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# Adaptive Traffic Management Model for Signalised Intersections

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***Abstract*—As population increases, one of the factors affecting life is traffic. Efficient traffic management has a direct positive impact on issues such as time, carbon dioxide emissions, and fuel consumption. Today, an important parameter under the heading of traffic is the signalling systems for intersections, which are operated with fixed-time, semi-actuated, fully actuated, and fully adaptive control methods. In this study, an adaptive traffic management model is developed for signalised intersections. The adaptive traffic management model developed includes phase extension with minimum and maximum time intervals dependent on density and phase skip features. Additionally, the most distinctive feature of the model is its flexible phase structure rather than a sequential phase. The Heybe intersection, located within the boundaries of Antalya province, is modelled one-to-one in the simulation of urban mobility (SUMO) simulation programme with real intersection data. The developed adaptive traffic management model is applied to the Heybe intersection, and the effects of the model are revealed. Improvements obtained from the SUMO simulation programme were verified through visual inspection, and high-accuracy results were determined. As a result of the studies, it was found that the application of the adaptive traffic management model developed at Heybe intersection, which has approximately 50,000 vehicles passing daily, resulted in a 27.2 % improvement in the average delay per vehicle parameter, a 32.4 % improvement in the average waiting time per vehicle parameter, and a 16.7 % improvement in the average speed per vehicle parameter.**

***Index Terms*—Adaptive control; Smart transportation; SUMO simulation programme; Traffic control.**

## I. INTRODUCTION

Signalling refers to a set of processes used to transmit, control, or organise information in a system or communication process. Traffic signalling arranges the systems used to organise, control, and coordinate daily life traffic. Traffic signalling is used to ensure safe and orderly traffic flow, prevent accidents, and efficiently manage traffic. It is also a strategy to optimise traffic flow.

There are a number of rules and structures that must be followed to create safe and efficient crossing patterns at signalised intersections. A systematic traffic signalling system at intersections creates phases. The cycle time of signalling is formed by the combination of all phase durations.

At signalised intersections, "phase" generally refers to a certain state of traffic lights. Considering a four-way intersection, the green light that allows any direction to pass is called "phase". Each phase also represents the flow of traffic in specific directions at the intersection. Phases are used to organise traffic management more effectively and ensure a safe and regular flow of traffic in a specific direction [1], [2].

Phases include green, yellow, and red light states that last for a certain period of time. Phases can operate cyclically in a certain order to make traffic flow more effective, minimise queue formation, and ensure the safe use of various roads at the intersection. The arrangement of phases in traffic signalling systems can vary depending on local traffic management policies, calculations by traffic engineers, and the traffic volume at the intersection [3], [4].

In traffic signalling systems, the "cycle time" refers to the time it takes to complete a traffic light cycle. This is the time interval during which a traffic light follows a specific sequence by switching between green, yellow, and red lights. In other words, it is the time it takes for a green light in a certain direction to turn on again after the right-of-way is given to other directions. Cycle time may vary depending on the intensity of traffic flow, the volume of roads at the intersection, and various traffic situations. Generally, at busy intersections, cycle times can be longer so that sufficient time can be allocated for vehicles coming from all directions [5], [6].

Traffic signalling cycle times include more than one phase within a period, and these phases work in a certain order to regulate the traffic flow at the intersection. Cycle times and phase durations can be programmed and adjusted as needed. Thus, these parameters can be optimised according to traffic conditions [7].

Traffic signalised intersection systems are operated with fixed-time, semi-actuated, fully actuated, and fully adaptive signalling management forms. Fixed-time signalisation management refers to a management strategy in traffic signal systems that includes fixed-time green, yellow, and red light conditions over a specific cycle time. This form of management refers to a fixed cycle time in which traffic lights operate in a certain order and each phase continues for a certain fixed period of time. In this type of management, the traffic signalling cycle time remains constant and the duration of each phase is a predetermined value. These times are generally determined with the analysis of traffic

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engineers [8], [9].

Fixed time signalling management is suitable for a simple and predictable traffic flow situation. However, if traffic density varies over time or needs change during times of heavy traffic in a particular direction, more complex management strategies may be preferred. Fully adaptive signalling management systems can adjust signal times and phases more sensitively to traffic conditions and demands [10], [11].

Fully adaptive signalling management refers to a management strategy that can dynamically adjust traffic signalling systems and adapt to changing traffic conditions. This type of management involves real-time monitoring and evaluation of traffic flow so that signal times and phases can be automatically adjusted according to traffic density [12], [13].

In fully adaptive signalling management, traffic density is constantly analysed through sensors, cameras, or other traffic monitoring systems. Signal durations, phases, and cycle times can be automatically adjusted according to the traffic situation. For example, longer green times may be assigned to a busy intersection direction. Fully adaptive signalling management is used to better adapt to fluctuations in traffic flow, unusual situations, and daily changes. Such systems can work effectively to optimise traffic flow, provide faster passage for drivers, and minimise queue formation [14]–[16].

The effects of the developed algorithms or models are seen in a simulation environment before applying them to real life producing both more efficient and safer results. Simulation of urban mobility (SUMO) is an open-source traffic simulation programme. SUMO is used to model urban mobility, simulate traffic flow, and evaluate different transportation scenarios. The flexible structure of SUMO allows simulating various transportation elements, including signalling systems.

SUMO's signalling module allows us to model traffic lights, road signs, and other signalling elements. This module allows users to predetermine what kind of traffic signalling they will implement at a particular intersection or road network. SUMO is also used to determine the results of the signalling method to be applied [17]–[19].

SUMO is a powerful tool used in a variety of applications in areas such as transportation planning, traffic engineering, and urban planning. Signalling features allow users to test different signal control strategies and scenarios [20], [21].

## II. ANTALYA HEYBE INTERSECTION STRUCTURE AND FEATURES

Antalya is the fifth largest city in Turkey in terms of population size. It is known as a tourist city in Turkey. As of November 2023, the number of motor vehicles in Antalya has reached 1,440,643 pieces. In this study, an adaptive traffic management model was developed and applied at the Heybe intersection in Antalya. Heybe intersection has been modelled in the SUMO simulation programme and adaptive traffic management strategies were developed on the model. The impacts of the added features to the developed model have been identified separately. The differences in the adaptive traffic management model developed compared to fixed-time signalling management have been revealed. To ensure the accuracy of the adaptive traffic management model, a visual detection-based verification method was developed at the Heybe intersection and compared with the results of the SUMO simulation programme.

