheelers, bicycles, light commercial vehicles, heavy commercial vehicles, etc. Heterogeneity in vehicle types and their lane-free movement result in complex driving behaviours with a large range of operating speeds and moving bottlenecks in the traffic stream. The consequences are sub-optimal throughput, increased delay, reduced utilisation of available road capacity, and escalated safety and environmental concerns. Therefore, it is important to address the heterogeneity in traffic networks and develop models to overcome these adverse effects. In this regard, vehicle segregation can be a viable solution to alleviate the ill effects of mixed traffic. Vehicle segregation here is defined as the segregation of mixed vehicle type 'streaml' on the links based on vehicle types. Thus, the aim of this study is to identify a vehicle type to be segregated or a combination of vehicle types on the links of a network. It is hypothesised that this will reduce the adverse effects of mixed traffic. It is expected to reduce the intra-modal impedance due to the heterogeneity and the unutilised white spaces on the road that occur due to the varying sizes of different vehicle types (during vehicle movement in the midblock sections and during the stopped conditions near the intersections), thereby increasing the network capacity. Segregating traffic by vehicle type may increase network efficiency and enhance stability and safety.

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Segregation of one vehicle type like trucks or buses has been studied by many researchers [1], [2], [3], [4], [5]. The bounded accelerations of the trucks limit their operating speeds reducing the average speed of the entire traffic stream. Also, their size affects the line of sight of the drivers of smaller vehicles travelling behind [6], [7]. Based on these drawbacks and others, studies have shown that controlling the truck movements in a network can reduce the binding effect and emissions, improve safety, prevent abrupt pavement deterioration and improve the operational efficiency of road networks [8], [9], [10], [11]. Also, different types of restrictions for trucks are investigated and have been found to be beneficial for the entire traffic network [12], [13], [14]. Moreover, lane restrictions for trucks have been implemented in many places depending on the topography [15]. Many studies showed the large operational potential of separate bus lanes which segregate buses from other vehicle classes [16], [17].

In the area of safety, the author proposed lane restrictions for trucks on a freeway to improve traffic safety [18]. The author studied mixed traffic characteristics and concluded that excluding three-wheelers and a combination of three-wheelers and heavy vehicles can potentially improve stream speed [19]. Another study recommended dedicated lanes for motorised two-wheelers to address the ill effects of mixed traffic on multi-lane urban corridors, which could enhance safety and efficiency [20]. IRC 70-2017 and IRC Sp-043 recommend segregating slow-moving vehicles from fast-moving vehicles to enhance safety [21]. A recent study in mixed traffic networks also shows that implementing bus priority lanes can reduce travel times [22]. Therefore, from the literature, it is clear that several ways of segregation implemented in mixed traffic based on vehicle type can enhance efficiency and safety.

However, all the studies considered the segregation of only one vehicle type by implementing restrictions or dedicated lanes. Also, the vehicle type to be segregated is pre-defined in most of the cases without a systematic approach for identifying the combination of vehicle classes for segregation and how it could be beneficial in enhancing factors like efficiency and safety. Towards this, network-level multi-class segregation models are proposed in this paper for the segregation of a combination of vehicle types in mixed traffic. Two formulations are proposed for the multi-class segregation problem considering two types of objective functions. The first objective is to minimise the total system travel time in the network to improve the efficiency and the second objective considered is minimising the crash risk in the network to enhance safety through the segregation of vehicle types. Considering the highly mixed nature of Indian traffic, it may not always be possible to segregate each vehicle type and provide separate routes for each origin-destination pair. Therefore, the goal is to identify the vehicle type to be segregated from remaining traffic or a combination of vehicle types on a link or path of the network that reduces the travel time or crash risk. Also, a heuristic solution is proposed for vehicle segregation in mixed traffic networks that gives a good trade-off solution with respect to efficiency and safety.

In a conventional system, optimal traffic assignment means that the vehicles are routed together without differentiating based on the vehicle type and the total flow is considered in PCU/ hour. In this study, for multi-class vehicle segregation in mixed traffic, each vehicle type is routed separately with independent Origin-Destination (OD) demand for each vehicle type and the flow of each vehicle type is considered in vehicles/ hour. The research questions addressed in this paper are:

1) Can multi-class vehicle segregation be a viable solution to the adverse effect of increased delay and safety concerns in mixed traffic network?
2) Can a solution to multi-class vehicle segregation problem provide a trade-off solution with respect to safety and efficiency?
3) Can a multi-class segregation model identify the combination of vehicle types on a link to improve efficiency and safety?
4) Are link cost and link capacity functions considered in the traffic assignment model suitable for mixed traffic networks?

II. FORMULATIONS

The multi-class vehicle segregation proposed in this paper refers to the segregation of mixed traffic to identify the combinations of vehicle types on the links in a network that will minimise the travel time or crash risk. In this regard, the mathematical optimisation problem is formulated such that each link in the network will have one vehicle type or a combination of vehicle types.

The context of the study is a road network represented as a graph with multiple origins and destinations. Each OD pair is connected by more than one route. Three vehicle types are considered for the problem to represent mixed traffic: two-wheelers (2W), four-wheelers (4W), and heavy vehicles (HV). The OD travel demand for each vehicle type is known a priori and remains static during the analysis. Formulations are proposed for multi-class vehicle segregation to identify the optimal combination of vehicle types on the links; one for efficiency and another for safety. The two formulations proposed for multi-class vehicle segregation are presented in the next two subsections.

The first model addresses efficiency and the second addresses safety in a mixed traffic network. Travel time on a link is the considered measure of efficiency in the formulation. Path-based mathematical formulations are developed to minimise total system travel time and total crash risk in the network. Significant formulation constraints include the node balance constraints for each vehicle type and the capacity constraint for each link. Finally, the decision variables in the formulations are the flow of each vehicle type k on the link (i, j), x_{ij}^k.

A. TRAVEL TIME-BASED VEHICLE SEGREGATION

The first multi-class segregation is formulated considering travel time as a measure of efficiency. A path-based optimisation formulation is developed to minimise the total system travel time with node balance constraints for each vehicle type and the link capacity constraint bounding the total flow on each link. This segregation problem cannot be addressed without a link cost function suitable for mixed traffic flow. Similarly, a constant link capacity function that is generally considered in traffic assignment problems cannot represent the mixed traffic flow efficiently.

Therefore, a new link cost function and varible link capacity suitable for accurate traffic assignment in mixed traffic is required in the formulation [23]. Let C_{ij} be the travel time on the link (i, j) which is derived from the novel link cost function as a function of traffic composition and signal settings as shown in **Equation 1**. This cost function is used to capture the features of mixed traffic and signal control settings and incorporate them in the formulation.

$$C_{ij} = \frac{L_{ij}}{u_{ij}} + \frac{r_{ij}^2}{2c_j\left(1 - \frac{x_{ij}}{Q_{ij}}\right)} \tag{1}$$

Here, for link (i,j), L_{ij} is the link length, u_{ij} the free flow speed, r_{ij} is the red duration, c_j is the cycle time for node j, x_{ij} gives the flow, and Q_{ij} is the saturation flow. It is shown to perform well under mixed traffic conditions using composite fundamental diagram parameters. The composite fundamental diagram parameters can be estimated using models from the literature. Due to the simplicity of the models, the parameters are estimated using the Logghe and Immers model [24] which proposed the concept of composite parameters to account for the vehicle type composition. The study used two vehicle types a and b described by separate fundamental k-q diagrams. The scalar factor γ is defined to explain the relationship between the two fundamental diagrams. According to the model, the equations for composite wave speed (ω_{ij}) and saturation flow (Q_{ij}) for a link (i,j) can be written as shown in **Equations 2** and **3** respectively.

$$\omega_{ij} = \frac{\mathrm{uf}_{ij}^b \times \mathrm{kM}_{ij}}{\mathrm{kM}_{ij} - \mathrm{kJ}_{ij}} \tag{2}$$

$$Q_{ij} = \omega_{ij}(\mathrm{kJ}_{ij} - \mathrm{kM}_{ij}) \tag{3}$$

Here, uf_{ij}^b is the free flow speed of vehicle type b and kJ_{ij} and kM_{ij} are the composite jam density and composite critical density respectively on the link (i,j).

To introduce vehicle composition in these equations for the composite fundamental diagram parameters, it is assumed that in congestion, all vehicle types travel at the same speed. Hence, $d_{ij}^k/(\sum d_{ij}^k) = x_{ij}^k/(\sum x_{ij}^k)$, where d_{ij}^k and x_{ij}^k are the density and flow of vehicle type k in link (i,j). Therefore, considering two vehicle types a and b, the equations for composite jam density (kJ_{ij}) and composite critical density (kM_{ij}) can be written as shown in **Equations 4** and **5** respectively.

$$\mathrm{kJ}_{ij} = \frac{x_{ij}^a + x_{ij}^b}{\frac{x_{ij}^a}{\mathrm{kJ}_{ij}^a} + \frac{x_{ij}^b}{\mathrm{kJ}_{ij}^b}} \tag{4}$$

$$\mathrm{kM}_{ij} = \frac{\gamma \times \mathrm{kM}^b(x_{ij}^a + x_{ij}^b)}{x_{ij}^a + \gamma x_{ij}^b} \tag{5}$$

Here, x_{ij}^a and x_{ij}^b are the flows and kJ_{ij}^a and kJ_{ij}^b are the jam densities of vehicle types a and b respectively on link (i,j). kM^b is the critical density of vehicle type b.

