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Traffic Congestion Mitigation on Highways by using the Feedback Strategy

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ABSTRACT

The design of highways in urban areas aims to reduce congestion. When congestion occurs on a highway, it presents a problem that must be solved. The Al-Dawrah Expressway experienced severe congestion, particularly at its entrance, negatively impacting traffic flow. Data was collected via cameras installed along the highway. After calibrating and verifying the data, the ALINE algorithm was used to control traffic flow at highway entrances (Ramp Metering) to congestion mitigation by control of three parameters(flow, occupancy and speed). The results were significant, with four scenarios performed at different time points. The fourth scenario, lasting 10 seconds, showed the highest improvement rate of 20.1%, encompassing increased traffic flow, reduced congestion, decreased critical occupancy and increased speed.

1. Introduction

Traffic jams are not uncommon and are a big concern, particularly in big cities around the world. Traffic jams will result in social problems, economic issues, safety, pollution of the environment and other problems. Usually, it is not an economically and spatially realisable solution to reduce the traffic pressure by building further lanes and building new freeways. On the other hand, dynamic traffic control strategies such as ramp metering (RM) or variable speed limit (VSL) can be applied to enhance the efficiency of traffic operation of existing roads. Freeway traffic control technologies, such as those used for RM and VSL, are the subject of extensive study. Recently, these control strategies have been successfully put into practice in the U.In many other countries including S, Spain, Germany [1]. Many methods have been developed over the years for designing and implementing such dynamic traffic control strategies, such as neural networks [2,3], expert systems, fuzzy systems [3,4] and optimal control. A number of feedback control strategies are employed in the context of ramp metering, because they are simple and reliable. One of the interesting applications is Asservissement Lin´eaire d'Entr´ee Autorouti`ere(ALINEA) [6]. ALINEA is designed with a feedback loop to adjust the occupancy of the current downstream to the deviation from the critical occupancy. Given its simplicity, many variants of ALINEA have been suggested to tackle traffic control in different settings: Wang et al. [7]. The difference between the actual occupancy and the critical occupancy is used

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by ALINEA to give a feedback signal to the next control step to compute the ramp metering rate.

2. Feedback

A local feedback strategy that seeks to maximiser freeway flow in a merging area by keeping the bottleneck density near critical value [8]. The most well-known and widely adopted algorithm is ALINEA [9].

The design of strategies to control entering flow in such a manner that freeway congestion and the length of the queue at the on-ramp are balanced, with neither being a goal in itself, but where both are goals that are in conflict [9,10]. a local feedback control algorithm that adjusts ` ramp metering rates based on observed downstream traffic occupancy. Several extensions of ALINEA have been developed, utilizing alternative measurements or feedback laws.

Ramp metering is a widely used traffic control technique in freeways and has been used successfully in several countries [11, 12]. The purpose of this control strategy is to control the merging flow from an on-ramp to the main road by controlling the ramp traffic signals in order to alleviate congestion and increase traffic efficiency. The use of feedback control strategies is common in ramp metering, as they are relatively simple and reliable. An interesting example is Asservissement Lin´eaire d’Entr´ee Autorouti`ere(ALINEA) [13]. ALINEA includes a feedback loop which adjusts the downstream occupancy according to the deviation from the critical occupancy. Given the simplicity of implementation, several different variants of ALINEA have been suggested to deal with traffic management in different scenarios [14]. This unblocked condition extends upstream, which speeds up the movement of mainline vehicles and decreases the traveling time of mainline vehicles. The vehicle limit on the ramp however is limited. If this limit is surpassed, then the queued vehicles should be released. When ramp flow releases, cars merge and clog up, and a noticeable and periodic congestion state occurs, which propagates upstream. As a result, the entire road section is a part of the control cycle, ‘ramp flow released - mainline congestion - ramp closure - mainline smooth - ramp flow released' [15].These local feedback control algorithms assume downstream traffic measurements including flow and occupancy are only influenced by the immediate upstream ramp-metering rate. However, for large-scale networks, local feedback control algorithms may not yield optimal control solutions, as they overlook the coordinate dynamics within the highway network [16]. Both the capacity and occupancy-demand strategies reject the open-loop policy of disruptions, meaning that the system's outputs are not used as inputs in the next iteration. The ramp metering strategy ALINEA,is alternative closed-loop, proposed by [6], relies on classical feedback concepts. Equation 1 illustrates Alinea algorithm and Figure 1 shows implemented the Rm of feedback strategy's in entrance of highway.

qr(k)=qr(k-1)+KR (O_des-O_out (k-1)) 100 ……(1).