The structure of the Antalya Heybe intersection is given in Fig. 1. The intersection has a structure with left-turn bays on the main roads.

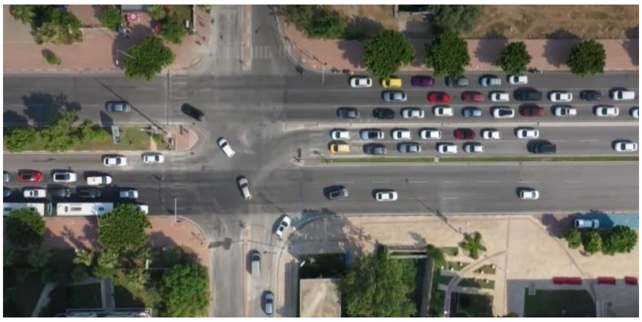

Fig. 1. Antalya Heybe intersection structure.

As seen in Fig. 2, Heybe intersection consists of four directions (Direction-1: Kemer, Direction-2: Coast, Direction-3: Centre, and Direction-4: North) and six traffic flows named Q5, Q6, Q7, Q8, Q9, and Q10.

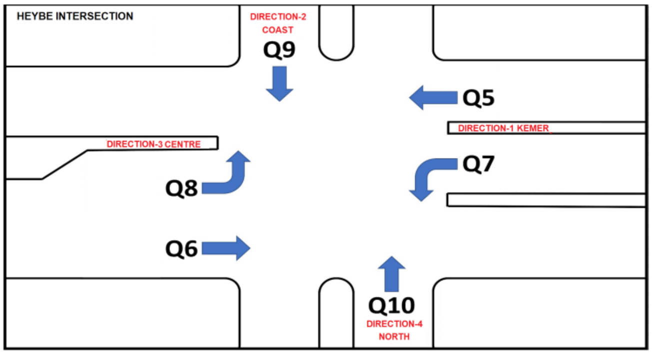

Fig. 2. Antalya Heybe intersection directions and traffic flows.

In the study, peak hour count data from the date of May 23, 2023, between 08.30 a.m. and 09.30 a.m., have been used. In the simulation modelling, the adaptive management model subfeature operations and visual verification method were performed during the same date and time period. The most crowded time zone was chosen as traffic, and thus, it was aimed to observe the effect of the model on improvement in the most crowded traffic. Table I includes origin-destination counts for Heybe Intersection during the period of May 23, 2023 date, between 08.30 a.m. and 09.30 a.m.

TABLE I. HEYBE INTERSECTION VEHICLE COUNTS BASED ON ORIGIN-DESTINATION.

| **Direction-Direction Name** | **Kemer** | **Coast** | **Centre** | **North** |
|---|---|---|---|---|
| **Kemer** | 81 pcs | 54 pcs | 1333 pcs | 434 pcs |
| **Coast** | 45 pcs | 0 pcs | 22 pcs | 104 pcs |
| **Centre** | 1245 pcs | 70 pcs | 51 pcs | 59 pcs |
| **North** | 113 pcs | 201 pcs | 275 pcs | 0 pcs |
| **Total** | **1484 pcs** | **325 pcs** | **1681 pcs** | **597 pcs** |

Table II shows the classification-based counts of the Heybe intersection between 08.30 a.m. and 09.30 a.m. on May 23, 2023.

TABLE II. HEYBE INTERSECTION CLASSIFICATION-BASED VEHICLE COUNTS.

| | |
|---|---|
| **Motorcycle/Bicycle** | 289 pcs |
| **Car** | 3199 pcs |
| **Commercial Vehicle/Pickup Truck** | 361 pcs |
| **Truck/Bus** | 238 pcs |
| **Total Vehicle** | **4087 pcs** |

Table III contains the classification counts divided into the arrival directions of Heybe intersection between 08.30 a.m. and 09.30 a.m. on May 23, 2023.

TABLE III. HEYBE INTERSECTION CLASSIFICATION DIRECTION-BASED VEHICLE COUNTS.

| **Classification-Direction Name** | **Kemer** | **Coast** | **Centre** | **North** |
|---|---|---|---|---|
| **Motorcycle/Bicycle** | 99 pcs | 27 pcs | 105 pcs | 58 pcs |
| **Car** | 1139 pcs | 248 pcs | 1329 pcs | 483 pcs |
| **Commercial Vehicle/Pickup Truck** | 134 pcs | 36 pcs | 144 pcs | 47 pcs |
| **Truck/Bus** | 112 pcs | 14 pcs | 103 pcs | 9 pcs |
| **Total** | **1484 pcs** | **325 pcs** | **1681 pcs** | **597 pcs** |

## III. SUMO Simulation Modelling

SUMO modelling of the intersection, an image of which is shown in Fig. 3, was carried out with real traffic data obtained from Heybe intersection. Traffic vehicle counts and classification data between 08:30 a.m. and 09:30 a.m. on May 23, 2023, were converted into route data for use in the SUMO simulation programme. The geometry of Heybe intersection was drawn in the SUMO simulation programme and traffic operation was provided with the traffic data in this route file.

Traffic data used in the SUMO simulation are based on cumulative vehicle counts taken in five-minute intervals between 08:30 a.m. and 09:30 a.m. These vehicles were then added to the simulation within five-minute time intervals with the prediction of real traffic flow. The data of the traffic model used in the simulation include the arrival directions of vehicles, the departure directions of vehicles from the intersection, the total counts of vehicles, and the classes of vehicles. Various inputs affecting traffic congestion, such as road width, length of roads, number of lanes, turning lanes, capacity of roads and intersections capacity, speed limits, and signalisation placement, were used in the created simulation.

To determine the driving model of the vehicles, the driver error coefficient, driver reaction time, and similar parameters optimisation process was calibrated in line with observations made at the intersection.

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Loading net-file from 'nets/S_heybe.net.xml' ... done (6ms).
Loading done.
Simulation started with time: 0.00
'heybe.sumocfg' loaded.
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Fig. 3. Heybe intersection SUMO modelling.