Now considering K number of vehicle types present on link (i,j), using **Equations 2 to 5**, the travel time function for the link is derived as given in **Equation 6**.

$$C_{ij} = \frac{L_{ij}}{u_{ij}} + \frac{r_{ij}^2 m_{ij}}{2c_j\left(m_{ij} - \sum_k \frac{x_{ij}^k}{Q^k}\right)} \tag{6}$$

where, for a link (i, j), C_{ij} is the total travel time, L_{ij} is the link length, u_{ij} is the speed of the traffic stream, c_j is the cycle time, r_{ij} is the red duration, m_{ij} is the number of lanes, x_{ij}^k is the flow of vehicle type k, and Q^k is the saturation flow of vehicle type k per lane.

Similarly, the link capacity function (in **Equation 7**) as developed in the recent study is used to define the capacity constraint.

$$B_{ij} = \frac{L_{ij}\omega_{ij}\mathrm{kJ}_{ij}u_{ij}}{ru_{ij}\omega_{ij} + L_{ij}\left(u_{ij} + \omega_{ij}\right)} \tag{7}$$

Here, ω_{ij} is the wave speed, and kJ_{ij} is the jam density. The constraint is given as total flow to be less than or equal to the link capacity. Assuming a triangular fundamental diagram, with kJ^k as the jam density of the vehicle type k, the constraint $x_{ij} \leqslant B_{ij}$ will be written as shown in **Equation 8**.

$$r_{ij}\sum_k \frac{x_{ij}^k}{\mathrm{kJ}^k} + L_{ij}\sum_k \frac{x_{ij}^k}{Q^k} \leqslant L_{ij} \times m_{ij}. \tag{8}$$

The composite fundamental diagram parameters are employed in the link cost and capacity functions of the proposed multi-class models to account for the vehicle class composition. The parameters are used in the travel time-based vehicle segregation model and the crash risk-based vehicle segregation model.

The formulation for travel time-based vehicle segregation is given as,

$$Min\ \ Z_t = \sum_{(i,j)}\left(C_{ij}\sum_{(k)} x_{ij}^k\right) \tag{9}$$

$$\text{subject to} \quad \sum_p f_{od}^p = b_{od}^k \quad \forall k, od\ \ pairs \tag{10}$$

$$x_{ij}^k = \sum_o \sum_d \sum_p \delta_{od,p}^{ij} f_{od}^{p,k} \quad \forall od\ \ pairs \tag{11}$$

$$C_{ij} = \frac{L_{ij}}{u_{ij}} + \frac{r_{ij}^2 m_{ij}}{2c_j\left(m_{ij} - \sum_k \frac{x_{ij}^k}{Q^k}\right)} \quad (12)$$

$$r_{ij}\sum_k \frac{x_{ij}^k}{\mathrm{kJ}^k} + L_{ij}\sum_k \frac{x_{ij}^k}{Q^k} \leqslant L_{ij} \times m_{ij} \quad \forall(i,j) \quad (13)$$

$$x_{ij}^k \geq 0 \quad \forall(i,j) \quad (14)$$

$$f_{od}^p \geq 0 \quad \forall(o,d) \quad (15)$$

$$\delta_{od,p}^{ij} = \begin{cases} 1, (i,j) & \epsilon p \\ 0, & o/w \end{cases} \quad \forall(i,j). \quad (16)$$

Z_t in **Equation 9** gives the objective function to minimise the total system travel time with the decision variable, x_{ij}^k. The sum of the flow of each vehicle type on the link (i, j) is multiplied by the link travel time c_{ij} to obtain the cost of each link. **Equations 10 and 11** provide the flow balance constraint for each vehicle type and the expression linking the link flow and the path flow, respectively. Here, b_{od}^k is the demand of vehicle type k between the OD pair (o, d) and f_{od}^p is the flow on path p between the OD pair (o, d). For considering possible paths for each OD pair, n shortest paths are generated for each OD pair employing Yen's algorithm [25]. **Equations 12 and 13** give the expressions for link travel time and link capacity constraint. The capacity constraint in the formulation ensures that there is no spill-back from the links during the red time. Finally, **Equations 14 and 15** represent the non-negativity constraints for the decision variables, and Equation 16 defines the input binary variable $\delta_{od,p}^{ij} = 1$ if the link (i,j) belongs to path p and zero otherwise.

B. CRASH RISK-BASED VEHICLE SEGREGATION

The second multi-class segregation is formulated considering crash risk as a measure of safety. A path-based optimisation formulation is developed to minimise the total crash risk of the network with node balance constraints for each vehicle type and the link capacity constraint bounding the total flow on each link. The variable link capacity constraint is employed in the formulation as explained in the previous section. The total crash risk of the network can be formulated using an accident prediction model.

According to existing Accident prediction models (APM), the crash risk on a link (or a node) in the network is estimated by normalising the expected number of crashes, E_{ij} with the traffic flow, q_{ij} [26], as shown in **Equation 17**.

$$\mathrm{AR}_{ij} = \frac{E_{ij}}{q_{ij}} \quad (17)$$

Here, AR_{ij} is the crash risk, E_{ij} is the crash frequency on the link (i, j) and q_{ij} is measured (in Annual Average Daily Traffic, AADT) in vehicles per day.

APM for urban road links was studied by [27] to establish a simple and practical model that involved two types of vehicles, i.e., cars and two-wheelers. The model is given as shown in **Equation 18**.

$$E_{ij} = \alpha_1 \left(q_{ij}^1\right)^{\beta_1} \left(q_{ij}^2\right)^{\beta_2}. \quad (18)$$

Here, $\alpha_1 = 4.44 \times 10^{-5}$, q_{ij}^1 and q_{ij}^2 represent the flow of cars and two-wheelers respectively, and $\beta_1 = 0.68$ and $\beta_2 = 0.49$. This model is used in this study to estimate the crash risk on links of the network. Since none of the studies have considered more than two vehicle types, the model is extended for three vehicle types assuming a coefficient value from literature, which reported that heavy vehicles have a relatively smaller coefficient compared to cars [28]. Therefore, a smaller coefficient is assumed for heavy vehicles, but a sensitivity analysis was conducted to evaluate the impact of variability in the coefficient values.

Therefore, the crash risk-based vehicle segregation model is based on the existing accident prediction model which includes another set of parameters, viz., flow on the link, coefficient α_1 and the exponents β_1 and β_2. Note that the coefficient α_1 and the exponents β_1 and β_2 depend on the vehicle types present on the link.

The formulation for crash risk-based vehicle segregation is given as

$$Min \ Z_a = \alpha_1 \sum_{(i,j)} \mathrm{AR}_{ij} \quad (19)$$

$$\text{subject to} \quad \sum_p f_{od}^p = b_{od}^k \quad \forall k, od \ \ pairs \quad (20)$$

$$x_{ij}^k = \sum_o \sum_d \sum_p \delta_{od,p}^{ij} \times f_{od}^{p,k} \quad \forall od \ \ pairs \quad (21)$$

$$\mathrm{AR}_{ij} = \prod_k \left(x_{ij}^k\right)^{\beta_k} \quad \forall(i,j) \quad (22)$$

$$r_{ij}\sum_k \frac{x_{ij}^k}{\mathrm{kJ}^k} + L_{ij}\sum_k \frac{x_{ij}^k}{Q^k} \leqslant L_{ij} \times m_{ij} \quad \forall(i,j) \quad (23)$$

$$x_{ij}^k \geq 0 \quad \forall(i,j) \quad (24)$$

$$f_{od}^p \geq 0 \quad \forall(o,d) \quad (25)$$

$$\delta_{od,p}^{ij} = \begin{cases} 1, (i,j) & \epsilon p \\ 0, & o/w \end{cases} \quad \forall(i,j). \quad (26)$$

Z_a in **Equation 19** gives the objective function to minimise the total crash risk of the network where α is taken as 4.44×10^{-5}. The AR_{ij} in **Equation 22** gives the crash risk on the link (i,j) where β_k is the power related to the flow of vehicle type k. All other constraints defined are the same as explained in the previous formulation.

The two proposed formulations used data from a transportation network with traffic demand between the OD pairs, cycle time and the red time of traffic signals and traffic flow parameters at signalised intersections. Note that there are no privacy concerns with this data since individual-level data is not collected.

III. CASE STUDY

This section presents a case study to evaluate the vehicle segregation formulation for travel time and crash risk minimisation.