2.1. Critical Occupancy

The downstream occupancy can be kept close to the critical value by modifying the metering rate in ALINEA [17]. Based on previous studies, the critical occupancy (oˆ) was determined as 17% highway traffic flow management [8]. The aim of using the RM techniques is to help to merge and avoid congestion formation in the main flow by controlling the outflows of the onramps. There are two types of RM techniques: local and coordinated. In local methods, each ramp outflow is controlled individually based on information from the neighborhood to address local congestion [6] develops a simple feedback control approach that addresses multiple bottlenecks while simultaneously considering the delay behind each actuator. But the method has been shown to be applicable to a particular layout if there is a spatial separation of bottlenecks and actuators [18]. The purpose of ramp management is to manage the number of vehicles entering and/or exiting the freeway using control devices including traffic signals, signing, and gates to meet freeway operational goals [14]. The objectives are typically expressed as follows: Balance freeway demand and capacity; maintain optimum freeway operation to minimize incidents causing traffic delays, improve safety [19,23] and a higher critical occupancy level was found to provide better safety benefits [6]. To control traffic flow onto freeways based on the varying traffic situation, ramp meters are used. They are intended to reduce congestion on the freeway in two aspects, [10] control the traffic volume entering the freeway, regulate freeway demand, and keep it under its capacity and [9] break up the platoons of vehicles released from an upstream traffic signal, to provide a safe merge [20].The demand capacity strategy determines the capacity of the downstream structure and the flow at the upstream structure and determines the allowable ramp traffic based on that.The demand capacity strategy is a calculation with the capacity of the downstream structure and flow at the upstream structure. ALINEA [6] is an algorithm that uses downstream occupancy to adjust ramp metering to keep it close to a desired target value but does not consider the capacity of the ramp and how the ramp affects each other [21,22]. Ramp metering control is a commonly employed approach on a highway onramp where the flow of vehicles entering the highway is controlled to improve the efficiency of highway traffic. The demand-capacity (DC) method is one of the basic methods used for ramp metering [21]. This approach relies on an accurate estimate of demand and capacity and takes into account the difference between the merged capacity downstream and the capacity upstream. ALINEA implements feedback control, controlling ramp inflow rates according to the traffic occupancy or density on the mainline. It is more stable and effective, because of its feedback, in reacting to changes in traffic conditions. The goal of ALINEA is to keep the flow of the mainline stable and at its maximum downstream of the ramp [23]. Although these traditional strategies of ramp metering have proven to work, they tend to be based on a fixed capacity or critical occupancy value, which might not be appropriate for situations with mixed traffic. To address this, a feedback control structure, such as bang-bang type, was developed and applied to control the inflow using real-time traffic measurements at the bottlenecks [2, 3]. These early controllers gave modest improvements because of oscillations, but paved the way for more advanced feedback systems, such as traffic-light-based entrance control. It is usually desired to have the same or slightly less occupancy 40 to 500 m downstream of the capacity occupancy, which have been variously used from 18% to 31%. The new cycle time is anticipated to be in the range of 40 s to 5 min, but is expected to be small if so. If the time involved in the updating is small, then the detector's location should be brought close to the entrance ramp. Otherwise, congestion may build-up in the interior of the stretch between ramp nose and detector. ALINEA has been evaluated to be good for KR = 70 (veh/h/%). The range of the KR (70 to 120) does not have significant impact on the metering rate [25, 26,27, 28].

3. Green time

It can be seen the metering rate r(k) should be within the range of [rmin, rmax] in order to avoid the ramp closure as mentioned in [1]. Otherwise, it is r(k) is cut off, However, it is added to the next time step as r(k-1) to avoid the well-known “wind-up” behavior of such regulators as ALINEA which are called I-type (integral) regulators. Note that the real ramp flow value qr at any period may be different than the r(k) ordered by ALINEA due to a multitude of possible reasons (e.g., traffic light operation inaccuracies, red-signal violations, by-pass ramp lanes for buses or high occupancy vehicles, lack of ramp demand, etc. Typical values 200-400 (veh/h) and 1800 (veh/h) for single-lane ramps are used for r min and r max respectively. If the signal heads are used for ramp control, then r(k) can be transformed into green phase duration of the signal head using Papageorgiou et al. (2008), [24]. Apply a measure of one car per one greened control measure (CM), to minimize levels of disturbance and congestion to mainstream traffic caused by large vehicle releases and to create ease of performing the following CMs. With this, the cycle time is dynamically adjusted to the computed metering rate r(k).Equation 2 illustrate work of Green time [29].

$$g = (r\ (k)/rsat.\ c).\ \ldots\ldots\ldots\ldots(2)$$

The above is the general equation for the duration of the green phase with the provided parameters where g is the duration of the green phase, rsat is the saturation flow for the ramp and c is the cycle time.