After SUMO modelling of Heybe intersection, as seen in Table IV, the intersection was operated with fixed signalling times determined by Antalya Metropolitan Municipality at peak time between 08.30 a.m. and 09.30 a.m. The protection time at the intersection is given as seven seconds.

TABLE IV. HEYBE INTERSECTION FIXED-TIME SIGNALLING MANAGEMENT TIMES.

| **Direction Name** | **Phases** | **Fixed-Time Signalling Management Times (s)** |
|---|---|---|
| Kemer | Q5–Q7 | 65–36 |
| Coast | Q9 | 20 |
| Centre | Q6–Q8 | 43–14 |
| North | Q10 | 22 |

After Heybe intersection was operated with fixed-time signalling management, the results were obtained as output from the SUMO simulation programme. Average delay per vehicle, average waiting time per vehicle, and average speed per vehicle for fixed-time signalling management, which will be compared separately with subfeatures of adaptive traffic management model, are shown in Table V.

TABLE V. HEYBE INTERSECTION FIXED-TIME SIGNALLING MANAGEMENT RESULTS.

| | **Delay (s/veh)** | **Waiting Time (s/veh)** | **Average Speed (km/h)** |
|---|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 87.9 | 5.44 |

## IV. Adaptive Traffic Management Model

Algorithms have been developed to adapt to changing traffic conditions. The most innovative aspect of the algorithms developed is that the adaptation to changing traffic conditions is based on changes in traffic flows, not on phases. Adaptation aims at changes made to traffic flows. Thanks to the algorithms built on traffic flows, flexibility is provided on phase and cycle time, which are larger structural units. This provides an advantage in terms of efficiency. The algorithms developed have been applied in the field. In other words, the performance of the developed model was demonstrated at a real intersection and with real traffic data. The study has been transformed from theory to practice. The developed model was used in peak traffic during the day. Peak traffic results have been shared.

Additionally, the developed model is also compatible with other traffic sensors. In the study, loop sensors were used, but the model can also be operated with sensors such as radar or image processing.

In this study, minimum maximum time range phase operation, phase skipping and matrix structure, and dynamic phase algorithms and codes were developed under the adaptive traffic management model. These algorithms and codes developed were applied to the Antalya Heybe intersection with real traffic data. The general system diagram is given in Fig. 4.

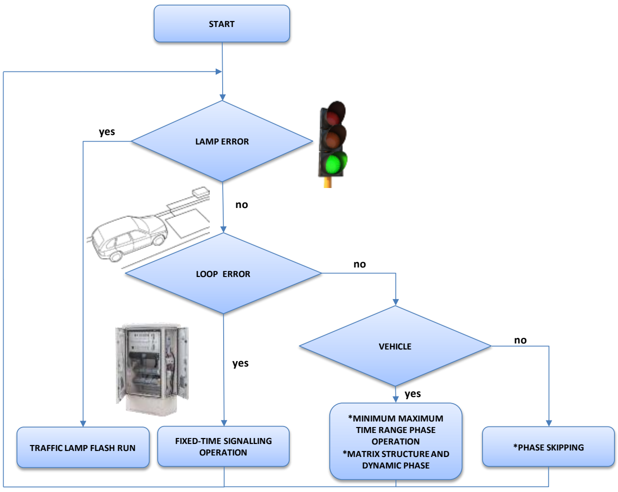
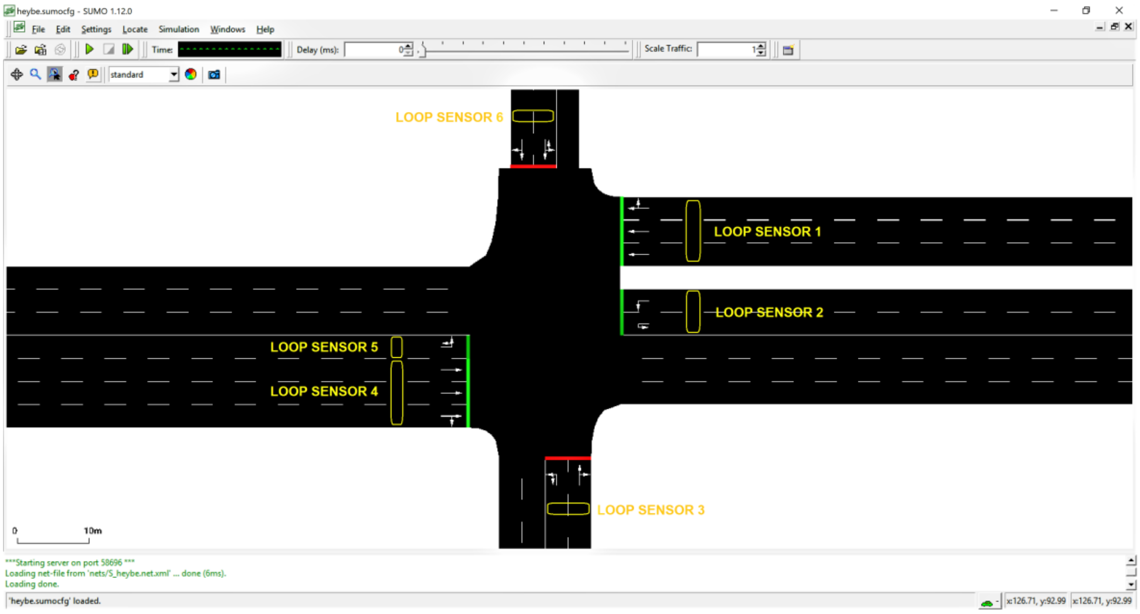


Fig. 4. General system diagram.

### A. *Minimum Maximum Time Range Phase Operation*

In this operating feature, minimum and maximum times have been determined for traffic flows. As seen in Fig. 5, sensors have been placed in the directions of intersections to obtain vehicle count and vehicle presence information.