A. STUDY AREA

The Surat-West zone, the largest among the seven administrative zones of Surat city in the Gujarat state of India, was considered for the case study (see **Figure 1**). A sub-network of this administrative zone is used in the case study. The data set developed and provided by Urban Road Networks [29] is used to define the transportation network parameters for the study area. The data consisted of a graph edge list for the city and the length and number of lanes for each link.

FIGURE 1. Study area: Surat-West zone, Gujarat, india.

The study network consists of 82 nodes (considering major intersections in the study area) and 252 links, as shown in **Figure 2**. The origins and destinations identified in the network are shown in this figure.

According to the traffic composition data, Surat city is comprised of 75% two-wheelers, 20% four-wheelers, and 5% heavy vehicles. The demand estimated for the three vehicle types for twelve OD pairs considered is given in **Table 1**.

TABLE 1. OD demand for three vehicle types in Surat-West zone.

Sl No.	OD Pair	Demand (vehicles/hour) 2W	4W	HV
1	(4,82)	300	80	20
2	(67,75)	660	176	44
3	(52,2)	915	244	61
4	(52,19)	1125	300	75
5	(52,82)	210	56	14
6	(32,49)	465	124	31
7	(32,2)	285	76	19
8	(55,79)	1500	400	100
9	(20,79)	660	176	44
10	(20,75)	90	24	24
11	(19,49)	285	76	19
12	(19,79)	90	24	6

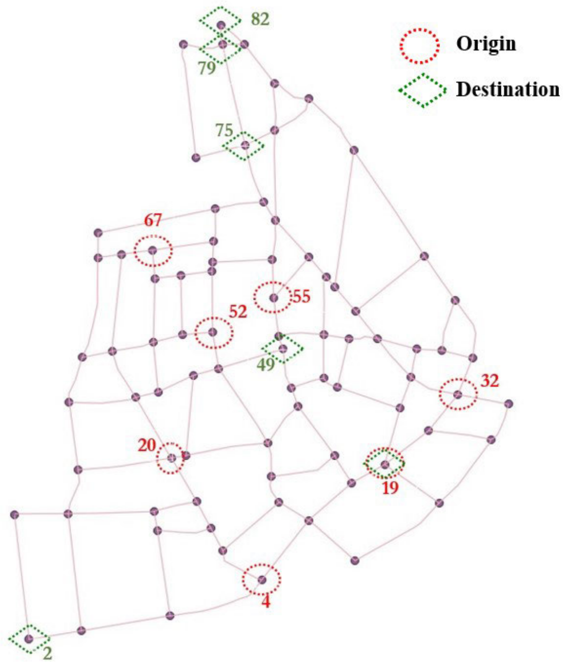


FIGURE 2. Surat-West zone transportation network with 82 nodes and 252 links.

The traffic conditions observed in the network were moderate with some links having higher degrees of saturation level.

Another input for the link cost function is the cycle time and the red time at signalised intersections in the network. A heuristic method is adopted to determine the two parameters based on the number of lanes on all approaches around the intersection [30].

Next, the jam density, saturation flow, and wave speed values required for the link cost and capacity functions are calculated from the vehicle dimensions values in the literature [31], [32] as given in **Table 2**.

TABLE 2. Vehicle type-specific fundamental diagram parameters.

Vehicle type	Jam Density (vehicles/ km)	Wave Speed (km/ hour)	Saturation Flow (vehicles/ hour)
Two-wheelers	420	13	4500
Four-wheelers	200	12	2000
Heavy vehicles	80	9	800

Using these inputs, the proposed formulations are solved to obtain the optimal paths for the three vehicle types in the network.

The non-linear problems are solved using the Branch-And-Reduce Optimisation Navigator (BARON) solver used for global optimisation of non-linear problems in GAMS optimisation software. To ensure the robustness of the solutions, different starting points were used to derive the solutions. The GAMS solver was iterated for 15 minutes and checked for no improvement before the solution was selected.

IV. RESULTS

A. CASE I: MINIMISING TOTAL SYSTEM TRAVEL TIME

The travel time on a link and the link capacity depends on geometric factors (link length and number of lanes), signal control (cycle length and red time at downstream intersection), and the traffic composition on the link. Therefore, a number of influencing factors make the analysis complex to derive insights.

The results from the multi-class segregation model for minimising the total system travel time are analysed to study the segregation characteristics and their effects. From the solution, the flow of two-wheelers, four-wheelers, and heavy vehicles on each link of the network are obtained separately. Similarly, also the paths for each vehicle type for each of the twelve OD pairs are obtained. Different combinations of vehicle types are observed in the network links. These include 1) only two-wheelers, 2) only four-wheelers, 3) only heavy vehicles, 4) two-wheelers and four-wheelers, 5) four-wheelers and heavy vehicles, and 6) a mix of three vehicle types. It is to be noted that the combination of two-wheelers and heavy vehicles is not observed on any of the links in the network. This may be because heavy vehicles have very low saturation flow compared to that of the two-wheelers, the combination of which may increase the delay.

The traffic composition on links with the increasing total flow is shown in **Figure 3**. From the composition on the links, it can be observed that there are few links with all three vehicle classes (based on the non-zero proportion for each vehicle class) and they have higher saturation levels. A closer examination of the position of these links revealed that most of these links are peripheral links directly connected to the origins or destinations. Within the interior of the network, all three vehicle combinations are rarely observed. It must also be noted that the links with a mix of all vehicle types were observed to maintain the same traffic composition as that of the network.

Heavy vehicles alone are observed on a significant number of links compared to links with only two-wheelers or four-wheelers. This means that the number of links used may be inversely proportional to a combination of fundamental diagram parameters. One can verify this also with a sensitivity analysis.

Links with two-wheelers and four-wheelers are observed to have higher saturation levels compared to links with a combination of four-wheelers and heavy vehicles. This may be because a large volume of four-wheelers and heavy vehicles if sent together, increases the travel time. On the other hand, links with all vehicle types are observed to have graded saturation levels since the peripheral links had variable geometry and signal settings. Furthermore, the four-wheelers are observed to be distributed across the largest number of links in the network.

According to the nature of the link cost function, the presence of heavy vehicles and four-wheelers on a link increases the travel time compared to that of two-wheelers when all other factors are constant, which is reflected in the traffic assignment.

Additionally, the average travel time per vehicle on all the paths for each OD pair is also analysed for each vehicle type (see **Figure 4**). It is observed that in the case of OD pair with flow assigned on more than one path, all paths have similar travel times. Also, heavy vehicles are routed on paths with the highest travel time and two-wheelers on the shortest paths.

The corresponding distribution of crash risk on the links for this solution is shown in **Figure 5**. The crash risk is found to be increasing with traffic volume and high risk is observed on links with a mix of all vehicle types. By analysing the flow of each vehicle type on all the links, it is observed that the total flow and the composition of a link influence the range of crash risk observed on the link. Though the range of crash risk is higher for links with higher flow, significant variation can be observed in the crash risk among the last links. This is the influence of the traffic composition on the links. For example, link 91 has a lower crash risk, as there are only two vehicle types present (two-wheelers and four-wheelers), compared to links 89 and 90 which have a combination of all vehicle types. Also, it is found that there are several links with significant crash risk with the travel time minimisation objective.

B. CASE II: MINIMISING CRASH RISK

A similar analysis is carried out to minimise total network crash risk. The coefficients considered in this case study are 0.49, 0.68, and 0.2 for two-wheelers, four-wheelers, and heavy vehicles, respectively. The coefficients for two-wheelers and four-wheelers are adopted from the model developed by [27], and the model is extended for three vehicle types assuming a parameter value of 0.2 for heavy vehicles. From the solution, the traffic composition, total flow, crash risk, and saturation level (q/s ratio) for each link are analysed. Unlike Case I, where the combination of two-wheelers and heavy vehicles is not observed on any of the links, all possible combinations of vehicle types are observed in the network, with the crash risk minimisation objective.

The traffic composition on links with the increasing total flow is shown in **Figure 6**. Similar to Case I, the highest flow is observed on links with mixed traffic. The traffic flow is observed to be spread over even more links as compared to Case I, i.e., a lesser number of links are observed to have mixed traffic and more links are observed to have one or a mix of two vehicle types.