The detector at the downstream end is one of the four parameters of ALINEA that needs to be calibrated, as does the parameter KR, which sets the strength of the radiation. The other three parameters of ALINEA that need to be calibrated are σ and the update cycle time of each of the metering rates r(k) by their location in the downstream detector. Naval Jindal and Agrawal (1993), Papageorgiou et al. (1991) and Chu et al. (2004) suggested that the detector location for the downstream station should coincide with the location of the congestion (ramp nose). The green-phase durations of the signal heads that are installed at the on-ramps entrance, have been manipulated online to assign the calculated metering rates of the ramp. Each day, ALINEA algorithm operation for smooth traffic conditions within the freeway capacity limit is tested. Sometimes it can only be done by overriding the calculation and ignoring the signal or keeping the signal green until the queue has cleared up, to get an even bigger entering volume. In this way the vehicles to be loaded at the ramp will be able to be sent on the main carriageway as forming a platoon [30].

4. Methodology

Data for the highway was collected via cameras placed along the road between 12 PM to 5 PM. The data was then manually calculated and fed into a program to test whether the simulated data matched the actual collected data using the Geh law. The difference between the data before and after the addition of the RM was then tested using the Alinea algorithm to determine the improvement.

5. Case study

The study site was chosen for the Al-Dorah highway and the entrance to this highway from the New Baghdad side, as this entrance experiences severe congestion, which affects the highway. Figure 2 shows the severe congestion on the Al- Dorah highway. The acceleration lane of the ramp is 71.25 meters long. The slip road of the ramp is 461.32 meters long and 9.00 meters wide. The data collected flow of traffic over 5 hours, spread over five minutes. The downstream begins with a flow of 3070 veh/hr at 7:00 and increases until it reaches 5328 veh/hr at 10:45, which represents (on peak) time. Following this, it gradually increases to 5724 veh/hr at 15:25, then drops to 4680 veh/hr at 10:20, the highest congestion period. Additionally, this total drops to 5256 veh/hr at 15:55. Then the flow drops to 4704 veh/hr in 16:35, falls gradually to 4344 veh/hr in 16:45, which represents (off-peak) time.

5.1 GEH Testing

The Statistic of GEH is a technique employed in traffic engineering, traffic forecasting, and traffic modeling to assess and compare two sets of traffic volumes. The GEH formula is attributed to Geoffrey E. Havers (GEH), a transportation designer based in London, England, during the 1970s. The simulation and real-time volumes recorded are used to calculate the GEH Statistics [33]. Equation (3) explains the GEH formula.

$$GEH=\sqrt{(\ 〖2(m-c)〗\ ^{\wedge}2/(m+c))}\ \ldots\ldots(3)$$

Where m = output traffic volume from the simulation model (vph), c = input traffic volume (vph). Overall, a value below or equal to 5 can be regarded as good, indicating an adequate fit between the predicted outcomes and the actual traffic levels.

5.2 Calibration and validation Process

Calibration is the collection of real data and its input into a simulation program. The accuracy is verified by applying the GEH law, and the validity is verified by the results of the GEH law. If the result between the real data and the simulation data is less than 5, then the data cannot be used in the simulation program. If it is more than 5, then the data can be used in simulation software (AIMSUN next 24) and algorithms can be applied to it. Data (upstream, ramp and downstream) were collected from cameras placed along the highway from 12PM to 5 PM, 5 oct. 2025. The downstream begins with a flow of 4850 veh/hr at 12:00 and gradually increases until it reaches 5460 veh/hr at 14:10, It continues to increase until it reaches 5923veh/hr at 14:55 which represents (on-peak) time. Following this, it decreases to 5222 veh/hr at 15:00, then drops to 4582 veh/hr at 15:10, Additionally, continues to increase to 5400 veh/hr at 15:25. Then the flow drops to 4780 veh/hr in 15:45, falls gradually to 4315 veh/hr in 16:55, which represents (off-peak) time. Figure 3, 4 depicts the gather data of Al-Dorah highway. Figure 5 illustrates the extent of the consistency between the actual data and the simulation After inputting the real data into the AIMSUN simulation software, simulated data was obtained and, after verification using the GEH law, yielded a value of 0.01. This is a significant difference between the real and simulated data. The data can then be represented in simulation software.