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***Starting server on port 58696 ***
Loading net-file from 'nets/S_heybe.net.xml' ... done (6ms).
Loading done.
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'heybe.sumocfg' loaded.
```

Fig. 5. Heybe intersection sensor placement.

Sensors located in the direction of intersections are used to obtain vehicle presence information. On the basis of these vehicle presence data, the times of traffic flows are operated between minimum and maximum limits. Therefore, depending on the traffic density in the intersection directions, the times between the minimum and maximum times are operated. The minimum and maximum traffic flow times used are shown in Table VI.

Figure 6 shows an example of the general algorithm scheme for the Q9 phase, and with this algorithm, the green signal times in the crowded intersection directions are operated for a long time up to the maximum duration, while the green signal times in the uncrowded intersection directions are operated for a short time down to the minimum duration.

TABLE VI. MINIMUM AND MAXIMUM TIMES OF TRAFFIC FLOWS.

| **Traffic Flow** | **Minimum Time (s)** | **Maximum Time (s)** |
|---|---|---|
| Q5 | 15 | 50 |
| Q6 | 15 | 70 |
| Q7 | 10 | 50 |
| Q8 | 10 | 20 |
| Q9 | 10 | 20 |
| Q10 | 15 | 30 |

The results after operating the phase timings of Heybe intersection within the minimum and maximum time intervals were obtained as output from the SUMO simulation programme. The average delay per vehicle, the average waiting time per vehicle, and the average speed per vehicle at the intersection with minimum and maximum time interval phase operation are shown in Table VII.

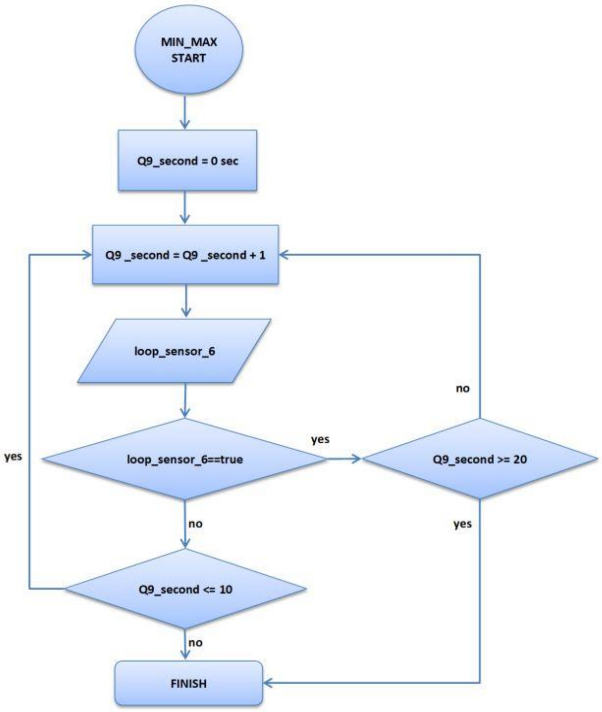


Fig. 6. General algorithm for the Q9 phase minimum maximum operation.

TABLE VII. MINIMUM MAXIMUM TIME RANGE PHASE OPERATION RESULTS.

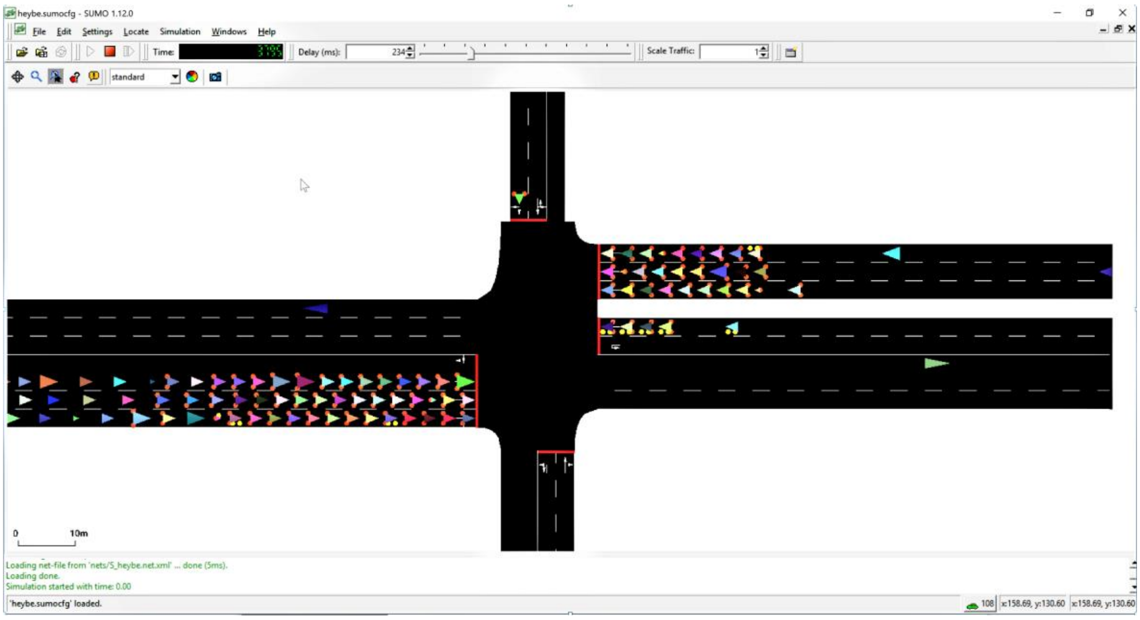
| | Delay (s/veh) | Waiting Time (s/veh) | Average Speed (km/h) |
|---|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 87.9 | 5.44 |
| **Minimum Maximum Time Range Phase Operation** | 80.3 | 67.6 | 6.21 |

## *B. Phase Skipping*

In this feature, the developed application enables a direct transition to the next phase without providing a green signal time to the direction where no vehicles are present. Thus, based on the absence of vehicle information obtained through sensors in the intersection directions, the phase for that intersection direction is skipped, and a direct transition to the next phase is operated.

As seen in the example in Fig. 7, during the transition to phase Q10, there are no vehicles in the intersection direction. In this situation, the Q10 phase is skipped to the next phase directly without being operated for the minimum time.

An example general algorithm diagram for the Q9 phase is given in Fig. 8, the operation in here is provided without giving a green signal time to the directions where no vehicle is coming.



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Loading net-file from 'nets/S_heybe.net.xml' ... done (5ms).
Loading done.
Simulation started with time: 0.00
'heybe.sumocfg' loaded.
```

Fig. 7. Q10 phase skip status.