The crash risk on links with the increasing total flow is shown in **Figure 7**. The crash risk is observed to increase with the total flow. Links with mixed traffic of all vehicle types are observed to have a very high crash risk compared to other links. It is observed that most of the links had very small crash risk, and only a handful of the links had significant risk. A closer look at the abrupt spikes revealed that even at relatively lower total flows, high values of crash risk are observed when the links have a mix of all vehicle types. This is consistently observed across multiple links indicating that multiple vehicle types on a link significantly increased the

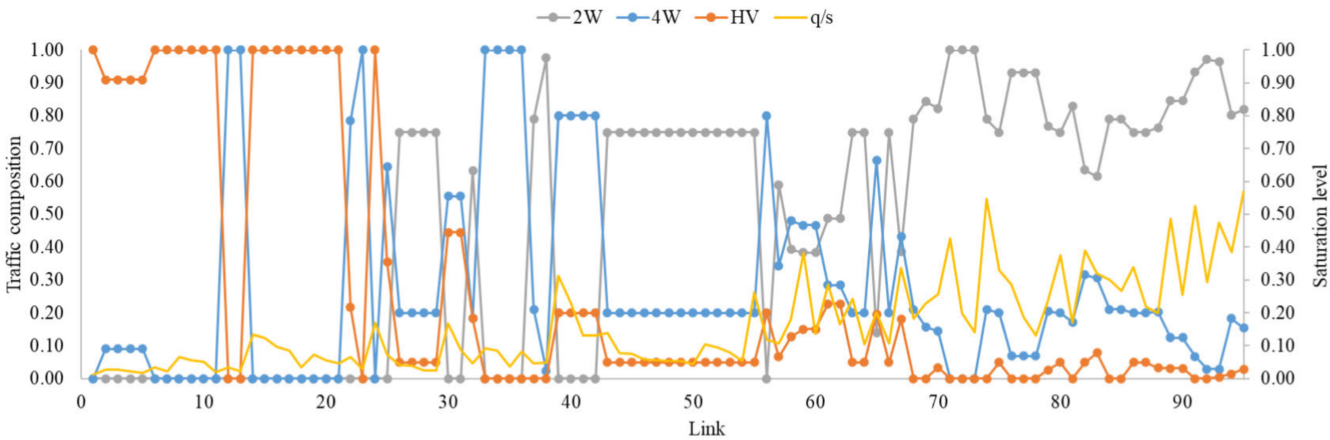


FIGURE 3. Case I: Traffic composition and saturation level on links with an increasing total flow.

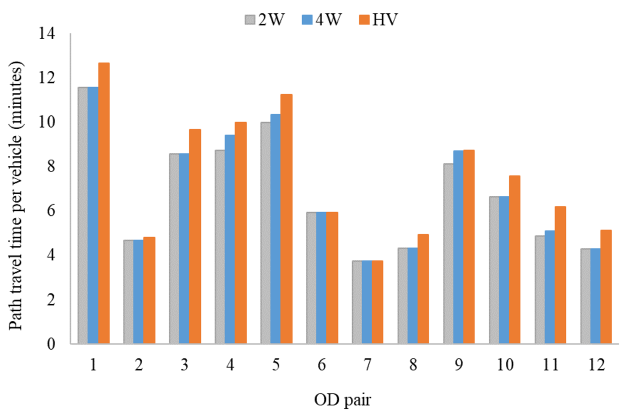


FIGURE 4. Case I: Travel time per vehicle on paths of 12 OD pairs for each vehicle type.

crash risk compared to that with only one or two vehicle types. This is primarily due to the nature of the crash risk function that uses the product of the flows of the available vehicle types for computing the crash risk.

Similar to Case I, crash risk on all the paths between each OD pair is also analysed for each vehicle type (see **Figure 8**). For most of the OD pairs, only one path is observed to be used for traffic assignment, but the path used for each vehicle type is different, unlike in Case I. Here, the saturation level on the links is observed to be higher than that in case I. This may be because, according to the nature of the expression for crash risk, high flows will not drastically increase the crash risk, unless the most contributing vehicle type is the 4W (highest parameter value). Therefore, links can have higher flows compared to Case I where high flows may increase the travel time on the links.

V. COMPARISON WITH CONVENTIONAL TRAFFIC ASSIGNMENT USING BPR COST FUNCTION

The proposed travel time-based and crash risk-based vehicle segregation problems are compared with the conventional traffic assignment method. In traffic assignment problems, the most commonly used link cost function is the Bureau of Public Roads (BPR) function, shown in Equation 27.

$$t = t_0 \left(1 + \alpha \left(\frac{x}{C}\right)^{\beta}\right) \tag{27}$$

Here, t, t_0, x, and C are the travel time, free-flow travel time, flow, and link capacity, respectively, and α and β are constant coefficients. Generally, 0.15 and 4 are used for α and β, respectively [33]. This function does not consider the traffic composition and therefore does not include the fundamental diagram parameters. This is one of the well-documented limitations related to the traditional BPR function making it unsuitable for mixed traffic conditions and therefore is not employed in the proposed vehicle segregation models in this paper.

The formulation for conventional traffic assignment is given as,

$$Min\ \ Z_t = \sum_{(i,j)} \left(C_{ij} \sum_{(k)} x_{ij}^k \right) \tag{28}$$

$$\text{subject to} \quad \sum_{p} f_{od}^p = b_{od}^k \quad \forall k, od\ \ pairs \tag{29}$$

$$x_{ij}^k = \sum_o \sum_d \sum_p \delta_{od,p}^{ij} \times f_{od}^{p,k} \quad \forall od\ \ pairs \tag{30}$$

$$C_{ij} = \frac{L_{ij}}{u_{ij}} + \left(1 + \alpha \left(\frac{\sum_{(k)} \left(x_{ij}^k p^k\right)}{m_{ij} \times U_{ij}}\right)^{\beta}\right) \tag{31}$$

$$x_{ij}^k \geq 0 \quad \forall (i,j) \tag{32}$$

$$f_{od}^p \geq 0 \quad \forall (o,d) \tag{33}$$

$$\delta_{od,p}^{ij} = \begin{cases} 1, (i,j) & \epsilon p \\ 0, & o/w \end{cases} \qquad \forall (i,j). \tag{34}$$

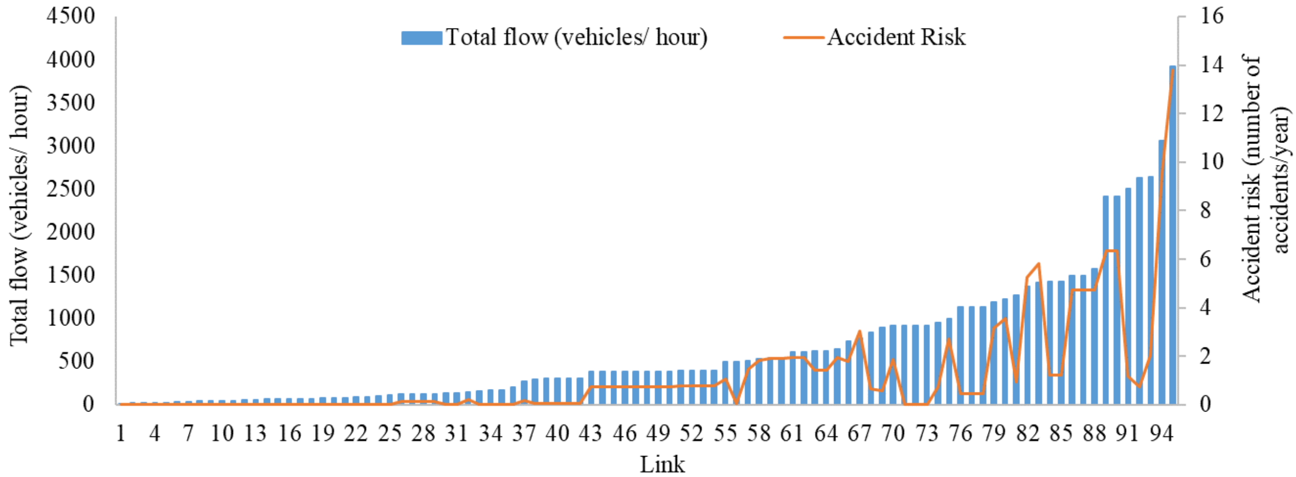


FIGURE 5. Case I: Crash risk on links with an increasing total flow.

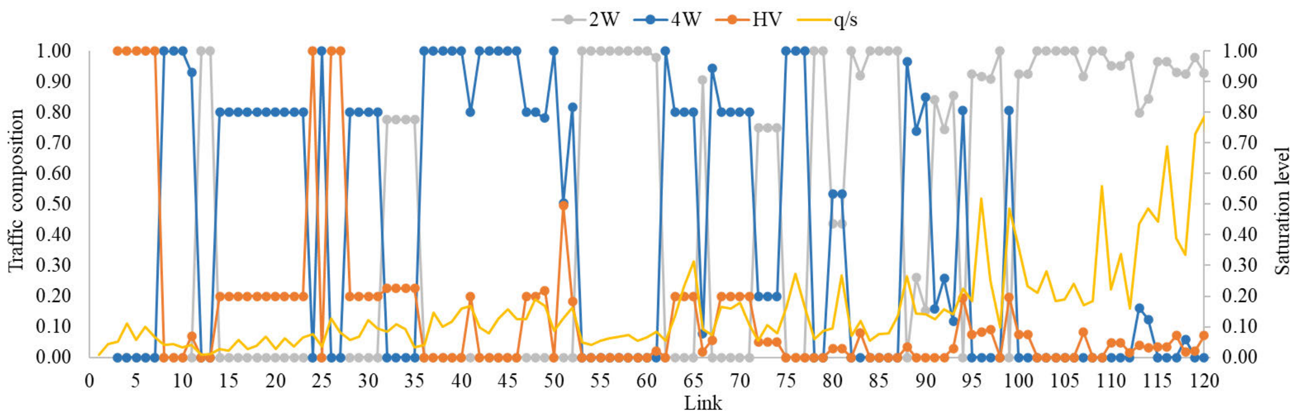


FIGURE 6. Case II: Traffic composition and saturation level on links with an increasing total flow.