6. Simulation without Ramp Metering

After data is entered into the program, important parameters (speed, occupancy, and flow), as the results before using RM. Figure 6 demonstrate the relationship between flow (occupancy and speed) for the three lanes. The values of (flow, occupancy) are as follows. The third lane (11%, 1620 veh/hr), the second lane (14.5%, 2050 veh/hr) and the first lane (20%, 2000 veh/hr). Congestion is reflected in the decrease in speeds in the third and second lanes. Figure 7 depicts the values of (flow, speed) for the third, second, and first are (1620 veh/hr, 98.2 km/hr), (2050 veh/hr, 97.9 km/hr), and (2000 veh/hr, 69.2 km/hr), respectively.

7. Simulation with RM

In this section, feedback is applied to the ALINEA algorithm which was improved by ramp metering. Cycling time is the number of seconds it takes to complete one cycle when the traffic light turns green. The green time is calculated for each site to achieve the best results.

7.1Green Time 10 for Entrance

A ramp metering was implemented on all lanes. Figure 8 shows the relationship between flow, occupancy, and speed for the three lanes. The values of (flow, occupancy) are as follows. The values for Lanes 3 and 2 are (10%, 1850 veh/hr) and (13.5%, 2120 veh/hr), respectively, while the value for Lane 1 is (18.2%, 2050 veh/hr). The flow has increased by 350 veh/hr. This is the best-case scenario. The flow increased by approximately 230 veh/hr for the third lane, 70 veh/hr for the second lane, and 50 veh/hr for the first lane. The flow value in all lanes has increased from 5670 veh/hr without metering to 6020 veh/hr with metering. Figure 9 depicts the relationship between flow and speed with ramp metering. This represents a significant improvement compared with the case without ramp metering, due to the increase in flow, and hence the discharge and capacity have increased. The values of (flow, speed) for the third, second, and first lanes are (1850 veh/hr, 1017.3 km/hr), (2120 veh/hr, 104.2 km/hr), and (2050 veh/hr, 75.2 km/h), respectively in reference to the 10-second cycle. Table 1 compares the parameter values (flow, occupancy, and speed) for the 40, 30, 20, and 10-green time metering cases to the case without metering. Table 2 improvement rate for all case.

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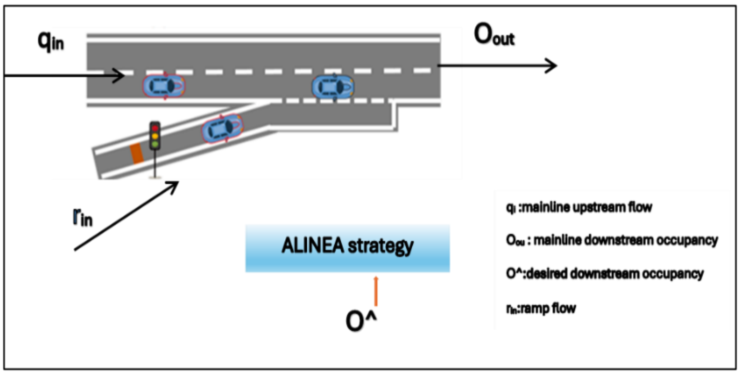

Figure 1. RM feedback strategies at the entrance of highway.

Figure 2. Al-Dorah highway.