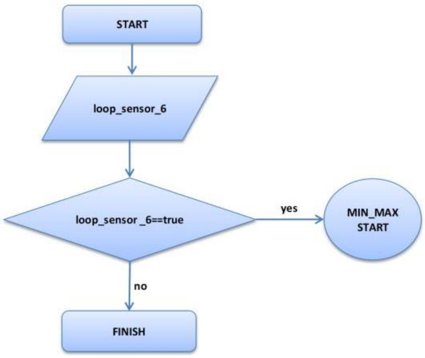

Fig. 8. General algorithm for the Q9 phase skipping operation.

TABLE VIII. MINIMUM MAXIMUM TIME RANGE PHASE OPERATION + PHASE SKIPPING RESULTS.

| | Delay (s/veh) | Waiting Time (s/veh) | Average Speed (km/h) |
|---|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 87.9 | 5.44 |
| **Minimum Maximum Time Range Phase Operation + Phase Skipping** | 79.3 | 64.6 | 6.25 |

The results after operating the phase skipping feature at Heybe intersection were obtained as output from the SUMO simulation programme. Phase skipping codes were developed to work with minimum maximum time range phase operation. With the addition of the phase skipping feature, the average delay per vehicle, the average waiting time per vehicle, and the average speed per vehicle at the intersection are shown in Table VIII.

### *C. Matrix Structure and Dynamic Phase*

The smallest operating structure of signalling systems is phase. The phase consists of a combination of traffic flows. The cycle time is formed by the combination of phases. In signalling systems, phases are generally operated in a predetermined order. However, operating phases in a certain pattern in signalling systems negatively affect adaptive management systems.

In adaptive traffic management systems, the operation of phases according to dynamically changing conditions increases efficiency. In this study, a traffic flow conflict matrix was created for the dynamic phase structure. Thus, the flexible phase structure has been developed according to the traffic conditions by determining the traffic flows that can and cannot work with each other. The conflict matrix is in Table IX.

TABLE IX. TRAFFIC FLOWS CONFLICT MATRIX.

| **Conflict Matrix** | **Q5** | **Q6** | **Q7** | **Q8** | **Q9** | **Q10** |
|---|---|---|---|---|---|---|
| **Q5** | * | ✓ | ✓ | X | X | X |
| **Q6** | ✓ | * | X | ✓ | X | X |
| **Q7** | ✓ | X | * | ✓ | X | X |
| **Q8** | X | ✓ | ✓ | * | X | X |
| **Q9** | X | X | X | X | * | X |
| **Q10** | X | X | X | X | X | * |

As can be seen in Table IX, when different traffic flows are active, it becomes possible to activate different traffic flows. In other words, a dynamic phase structure emerges according to traffic conditions.

For example, when Q6 is active:

– Alternative Phase-1: Q6 + Q8;

– Alternative Phase-2: Q6 + Q5.

When Q7 is active:

– Alternative Phase-1: Q7 + Q5;

– Alternative Phase-2: Q7 + Q8.

When the traffic flow Q6 needs to be active, two different alternative phases emerge: Q6 + Q8 or Q6 + Q5. Similarly, when the traffic flow Q7 needs to be active, two different phase alternatives arise: Q7 + Q5 or Q7 + Q8.

For example, when Q6 is active, if there are few vehicles in Q8, the Q6 + Q5 phase can be operated. Or, if the queueing in Q8 is too large when Q6 is active, the Q6 + Q8 phase can be operated. With its dynamic phase structure according to changing traffic conditions, the adaptive traffic management model has become a structure that is more flexible and can adapt to traffic conditions in more ways.

After Heybe intersection with matrix structure and dynamic phase features was run, the results were obtained as output from the SUMO simulation programme. The matrix structure and dynamic phase codes have been developed to work with minimum maximum time range phase operation and phase skipping. With the addition of the matrix structure and dynamic phase feature, the results of average delay per vehicle, average waiting time per vehicle, and average speed per vehicle at the intersection are shown in Table X.

TABLE X. MINIMUM MAXIMUM TIME RANGE PHASE OPERATION + PHASE SKIPPING + MATRIX STRUCTURE AND DYNAMIC PHASE RESULTS.

| | **Delay (s/veh)** | **Waiting Time (s/veh)** | **Average Speed (km/h)** |
|---|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 87.9 | 5.44 |
| **Minimum Maximum Time Range Phase Operation + Phase Skipping + Matrix Structure and Dynamic Phase** | 75.1 | 59.4 | 6.35 |

## V. DISCUSSION

In the study, an adaptive traffic management model was developed and the effects of each substep were examined. It has been revealed that adaptive traffic management model positively affects the delay, waiting time, and average speed parameters at Heybe intersection.

The SUMO simulation programme was used for the studies and codes and algorithms for each subfeature were developed in this programme. To confirm and discuss the accuracy of the study result, a study was conducted on the delay parameter based on the visual detection method with the camera at the Heybe intersection. Additionally, a Webster model calculation was carried out to confirm and discuss the accuracy of the fixed-time signalling management results.

For fixed-time signalling management delay times calculations, the data of Antalya Heybe intersection for the date of May 23, 2023 and the peak time between 08.30 a.m. and 09.30 a.m. were obtained from the intersection control device. The Webster model was used in calculations to minimise delay [22]. The average delays per vehicle were calculated by substituting the data obtained from the intersection control device into the Webster delay formula [23]. To increase the accuracy rate, separate calculations were carried out for the intersection directions. The relevant formula is presented in (1)

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0{,}65\left(\frac{C}{q^2}\right)^{\frac{1}{3}} x^{2+5\lambda}, \quad (1)$$

where $d$ is the average delay per vehicle (s/veh), $C$ is the cycle time (s), $q$ is the peak flow in the relevant phase (veh/h), $\lambda$ is the ratio of green time (G) to cycle time (G/C), and $x$ is the saturation ratio (x = (q/λs)(s = saturation flow)).

Calculation example for Q7:

$$s = 990 + 288TL + 8.5SL - 26G, \quad (2)$$

where $s$ is the saturation current (veh/h), $TL$ is the pieces of lanes (2 pieces of lanes for Q7), $SL$ is the speed limit (40 km/h for Q7), and $G$ is the slope (%0 for Q7).

Q7 traffic flow values: $q = 455\ veh/h$, $C = 200\ s$, $G = 36\ s$, $s = 1906\ veh/h$.