Equation 31 gives the expressions for the BPR link cost function. Since the BPR function inherently considers the link capacity, no separate capacity function is used. Here p^k is the PCU value taken for vehicle type k. m_{ij} and U_{ij} is the capacity on the link (i, j), where m_{ij} is the number of links and U_{ij} is the capacity per lane. All other constraints defined are the same as explained in the previous formulation. The formulation is also solved using the BARON solver on GAMS. A solution set of link flows for each vehicle type is obtained and the corresponding total system travel time is calculated using the new link cost function employed in Case I (**Equations 6**). The total network crash risk is also calculated using the objective function in Case II (**Equations 19**).

It is found that the total system travel time is higher than that of Case I and the total network crash risk is higher than that of Case II solutions respectively (see **Table 3**). The travel time of Case II (1106 vehicle hours) is found to be higher compared to the travel time using the BPR function (1003 vehicle hours) because the former minimises the total crash risk and does not consider the travel time impacts in the network. However, this pattern may change at other locations.

TABLE 3. Comparison of objective function values of the conventional traffic assignment solution against Case I and Case II.

Objective function	Case I	Using BPR function	Case II
Travel time (vehicle hours)	912	1003	1106
Crash risk (number of crashes)	121	196	31

Therefore, from the comparison, it is clear that the proposed multi-class segregation yields a better solution compared to the conventional traffic assignment model.

VI. SENSITIVITY ANALYSIS

To validate the results obtained, sensitivity analysis is carried out for each case explained in the previous section

A. CASE I ANALYSIS

1) CHANGE IN TRAFFIC COMPOSITION

The traffic composition is changed from 75%, 20%, and 5% to 50%, 45%, and 5%, respectively for two-wheelers, four-wheelers, and heavy vehicles. This latter composition is considered since such compositions are found in other

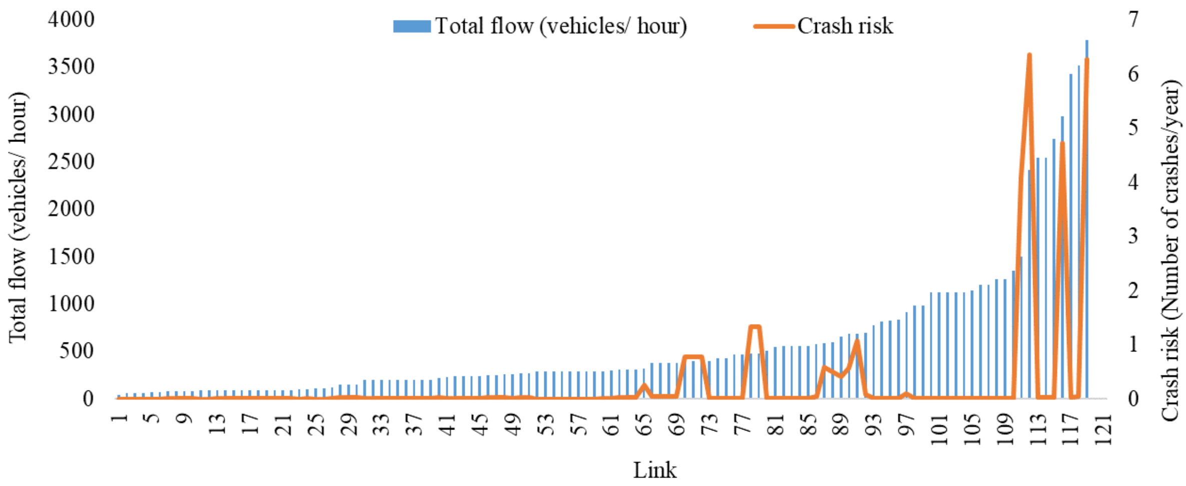


FIGURE 7. Case II: Crash risk on links with increasing total flow.

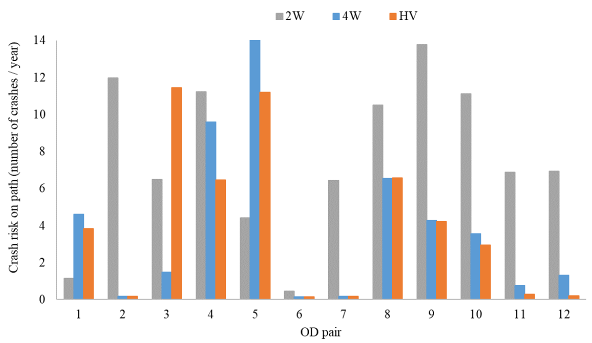


FIGURE 8. Case II: Crash risk on paths of 12 OD pairs for each vehicle type.

cities like Chennai, India. It is observed that the total system travel time increased to 936 vehicle-hours as the four-wheeler proportion increased, and the two-wheeler proportion decreased. All the observations made in Case I are observed to be true for the sensitivity analysis based on traffic composition. The highest flow values are observed on links with all vehicle types and no link is observed to have an exclusive combination of only two-wheelers and heavy vehicles (see **Figure 9**).

In the case of travel time values for different paths of each vehicle type, paths of the same OD pair are observed to have similar travel time values, and two-wheelers are observed to be routed on the shortest path and heavy vehicles on the longest path with respect to the travel time (see **Figure 10**).

2) CHANGE IN TRAFFIC FLOW

For the sensitivity analysis with respect to traffic flow, the OD demand for each vehicle type is changed by ±20%, ±40%, ±60%, and +/−80% in eight different cases, and a solution set is obtained for each of the cases. The total system travel time increased as total flow increased, and all the trends observed in Case I were also found to be true here. The sample plot of traffic composition on links with increasing total traffic flow for the case of traffic flow increased by 20% is shown in **Figure 11**. Similar trends are observed for this and all other cases also, similar to that in Case I.

Similar to Case I, the two-wheelers are observed to be routed on the shortest paths and heavy vehicles on the longest paths in terms of travel time (see **Figure 12**). With the increasing flow, vehicles are distributed on more links in the network with an increase in the saturation levels on the links. The number of links with a mix of all vehicle types remained almost the same with the increasing flow, but the number of links with two-wheelers or heavy vehicles only increased with increasing flow.

Therefore, from the evaluation of the results obtained, the following observations are made.

1) All the observations are found to be valid in moderate to high traffic flow conditions.
2) Different combinations of vehicles or segregating a vehicle is beneficial in terms of decreasing travel time or delay in a network.
3) A combination of only two-wheelers and heavy vehicles is never observed in the network in any of the cases studied.
4) Two-wheelers are found to be routed on paths with minimum travel time and heavy vehicles on paths with maximum travel time.

B. CASE II ANALYSIS

To evaluate the sensitivity of the parameters, the coefficient of trucks is changed from 0.2 to two cases of 0.3 and 0.4. Analyses show that all the trends observed in Case II are valid and also observed in the sensitivity analysis. All combinations of vehicle types are observed in the network. Sample traffic composition on links for the case when the coefficient of heavy vehicles is 0.3 is shown in **Figure 13** below. Less

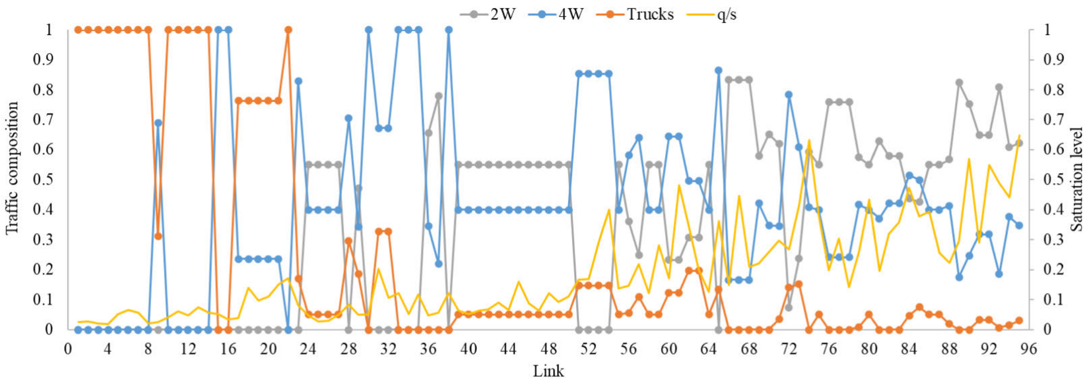


FIGURE 9. Sensitivity analysis for Case I: Traffic composition and saturation level on links with increasing total flow.