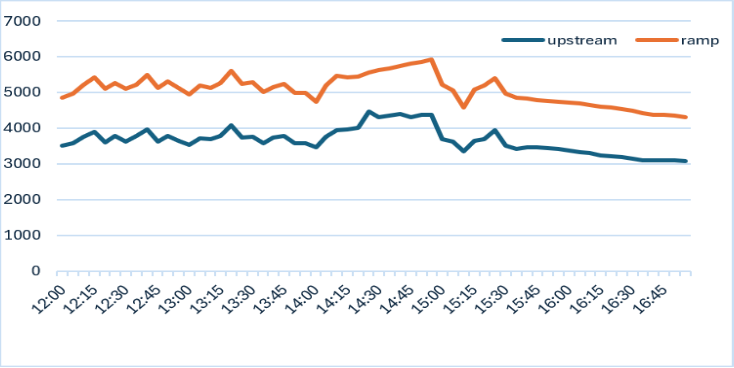

Figure 3. Data actual upstream and ramp

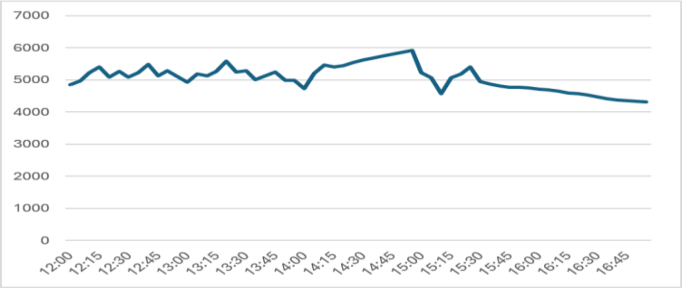

Figure 4. Data of actual downstream

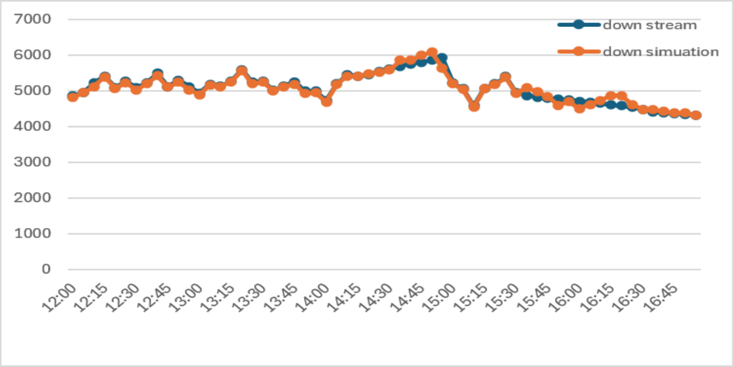

Figure 5. Data of actual downstream with simulation

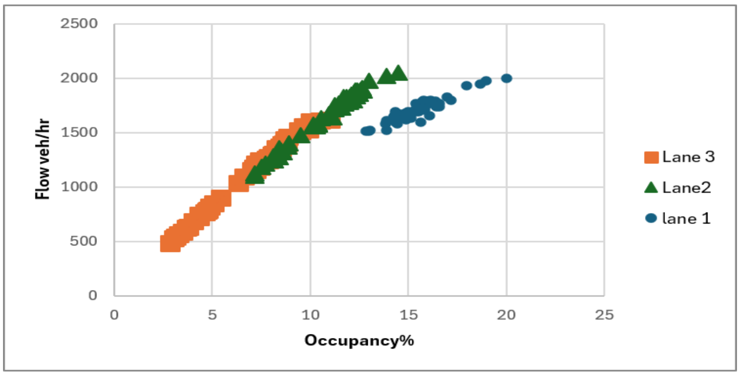

Figure 6. Flow against occupancy

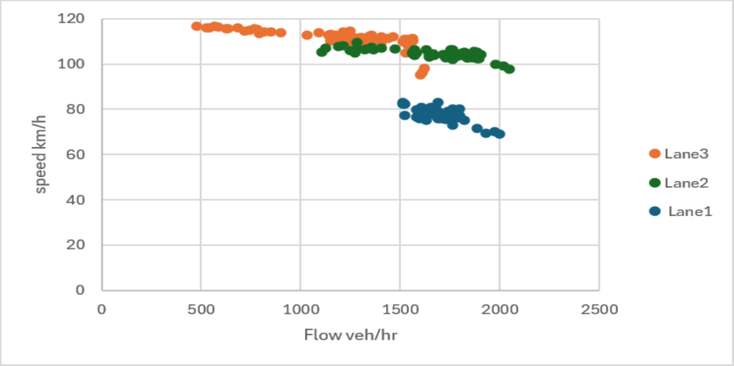

Figure 7. Flow against speed

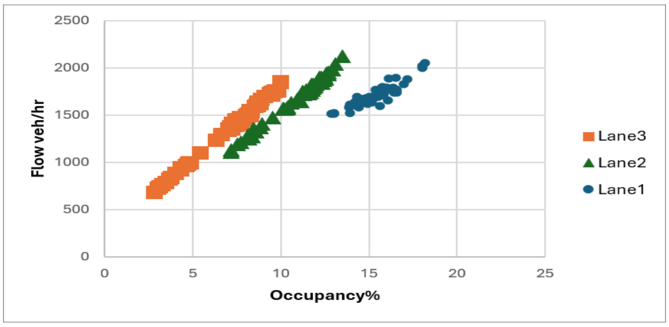

Figure 8. Flow against occupancy

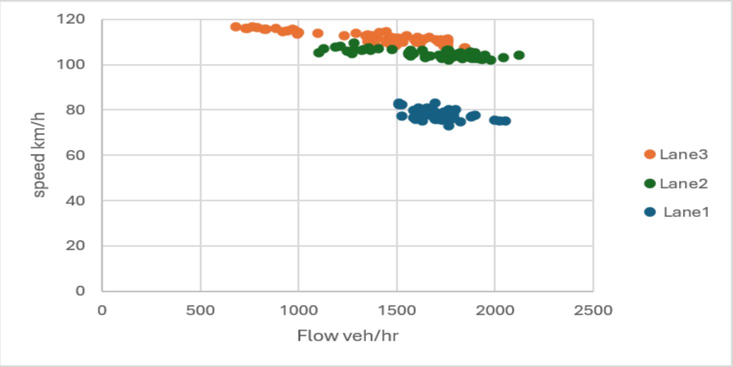

Figure 9: Flow against speed

Table 1: Comparing the Parameters for The Four Cases in the Green Time Scenario

Case	Lane	Occupancy, %	Flow, Veh/hr	Speed, km/h
Without metering	Lane3	11	1620	98.2
GT	Lane2	14.5	2050	97.9
	Lane1	20	2000	69.2
With metering	Lane3	10.8	1685	100.5
GT40	Lane2	14.2	2065	99.5
	Lane1	19.5	2010	71.1
With metering	Lane3	10.5	1785	103.2
GT30	Lane2	13.9	2095	102.1
	Lane1	19	2020	72.6
With metering	Lane3	10.5	1790	105.4
GT20	Lane2	13.7	2085	103.5
	Lane1	18.5	2015	73.9
With metering	Lane3	10	1850	107.3
GT10	Lane2	13.5	2120	104.2
	Lane1	18.2	2050	75.2

Table2: Improvement Rate

Case	Flow veh/hr	Improvement %
With metering GT40	1685	4.012345679
	2065	0.731707317
	2010	0.5
With metering GT30	1785	10.18518519
	2095	2.195121951
	2020	1
With metering GT20	1790	10.49382716
	2085	1.707317073
	2015	0.75
With metering GT10	1850	14.19753086
	2120	3.414634146
	2050	2.5

8. Results and discussion

Traffic flow parameters (volume, speed, and capacity) are among the most important elements in transportation engineering, representing the fundamental characteristics used to describe and analysed vehicle movement on roads. After applying the four scenarios to traffic management, the results were positive, with improvements in traffic flow, occupancy density, and speed. However, the fourth scenario, lasting 10 seconds, achieved particularly remarkable results in improving these parameters. Traffic volume increased by 110 vehicles/hour, speed