When the values are substituted into (1),

$$d=\frac{200\left(1-\left(\frac{36}{200}\right)\right)^{2}}{2\left(1-\left(\frac{36}{200}\right)\left(\frac{455}{\left(\frac{36}{200}\right)1906}\right)\right)}+\frac{\left(\frac{455}{\left(\frac{36}{200}\right)1906}\right)^{2}}{2\times 455\left(1-\left(\frac{455}{\left(\frac{36}{200}\right)1906}\right)\right)}-$$

$$-0.65\left(\frac{200}{455^{2}}\right)^{\frac{1}{3}}\left(\frac{455}{\left(\frac{36}{200}\right)1906}\right)^{2+5\left(\frac{36}{200}\right)}, \quad (3)$$

where $d = 88.17\ s/veh$.

Delay values were calculated by inserting peak hour data into the Webster delay formula specific to each intersection direction. The results of the average delay times obtained separately for each direction are presented in Table XI.

TABLE XI. WEBSTER MODEL DELAY RESULTS FOR FIXED TIME SIGNALLING MANAGEMENT SYSTEM.

| Traffic Flow | Delay (s/veh) |
|---|---|
| **Q7** | 88.17 |
| **Q5** | 134.88 |
| **Q9** | 89.33 |
| **Q8** | 90.51 |
| **Q6** | 162.86 |
| **Q10** | 116.39 |
| **Average Delay** | 110.98 |

Camera videos between 08.30 a.m. and 09.30 a.m. peak time on May 23, 2023 were used for delay calculations with visual detection method while the intersection operates in an adaptive traffic management model. The camera view at the intersection is given in Fig. 9.

Fig. 9. Camera image used for the visual detection method at Heybe intersection.

The results obtained by observing the camera videos are determined for each traffic flow and are presented in Tables XII to XV.

The delay times per vehicle according to the traffic flows provided in Tables XII, XIII, XIV, and XV are given in Table XVI, and the average delay time per vehicle is calculated by the visual detection method of the adaptive traffic management model.

TABLE XII. DELAY COUNTS FOR Q7 AND Q5 TRAFFIC FLOWS.

| Traffic Flow | Count | Tentry (s) | Texit (s) | Texit-Tentry (s) | Delay (s/veh) |
|---|---|---|---|---|---|
| **Q7** | **1st Vehicle** | 9 | 72 | 63 | 84.95 |
| | **2nd Vehicle** | 4 | 38 | 34 | |
| | **3rd Vehicle** | 10 | 72 | 62 | |
| | **4th Vehicle** | 12 | 109 | 97 | |
| | **5th Vehicle** | 13 | 116 | 103 | |
| | **6th Vehicle** | 9 | 107 | 98 | |
| | **7th Vehicle** | 6 | 57 | 51 | |
| | **8th Vehicle** | 11 | 116 | 105 | |
| | **9th Vehicle** | 9 | 107 | 98 | |
| | **10th Vehicle** | 5 | 41 | 36 | |
| | **11th Vehicle** | 6 | 106 | 100 | |
| | **12th Vehicle** | 9 | 138 | 129 | |
| | **13th Vehicle** | 11 | 122 | 111 | |
| | **14th Vehicle** | 9 | 102 | 93 | |
| | **15th Vehicle** | 7 | 78 | 71 | |
| | **16th Vehicle** | 11 | 113 | 102 | |
| | **17th Vehicle** | 8 | 111 | 103 | |
| | **18th Vehicle** | 6 | 75 | 69 | |
| | **19th Vehicle** | 11 | 116 | 105 | |
| | **20th Vehicle** | 6 | 75 | 69 | |
| **Q5** | **1st Vehicle** | 12 | 18 | 6 | 30.25 |
| | **2nd Vehicle** | 9 | 12 | 3 | |
| | **3rd Vehicle** | 13 | 14 | 1 | |
| | **4th Vehicle** | 8 | 66 | 58 | |
| | **5th Vehicle** | 10 | 30 | 20 | |
| | **6th Vehicle** | 10 | 64 | 54 | |
| | **7th Vehicle** | 7 | 28 | 21 | |
| | **8th Vehicle** | 8 | 57 | 49 | |
| | **9th Vehicle** | 10 | 23 | 13 | |
| | **10th Vehicle** | 9 | 63 | 54 | |
| | **11th Vehicle** | 1 | 27 | 26 | |
| | **12th Vehicle** | 9 | 32 | 23 | |
| | **13th Vehicle** | 7 | 62 | 55 | |
| | **14th Vehicle** | 8 | 29 | 21 | |
| | **15th Vehicle** | 10 | 58 | 48 | |
| | **16th Vehicle** | 9 | 62 | 53 | |
| | **17th Vehicle** | 10 | 22 | 12 | |
| | **18th Vehicle** | 11 | 39 | 28 | |
| | **19th Vehicle** | 7 | 23 | 16 | |
| | **20th Vehicle** | 9 | 53 | 44 | |

TABLE XIII. DELAY COUNTS FOR Q9 TRAFFIC FLOW.

| Traffic Flow | Count | Tentry (s) | Texit (s) | Texit-Tentry (s) | Delay (s/veh) |
|---|---|---|---|---|---|
| **Q9** | **1st Vehicle** | 8 | 49 | 41 | 76.05 |
| | **2nd Vehicle** | 9 | 105 | 96 | |
| | **3rd Vehicle** | 13 | 121 | 108 | |
| | **4th Vehicle** | 7 | 35 | 28 | |
| | **5th Vehicle** | 9 | 85 | 76 | |
| | **6th Vehicle** | 8 | 140 | 132 | |
| | **7th Vehicle** | 6 | 97 | 91 | |
| | **8th Vehicle** | 12 | 49 | 37 | |
| | **9th Vehicle** | 7 | 130 | 123 | |
| | **10th Vehicle** | 11 | 121 | 110 | |
| | **11th Vehicle** | 7 | 75 | 68 | |
| | **12th Vehicle** | 11 | 53 | 42 | |
| | **13th Vehicle** | 7 | 49 | 42 | |
| | **14th Vehicle** | 6 | 38 | 32 | |
| | **15th Vehicle** | 8 | 25 | 17 | |
| | **16th Vehicle** | 8 | 149 | 141 | |
| | **17th Vehicle** | 5 | 147 | 142 | |
| | **18th Vehicle** | 7 | 82 | 75 | |
| | **19th Vehicle** | 9 | 86 | 77 | |
| | **20th Vehicle** | 6 | 49 | 43 | |