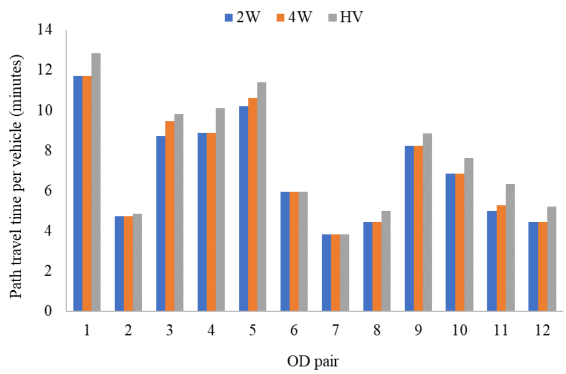


FIGURE 10. Sensitivity analysis (Change in traffic composition) for Case I: Travel time per vehicle on paths of 12 OD pairs for each vehicle type.

number of links are observed to have all vehicle types. This indicates that as the parameter value of the trucks increases, the vehicles are spread even more in the network. This is also evident from the higher number of links utilised for 0.3, compared to 0.2.

Similar to Case II, the crash risk is observed to increase with traffic flow and high on links with mixed traffic. The sample plot showing crash risk on links with increasing traffic flow is shown in **Figure 14**. The magnitude of crash risk increased significantly. Therefore, coefficient values are important to accurately quantify the crash risk. However, the patterns in terms of vehicle segregation are even with different coefficient values.

Also, in case of paths assigned for each vehicle type, although in total, a lesser number of paths were utilised, it is rare that two vehicle types share the same path of an OD pair. With a coefficient value relatively higher for heavy vehicles, the trends observed still hold true with a higher range of crash risk and other values.

Therefore, from the evaluation results for the case of minimising crash risk, the following observations were made.

1) A mix of traffic on a link increases the crash risk and therefore, segregation can help in reducing the crash risk.
2) A link with only one vehicle type or two vehicle types has very low crash risk compared to links with all three vehicle types.
3) As very few links are observed with mixed traffic, a lane segregation strategy could be adopted for only these links to reduce the crash risk.
4) The effect of coefficients on the crash risk is relative. The crash risk depends on whether the coefficient for one vehicle type is less or more than that of another vehicle type, rather than the exact value.

VII. HEURISTIC SOLUTION

The two vehicle segregation formulations developed lead to solutions improving safety and efficiency individually. The evaluation of the results obtained provide insight on how different vehicle types and combination of certain vehicle types travel time and safety in a mixed traffic network. Therefore, according to the results observed, a simple and efficient heuristic solution is proposed for the multi-class vehicle segregation problem to obtain a trade-off solution with respect to efficiency and safety.

From Case I solutions, it is observed that to minimise the travel time, the two-wheelers are to be routed on the shortest path in terms of travel time, followed by four-wheelers on the next longest path and heavy vehicles on the longest path. To minimise the crash risk, the traffic flow is to be distributed over the network with a different route for each vehicle type. In this regard, a heuristic solution is proposed such that the segregation of traffic with respect to vehicle type can enhance efficiency and safety. The pseudo code for the heuristic solution is shown in **Figure 15**.

Consider the k-shortest paths for each OD pair in the network and separate OD demands for three vehicle types. The first part of the heuristic solution adopts the assignment of the three vehicle types on the first three shortest paths. In step I, the first-shortest path is assigned for all OD pairs for two-wheelers. With the flows assigned on the links, check the q/s ratio of all the links. In step II, for all OD pairs, the second-shortest path is assigned for four-wheelers such that the q/s ratio is less than 1. And finally, assign heavy

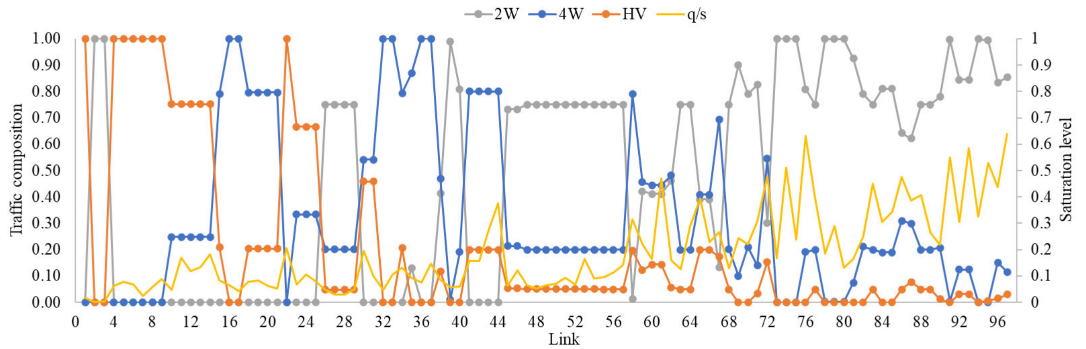


FIGURE 11. Sensitivity analysis for Case I: Traffic composition and saturation level on links with increasing total flow.

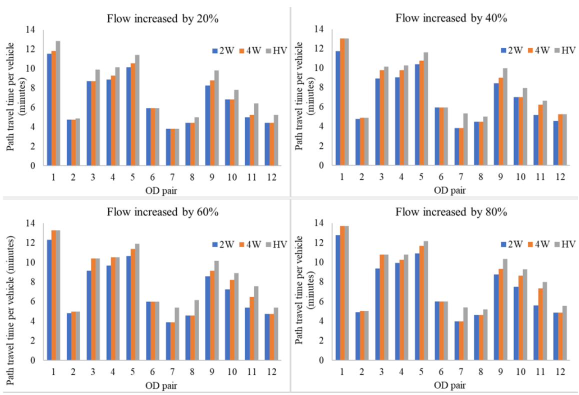


FIGURE 12. Sensitivity analysis (Change in traffic flow) for Case I: Travel time per vehicle on paths of 12 OD pairs for each vehicle type.

vehicles to the third-shortest path. After each step, the q/s ratio on all the links is checked and made sure it is less than 1. In case the q/s is greater than 1, assign α% of the flow on the present shortest link considered and (1-α)% of the flow on the next shortest path. Here, α is the threshold for the saturation level on the links. Next, determine the two objective function values for the heuristic solution. Check if the solution obtained is a trade-off solution with respect to the travel time and crash risk. In case the solution does not assure a good trade-off, additional steps are adopted. If the total network crash risk (or total system travel time) is greater than the corresponding objective function of Case I (or Case II), the second part of the heuristic is adopted, and one of the vehicle types is re-routed. In the case of crash risk, the link crash risk is higher on links with a mix of all vehicle types and particularly on links with a high flow of four-wheelers, as the coefficient in APM is highest for four-wheelers (0.68). Therefore, four-wheelers are re-routed if the crash risk is high. Similarly, travel time increases with an increase in the flow of heavy vehicles due to their lower speed. In this sense, the heavy vehicles are re-routed to decrease the travel time.

So in the second part, if the total network crash risk (or total system travel time) is greater than the corresponding objective function of Case II (or Case I), identify the critical link with the highest flow of four-wheelers (or heavy vehicles). Make the flow of four-wheelers (or heavy vehicles) on critical link = 0 and reroute the corresponding flow to the next shortest path between the origin node and the destination node of the critical link. In case an alternative path is unavailable from the origin node to the destination node of the critical link, identify the nearby node that has the highest outflow of four-wheelers (or heavy vehicles) and find the shortest path between the new node and the destination of the critical link for re-routing of vehicles. Save the shortest path in a set S. Again, perform a check on the objective function values. In case the trade-off solution is not obtained, repeat the step of re-routed considering the critical link with the next highest flow of four-wheelers (or heavy vehicles) such that the new path identified does not belong to set S. If an acceptable trade-off solution is obtained, and one wants to further decrease the objective function value, the re-routing can be continued by identifying the next critical link. However, decreasing one cost should not significantly increase the other cost, and the critical link identified should not be in the path used for re-routing. After each re-routing of vehicles, the links are checked for the q/s ratio and the next critical link is selected for re-routing if $q/s>1$.

Thus, the heuristic solution assigns the paths in the increasing order of travel time for two-wheelers, four-wheelers, and heavy vehicles, to reduce the total system travel time. Similarly, the three vehicle types are routed on different routes for all the OD pairs to reduce the total crash risk. However, note that in case there are common links for the shortest paths of two or more OD pairs, these links may have two or more vehicle combinations.

The proposed heuristic solution is compared with the solutions from the three cases of minimising total system travel time (Case I) and total network crash risk (Case II). It was observed that the total system travel time and the total network crash risk of the heuristic solution lie between the objective function values of case I and case II (see **Table 4**). This trend is also observed to be true with respect to each vehicle type.