increased in all three lanes, and capacity decreased. The improvement rate was 5.2% in the 40-second green light scenario, while traffic volume increased by 115 vehicles/hour in the 30-second green light scenario, with an improvement rate of 13.4%, The increase in traffic volume was 220 vehicles/hour for a 20-second green light, representing a 12.95% improvement. The fourth scenario, a10-second green light, saw an improvement of230 vehicles/hour, with a significant decrease in traffic density and a marked increase in speed compared to the previous scenarios, resulting in a 20% improvement.

9. Conclusions

Traffic congestion on the Al-Dorah Expressway is a significant problem requiring attention. Improving traffic flow using the ALINEA algorithm's feedback method, which relies on several parameters (flow, vehicle density, and speed) to measure congestion levels, has been facilitated using AIMSUN Next version 24 simulation software. This traffic flow control strategy at highway entrances significantly reduces congestion. Simulation results indicate that using traffic flow control at highway entrances with a fixed green light duration (10 seconds) resulted in an increase in flow of 230 veh/hr compared to other scenarios, improved traffic flow compared to the current situation, and a higher vehicle exit rate with less vehicle waiting time in the merging zone. The study found that a 10-second green light duration was the most effective among the tested scenarios, including 20, 30, and 40 seconds. This shorter duration was chosen because it reduces vehicle waiting time in the merging zone and increases exit rates. Consequently, the likelihood of congestion at highway entrances is very low. The results of this study demonstrate the potential of using feedback on vehicle flow at highway entrances as an effective traffic management strategy to reduce congestion and improve traffic flow on the highway loop.

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