TABLE XIV. DELAY COUNTS FOR Q8 AND Q6 TRAFFIC FLOWS.

| **Traffic Flow** | **Count** | $T_{entry}$ (s) | $T_{exit}$ (s) | $T_{exit}$- $T_{entry}$ (s) | **Delay (s/veh)** |
|---|---|---|---|---|---|
| **Q8** | **1st Vehicle** | 11 | 108 | 97 | 89.75 |
| | **2nd Vehicle** | 9 | 75 | 66 | |
| | **3rd Vehicle** | 10 | 56 | 46 | |
| | **4th Vehicle** | 7 | 73 | 66 | |
| | **5th Vehicle** | 12 | 116 | 104 | |
| | **6th Vehicle** | 13 | 131 | 118 | |
| | **7th Vehicle** | 11 | 129 | 118 | |
| | **8th Vehicle** | 10 | 130 | 120 | |
| | **9th Vehicle** | 6 | 106 | 100 | |
| | **10th Vehicle** | 9 | 95 | 86 | |
| | **11th Vehicle** | 11 | 116 | 105 | |
| | **12th Vehicle** | 9 | 110 | 101 | |
| | **13th Vehicle** | 8 | 73 | 65 | |
| | **14th Vehicle** | 9 | 69 | 60 | |
| | **15th Vehicle** | 7 | 113 | 106 | |
| | **16th Vehicle** | 13 | 116 | 103 | |
| | **17th Vehicle** | 12 | 112 | 100 | |
| | **18th Vehicle** | 9 | 81 | 72 | |
| | **19th Vehicle** | 12 | 79 | 67 | |
| | **20th Vehicle** | 10 | 105 | 95 | |
| **Q6** | **1st Vehicle** | 8 | 100 | 92 | 75.6 |
| | **2nd Vehicle** | 7 | 65 | 58 | |
| | **3rd Vehicle** | 9 | 61 | 52 | |
| | **4th Vehicle** | 9 | 93 | 84 | |
| | **5th Vehicle** | 9 | 88 | 79 | |
| | **6th Vehicle** | 9 | 104 | 95 | |
| | **7th Vehicle** | 9 | 86 | 77 | |
| | **8th Vehicle** | 10 | 112 | 102 | |
| | **9th Vehicle** | 8 | 113 | 105 | |
| | **10th Vehicle** | 8 | 106 | 98 | |
| | **11th Vehicle** | 9 | 102 | 93 | |
| | **12th Vehicle** | 11 | 80 | 69 | |
| | **13th Vehicle** | 13 | 94 | 81 | |
| | **14th Vehicle** | 7 | 107 | 100 | |
| | **15th Vehicle** | 11 | 112 | 101 | |
| | **16th Vehicle** | 9 | 95 | 86 | |
| | **17th Vehicle** | 6 | 48 | 42 | |
| | **18th Vehicle** | 15 | 52 | 37 | |
| | **19th Vehicle** | 10 | 28 | 18 | |
| | **20th Vehicle** | 10 | 53 | 43 | |

TABLE XV. DELAY COUNTS FOR Q10 TRAFFIC FLOW.

| **Traffic Flow** | **Count** | $T_{entry}$ (s) | $T_{exit}$ (s) | $T_{exit}$- $T_{entry}$ (s) | **Delay (s/veh)** |
|---|---|---|---|---|---|
| **Q10** | **1st Vehicle** | 9 | 103 | 94 | 105.2 |
| | **2nd Vehicle** | 8 | 100 | 92 | |
| | **3rd Vehicle** | 13 | 74 | 61 | |
| | **4th Vehicle** | 9 | 73 | 64 | |
| | **5th Vehicle** | 4 | 62 | 58 | |
| | **6th Vehicle** | 7 | 120 | 113 | |
| | **7th Vehicle** | 14 | 102 | 88 | |
| | **8th Vehicle** | 10 | 116 | 106 | |
| | **9th Vehicle** | 8 | 120 | 112 | |
| | **10th Vehicle** | 11 | 111 | 100 | |
| | **11th Vehicle** | 8 | 151 | 143 | |
| | **12th Vehicle** | 4 | 148 | 144 | |
| | **13th Vehicle** | 8 | 141 | 133 | |
| | **14th Vehicle** | 7 | 143 | 136 | |
| | **15th Vehicle** | 10 | 127 | 117 | |
| | **16th Vehicle** | 6 | 161 | 155 | |
| | **17th Vehicle** | 10 | 92 | 82 | |
| | **18th Vehicle** | 9 | 105 | 96 | |
| | **19th Vehicle** | 6 | 147 | 141 | |
| | **20th Vehicle** | 7 | 76 | 69 | |

TABLE XVI. VISUAL DETECTION DELAY RESULTS FOR ADAPTIVE TRAFFIC MANAGEMENT MODEL.

| **Traffic Flow** | **Delay (s/veh)** |
|---|---|
| **Q7** | 84.95 |
| **Q5** | 30.25 |
| **Q9** | 76.05 |
| **Q8** | 89.75 |
| **Q6** | 75.6 |
| **Q10** | 105.2 |
| **Average Delay** | 80.38 |

As a result of the verification studies, the delay parameter results of the SUMO simulation programme and the delay parameter results with the Webster model and the visual detection method are given in Table XVII.

TABLE XVII. VERIFICATION RESULTS.

| | **SUMO Simulation Programme Delay Results (s/veh)** | **Webster Model and Visual Detection Method Delay Results (s/veh)** |
|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 110.98 |
| **Adaptive Traffic Management Model** | 75.1 | 80.38 |

As seen in Table XVII, the results of the studies in the SUMO simulation programme and the studies of the Webster model and the visual detection method are approximately the same. Small differences can be explained as the difference between the simulation environment and the physical conditions of the real intersection or as external factors. In other words, simulation programmes simulate working under ideal conditions. However, external factors, such as asphalt deterioration or pedestrian behaviour in any direction of the intersection, can cause a difference in the delay parameter. The fact that the delay parameters are negligible and slightly less in the SUMO simulation programme can be explained in this way.