The traffic composition and saturation level on links with increasing traffic flow are shown in **Figure 16**. All types of combinations of vehicle types are observed on the links

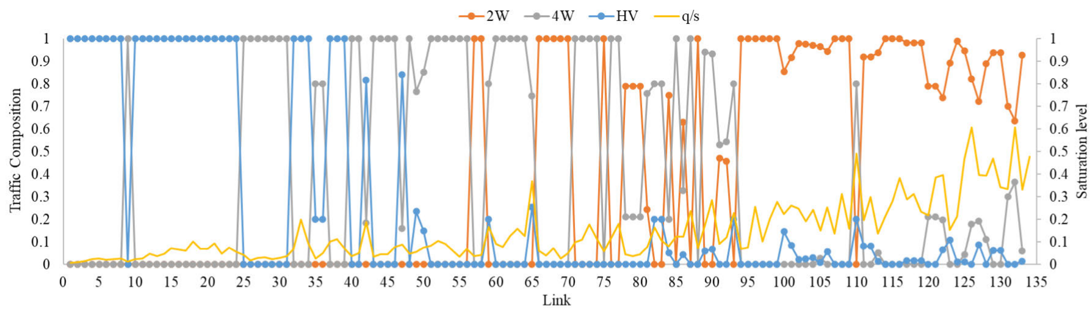


FIGURE 13. Sensitivity analysis for Case II: Traffic composition and saturation level on links with increasing total flow with the coefficient of HV = 0.3.

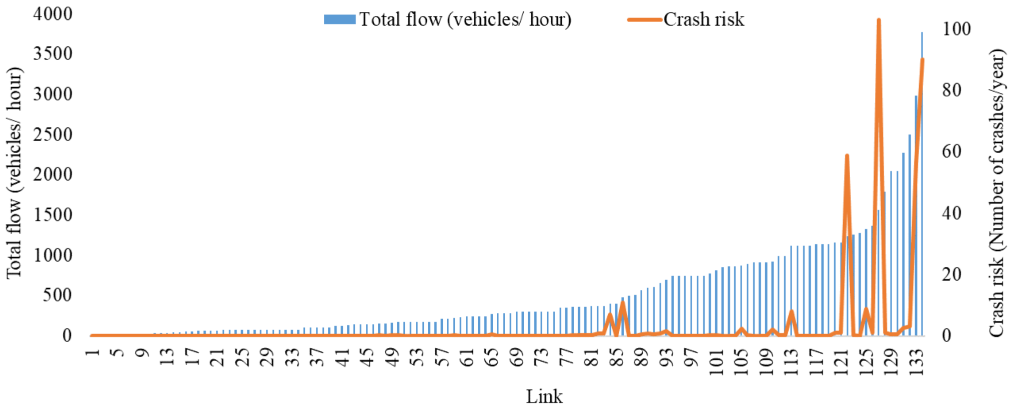


FIGURE 14. Sensitivity analysis for Case II: Crash risk on links with an increasing total flow with the coefficient of HV = 0.3.

TABLE 4. Comparison of objective function values of the heuristic solution against Case I and Case II.

Objective function	Flow	Case I	Heuristic	Case II
Travel time (vehicle hours)	2W	670	727	830
	4W	188	210	212
	HV	54	58	645
	Total	912	995	1687
Crash Risk (number of crashes per year)	2W	87	85	24
	4W	26	22	6
	HV	8	6	1
	Total	121	113	31

that are common for some OD pairs. The saturation level is observed to be high on links with mixed traffic. The maximum *q/s* ratio observed is 0.92, which is observed on a link with mixed traffic.

The comparison of link crash risk is shown in **Figure 17**. Crash risk on the links obtained from the heuristic solution is higher compared to the solution from Case II and lower from Case I.

Figure 18 shows a comparison of travel time and crash risk on paths for twelve OD pairs for Case I and Case II, and the heuristic solution. It is observed that in the majority of the cases, the heuristic solution gives a solution with a travel time or crash risk value that lies in between the values corresponding to Case I and Case II, respectively. The total crash risk is higher compared to Case II as there are more links with a mix of all vehicle types.

According to the comparison of the objective function values obtained, it is observed that a trade-off solution considering the two objectives of minimising the total system travel time and total network crash risk is obtained from the heuristic solution. For the multi-class vehicle segregation model, solving a bi-objective formulation considering the trade-off between efficiency and safety using the BARON solver is difficult since the objective functions are both non-linear and non-convex. The non-convexity of the functions was examined using the Hessian matrix approach. It was found that all the eigenvalues of the Hessian matrix were not strictly positive for the functions, demonstrating that the functions are non-convex. This makes the problem more complex and increases the computational time. Therefore, the simple and effective heuristic solution proves to be beneficial in providing a reasonably good trade-off solution.

A. SENSITIVITY ANALYSIS FOR THE HEURISTIC SOLUTION

The sensitivity analysis is performed to validate the heuristic solution with a 20% increase in the total flow. Initially, the three vehicle types are routed on the first three shortest paths according to the first part of the heuristic solution, and the objective function values are obtained. It is observed that the solution obtained is not acceptable. The total system travel

```
Heuristic Algorithm
INPUT: (1) OD demand for each vehicle type
       (2) Shortest path for each vehicle type
OUTPUT: Flow of each vehicle type on each link
ALGORITHM:
01: Assign 2W on shortest paths of all OD pairs
02: if q/s <1 for all links do {
        Assign 2W on second shortest paths of all OD pairs
        Go to step 03
    else
        Assign α% 2W on the present shortest path considered
        Assign (1-α) % 2W on the next shortest path
        Go to step 02
        }
03: if q/s <1 for all links do {
        Assign 4W on third shortest paths of all OD pairs
        Go to step 04
    else
        Assign α% 4W on the present shortest path considered
        Assign (1-α) % 4W on the next shortest path
        Go to step 03
        }
04: if q/s <1 for all links do {
        Go to step 05
    else
        Assign α% HV on the present shortest path considered
        Assign (1-α) % HV on the next shortest path
        Go to step 04
        }
05: if Za(Zt)of heuristic < Za (Zt) of case II (Case I) do {
        Acceptable trade-off solution
    else
        Identify link (i, j) with highest 4W (HV) flow
        Reroute flow to next shortest path between i and j
        Go to step 05
        }
END
```

FIGURE 15. Heuristic solution for multi-class vehicle segregation.

TABLE 5. Sensitivity analysis: Comparison of objective function values of heuristic solution with an increased flow against Case I and Case II.

Objective function	Flow	Case I	Heuristic	Case II
Travel time (vehicle hours)	2W	820	893	1054
	4W	236	267	255
	HV	67	69	75
	Total	1123	1229	1384
Crash Risk (number of crashes per year)	2W	95	97	32
	4W	34	23	8
	HV	8	6	3
	Total	137	126	43

time for the heuristic solution lies between the corresponding objective function values of Case I and Case II. However, the total network crash risk is more than the maximum value of the objective function. Therefore, the second part of the heuristic solution is followed for re-routing the four-wheelers.

It is observed that the heuristic solution is a good trade-off solution with respect to the travel time and crash risk (**Table 5**). But, the objective function value with respect to each vehicle type does not always assure a good trade-off. When the total flow in the network increases, there is a chance that some of the vehicle types are penalised with respect to the travel time or crash risk. The maximum *q/s* ratio observed on a link is 0.98. As the traffic flow increases, the saturation level on links increases, and more links are observed with high saturation levels. Also, the number of links with a mix of all vehicle types increased with an increase in flow. Note that, as flow increases, the flow on common links with respect to the OD pair will have high flow, and therefore the performance deteriorates. Also, it was found that minimising the maximum link crash risk is not a suitable strategy.

VIII. APPLICATION

The literature gives evidence of benefits attained from partial vehicle segregation strategies such as the restriction of single vehicle type, like trucks, in a network. This study results can help planners systematically adopt appropriate policies or guidelines to segregate the traffic based on the vehicle type to enhance safety and efficiency in a mixed traffic network. The proposed multi-class segregation can be implemented in mixed traffic networks by restricting certain vehicle types on certain links in the network. It should be understood that enforcement is the key to successful implementation. However, it is widely accepted that implementing traffic assignment solutions in a real-world network is challenging.

Fortunately, several researchers have studied related problems and proposed potential strategies to encourage (or influence) road users to adhere to proposed route recommendations. Some of the strategies used to increase compliance include toll pricing methods [34], monetary incentives [35], route guidance systems [35], [36], traffic advisory systems [37], vehicle routing policies [38], path guidance for electric vehicles [39], etc. Similar policies and guidelines could be adopted to implement and encourage compliance with the proposed multi-class vehicle segregation strategies.