Various studies have been carried out to provide adaptive management of signalised intersections according to changing traffic characteristics. In these studies, different strategies, control algorithms, and artificial intelligence methods were tried in adaptive traffic management. In a study using the CRONOS control strategy, a 19.3 % improvement was achieved in the delay parameter of peak hour [24]. In another study [25], the effects of the isolated algorithm were examined in the adaptive traffic management model using fuzzy logic and the modified Webster optimal cycle formula and the average waiting times were reduced from 52.64 seconds to 41.44 seconds.

In a study on dynamic phase structures [3], a flow that can adapt to asymmetric traffic flows was carried out. The modelling was carried out on the Vissim simulation programme with real traffic data and a 28 % improvement in vehicle delay was estimated. In another study [26], an algorithm that can optimise phase sequence and time was developed, and the results were obtained through the Vissim simulation programme. At peak hour, reductions in average vehicle delays have been found between 17.22 % and 10.74 % for different management styles.

In a study in [27], a speed detector was used in an adaptive traffic management system developed based on the speed parameter. Improvements were achieved in the delay parameters within the phases with the application developed based on speed values.

As seen in the studies, an efficient improvement in peak hours is achieved with the adaptive traffic management algorithm developed in this study. The adaptive traffic management model developed in the study is an advantage due to the combination of three different features and the synchronous operation of these three different features. Minimum maximum time range phase operation, phase skipping, matrix structure, and dynamic phase features increased the positive improvement values at each step.

According to other studies, both the separation of traffic flows and the creation of phases from the combination of traffic flows have taken the performance of adaptive traffic management one step forward. The biggest difference of the adaptive traffic management model developed compared to other adaptive management models is the development of algorithms on traffic flows as the smallest structural unit. In other adaptive traffic management, the development has generally been made as the smallest structural unit phase. Since phases consist of traffic flows, a more effective and flexible management style has been introduced against changing traffic conditions.

In this study, the algorithms developed were run sequentially and the effect of each component was determined separately. This reveals which subcomponent is more effective in adaptive traffic management. If the developed codes were implemented holistically, it would not be possible to reveal which component was more effective. The reason why the adaptive traffic model is divided into subcomponents is to ensure that future developments on this model can intervene down to the subcomponents.

Since the flexible phase structure was created in the model developed based on traffic flows, an infrastructure was created for adaptive coordination between intersections. Its most important advantage compared to other adaptive traffic management is that more efficient and easier adaptive coordination can be achieved due to its flexible phase structure. This work lays the foundation for future adaptive coordination.

This study was carried out at the most crowded hour of the intersection. The developed model was operated on peak-hour traffic data. The contribution of the adaptive traffic management model to performance is expected to be higher when considering other time intervals with normal traffic volumes at the intersection. Especially in time zones where traffic loads at intersection directions are low, minimum and maximum time range phase operation, phase skipping, and dynamic phase structures will operate more efficiently and frequently. Therefore, the improvement difference in the delay, waiting time, and average speed data is thought to be higher.

The matrix structure and dynamic phase structure are expected to work more efficiently, especially at intersections with wide geometry and separate left-turns. If more traffic flows can work together in the matrix structure, phase alternatives will increase. This will create flexible phase structures according to traffic data and increase efficiency.

## VI. CONCLUSIONS

Fixed-time signalling systems are still common in the world. However, in recent years, adaptive traffic management systems have begun to be frequently implemented in the field at signalised intersections. In this study, an adaptive traffic management model that can be used at real signalised intersections was developed and applied in the field. The biggest innovation of this study is that the adaptive traffic management model developed consists of three different subcomponents. Since these three different components work synchronously according to different conditions, a more effective system has been created. In addition, the fact that the model works on the basis of traffic flows is a global innovation. In this way, automatic flexible phase structures were created from traffic flows. This resulted in a more efficient and quicker response to changes in traffic character in the smallest structure, the traffic flow.

The adaptive traffic management model developed was determined to make a significant positive contribution to the parameters of average delay per vehicle, average waiting time per vehicle, and average speed per vehicle at the intersection. The algorithms developed are designed to adapt to traffic loads at the intersection, allowing for variable times based on traffic flow density and the ability to operate alternative phases according to traffic conditions. These improvements also have a positive impact on the performance parameters, as seen in Table XVIII.

TABLE XVIII. PERFORMANCE EFFECTS OF ADAPTIVE TRAFFIC MANAGEMENT MODEL SUBFEATURES.

| | **Delay (s/veh)** | **Waiting Time (s/veh)** | **Average Speed (km/h)** |
|---|---|---|---|
| **Fixed-Time Signalling Management** | 103.2 | 87.9 | 5.44 |
| **Minimum Maximum Time Range Phase Operation** | 80.3 | 67.6 | 6.21 |
| **Minimum Maximum Time Range Phase Operation + Phase Skipping** | 79.3 | 64.6 | 6.25 |
| **Minimum Maximum Time Range Phase Operation + Phase Skipping + Matrix Structure and Dynamic Phase** | 75.1 | 59.4 | 6.35 |

Heybe intersection modelling has been performed in the SUMO simulation programme and the developed adaptive traffic management model has been separately operated with peak hour data for all its subfeatures. In the developed model, the primary performance parameters of signalised intersections, minimising the per vehicle average delay and per vehicle average waiting time and maximising the per vehicle average speed data have been targeted.

As seen in Table XIX, with the adaptive traffic management model at Heybe intersection, there is an improvement of 27.2 % in the average delay parameter per vehicle, 32.4 % in the average waiting time parameter per vehicle, and 16.7 % in the average speed parameter per vehicle.

TABLE XIX. ADAPTIVE TRAFFIC MANAGEMENT MODEL PERFORMANCE PERCENTAGES.

| | **Delay (%)** | **Waiting Time (%)** | **Average Speed (%)** |
|---|---|---|---|
| **Adaptive Traffic Management Model** | 27.2 | 32.4 | 16.7 |

When considering the improvement values and percentages, significant outputs such as time and fuel savings can be achieved at the signalised intersection with the developed model. In addition, based on the impact of vehicles on carbon dioxide emissions, a reduction in carbon dioxide emission can be achieved with the model. Thus, the developed model has a significant positive impact both economically and environmentally [28]–[30].

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## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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