IX. FINDINGS

Vehicle segregation with respect to the vehicle type can be carried out by either allowing only certain vehicle types or restricting a vehicle type on the road. The study presented the assignment of different vehicle types in a transportation network based on minimising the objectives of the total system travel time and total crash risk such that the vehicle types get segregated in a systematic manner. The results were analysed to study the vehicle segregation and corresponding different combinations of vehicle types for various objectives. The major findings from the study are:

1) For minimising the travel time in a network:
    a) Two-wheelers are to be routed on the shortest path, and heavy vehicles on the longest path in terms of travel time.

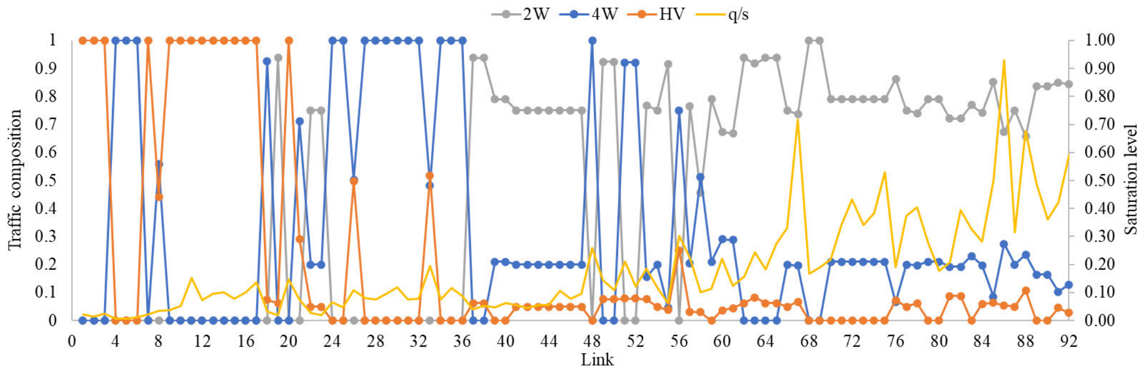


FIGURE 16. Heuristic solution: Traffic composition and saturation level on links with increasing flow.

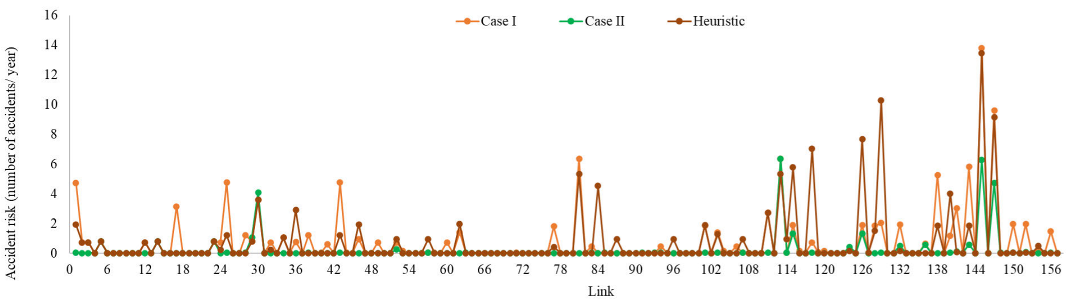


FIGURE 17. Comparison of link travel time for the heuristic solution against Case I and Case II.

   b) The presence of heavy vehicles on a link increases the travel time for all vehicles.
   c) The flow combination of two-wheelers and heavy vehicles is the least desirable due to the difference in saturation flow of the two vehicle types.
2) For minimising the crash risk in a network:
   a) The least number of links should have all vehicle types and the vehicle types need to be distributed to separate links as much as possible.
   b) Vehicle segregation with one vehicle type or a combination of two vehicle types decreases the crash risk on a link.
   c) Coefficient values are important to accurately quantify the crash risk. However, the patterns in terms of vehicle segregation are expected to be valid, even with different coefficient values, if the order of the magnitude of the coefficients and their relative values are maintained.
3) The proposed heuristic solution gives a good trade-off solution with respect to the two objectives of total system travel time and total network crash risk.

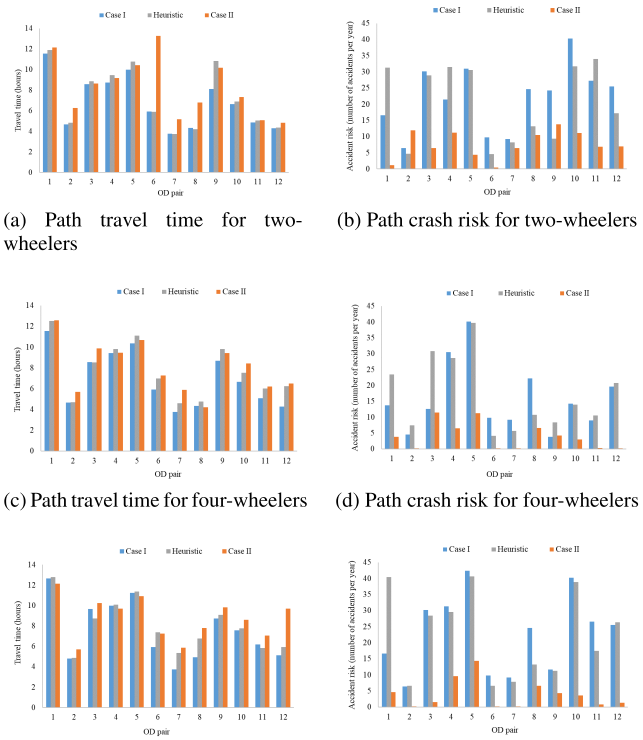
Based on the evaluation of results, a heuristic solution was proposed for the multi-class vehicle segregation problem. The method was based on the assignment of each vehicle type independently on different paths in the network, considering the k-shortest paths for each OD pair. It was found that the heuristic solution is a reasonably good trade-off solution with respect to the two objectives of total system travel time and total network crash risk. Finally, sensitivity analysis in different scenarios and traffic conditions proved the robustness of the formulations and the heuristic solution proposed. The comparison with conventional traffic assignment also establishes their better applicability in diverse real-world scenarios.

X. DISCUSSIONS

The major contributions of this study are:

1) Proposed network-level formulations for multi-class vehicle segregation in mixed traffic networks.
2) Identified the combination of vehicle types on links to improve efficiency and safety.
3) Developed a heuristic solution for vehicle segregation in mixed traffic networks that gives a good trade-off solution with respect to efficiency and safety.

The limitations identified are that the proposed formulation deals with static vehicle segregation strategies. However, dynamic segregation strategies may be more efficient since they can adapt to changing traffic conditions. And, the multi-class vehicle segregation model proposed to optimise safety depends on the crash risk in the network and does not consider the crash severity. This may be done once class-specific severity models are developed for different crash scenarios.



(a) Path travel time for two-wheelers
(b) Path crash risk for two-wheelers
(c) Path travel time for four-wheelers
(d) Path crash risk for four-wheelers
(e) Path travel time of each OD pairs for heavy vehicles
(f) Path crash risk for heavy vehicles

FIGURE 18. Comparison of path travel time and path crash risk of three vehicle types for Case I, Case II, and heuristic.

For future research, a bi-objective formulation can be modelled considering the trade-off between efficiency and safety. And, a solution method can be proposed to obtain the trade-off solutions with respect to each vehicle type. Also, other objective functions like operating cost or emission cost may be considered to route different vehicle types in the network with optimal segregation. There are research works that established multi-objective optimisation models considering different objective functions [40], [41]. The formulation may also be easily extended for other mixed traffic scenarios of connected autonomous vehicles, ego vehicles, and electric vehicles. A recent study focused on the safety and efficiency goals of the new mixed traffic flow of connected and autonomous vehicles and human-driven vehicles [42]. In addition, to accomplish dynamic segregation in a network, dynamic OD demand can be considered in the formulation. There are several methods proposed recently for the estimation of dynamic OD demand including optimisation problems utilising link travel time and traffic counts [43], machine learning algorithms [44], macroscopic fundamental diagram-based methods [45], etc. While the proposed study deals with static assignment, future studies can extend this model for stochastic conditions.

The vehicle segregation optimisation models presented in this paper are network-scale invariant; they are applicable for small, medium, and large-scale transportation networks. However, as the network size increases, the complexity increases and requires higher computational resources. Therefore, one of the future directions would be to develop faster and more efficient algorithms to solve large-scale problems in less time. In seeking to solve complex optimisation problems, researchers have consistently explored different techniques to optimise objective functions [46].

Potential hazards of travel routes can vary depending on the vehicle type and the specific route taken. It will depend on various factors like road conditions, traffic flow, infrastructure, weather conditions, human factors, environmental factors etc. Therefore, future studies can study how the formulations can be modified to include the potential hazard inputs from all the routes as a factor in minimising the total crash risk in the network. Future research could also focus on developing a lane-based multi-class segregation model. multi-segregation models can be developed to allocate lanes based on vehicle type or a combination of vehicle types. The assignment of lanes would depend on additional geometric features, such as the number of lanes, lane width, and the flow of crossing and turning vehicles at intersections.

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