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Comparison of Two Approaches for Preemptive Traffic Light Control

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***Abstract*—By implementing preemptive traffic light control systems in urban areas it is possible to reduce the travel time of specific groups of vehicles such as emergency vehicles. In this paper, two approaches for preemptive traffic light control are compared by applying a microscopic simulation model. The first approach uses fixed values of vehicle arrival time and queue lengths thresholds while the second is fuzzy logic based and hence more adaptive. Both approaches are tested in six different scenarios with an use case consisting of a simulated isolated intersection based on real traffic data. Analysis of the results shows that the travel time of emergency vehicles can be reduced by up to 24% in heavily congested conditions with a slight edge given to the fuzzy logic based approach. Both approaches show negligible negative effects on the total travel times of all vehicles in the network.**

***Keywords*— Intelligent transport systems; Preemptive traffic light control; Fuzzy logic; Microscopic traffic simulation; Urban intersections**

I. INTRODUCTION

One of the most applied traffic control methods in today's urban areas are traffic light control systems with one or more predetermined fixed signal programs. With the implementation of adaptive traffic light control systems, it is possible to modify the existing signal programs by changing the order of phases or by directly affecting a particular phase duration. In highly populated urban areas, traffic congestion can cause significant delays that are further increased by fixed signal programs that are unable to cope with the stochastic nature of traffic flows [1], [2]. Adaptive control systems can be implemented to reduce delay and increase intersection capacity. In addition, adaptive control can be also used for priority assignment of public transport and Emergency Vehicles (EV). Such a control approach is called preemptive traffic light control.

Priority assignment for public transport can be implemented using a passive or active approach, while EV priority also includes unconditional priority. Unconditional priority is generally rarely used because of its disruptive effect on the conflicting traffic flows. As for active approaches, the most commonly used is the green extension in which the duration of the green signal is extended to allow the EV to pass the intersection without stopping [3]. In order to keep the cycle duration constant, the conflicting phase duration is shortened by the same amount with regard to safety constraints such as predefined minimum green times [4]. Similar approaches for public transport preemptive traffic light control were used in [5–7]. Such approaches can also be used for EV priority assignment.

By giving priority to EVs, it is possible to minimize their delay and significantly reduce their travel times by up to 35% [8]. This is done by rescheduling the green phase time to the corresponding phase of the signal program on the EV approach. The drawback is the relatively high negative impact on the delay of other vehicles, mostly observed on the conflicting traffic flows. For this reason, algorithms for the return of rescheduled time should be activated after the preemption, such as the ones described in [9], and [10]. In addition, sufficient technical measures should be in place to inform the drivers on a particular intersection that preemption is in place to prevent a drop in intersection safety associated with variable green phase duration.

This paper is the result of the continuation of the work published in [9], [11], and [12]. The work published in the mentioned papers includes a MATLAB-VISSIM based simulation framework, several realistic traffic scenarios and an algorithm for preemptive traffic light control based on EV tracking and queue lengths including a normalized return of rescheduled green time. In this paper, two approaches for preemptive traffic control are compared using the same developed simulation framework. The first approach used is the preemptive control based on EV tracking and queue lengths as described in [9], while the second approach uses the same input values but combined with a fuzzy logic control algorithm.

This paper is organized as follows. The second section describes the chosen preemptive control approaches for comparison. In the third section, the used simulation framework is explained in general. The simulation setup, obtained results and a discussion about them are given in the fourth section. Conclusion and description of future work end the paper.

II. CHOSEN APPROACHES FOR COMPARISON

The main objective of the compared approaches for preemptive traffic light control is to reduce the travel time of EVs passing through an isolated signalized intersection. Both approaches are composed of two main parts. In the first part, preemptive traffic light control and assignment of priority are executed. Second part reduces the negative impacts caused by the first part by a periodic return of rescheduled time. The difference between these two compared approaches is the type of the used signal control. The first approach is based on fixed

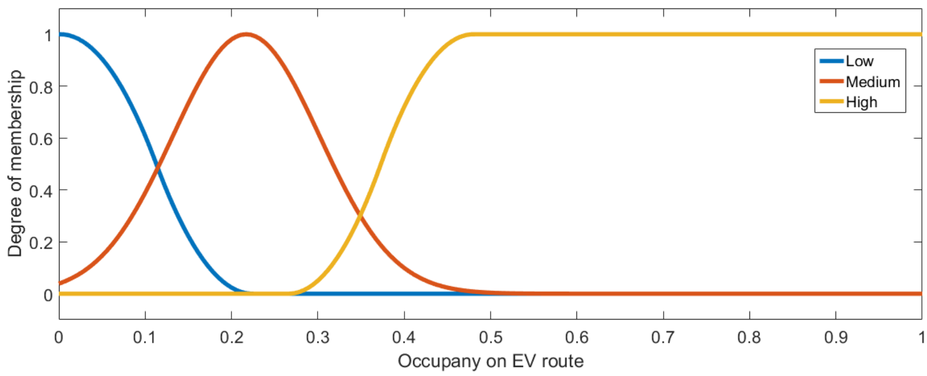

Figure 1. Fuzzy membership functions for occupancy on the EV approach

threshold values for EV arrival distance and queue lengths [9]. In the second approach for preemptive traffic light control fuzzy logic is used. The fuzzy logic approach also uses EV distance and queue lengths as input variables with the output being the percentage of the green phase extension. But, the output is being computed using appropriately defined fuzzy logic decision rules.

Another difference between the two approaches is that the first approach uses estimated arrival time of the EV as the main measured variable while the second one uses EV distance from the intersection. By using the estimated arrival time, it is easier to change the duration of the green phase according to the EV arrival. The drawback is that the computation is easily influenced by traffic congestion and fluctuations in EV velocity. When the distance is used as the main measured variable, the measurement is more accurate. The drawback is that it becomes more challenging to change the duration of the corresponding green phase.

A. Preemption based on vehicle tracking and queue lengths

The first approach for preemptive traffic light control operates in three distinct stages: (i) vehicle detection and tracking; (ii) reduction of congestion on the EV route based on queue lengths; and (iii) absolute priority [9]. In the first stage, the EV is detected and tracked through the traffic network. All relevant parameters (queue lengths, EV distance, and EV speed) are dynamically monitored and checked for engaging of the second stage which starts when EV arrival is estimated to be in less than four signal program cycles.

When the second stage starts, all queue lengths on the intersection are obtained first. In the case of a light congestion (short queues), the algorithm will dynamically increase the duration of the non-conflicting signal phase on the EV route in order to reduce congestion on the EV route. In cases of a heavier congestion, the duration of the conflicting signal phase will be decreased in addition to the increase of the duration of the non-conflicting phase. When EV arrival is estimated to be within one signal cycle the third stage will begin.

As soon as stage three begins, the algorithm will adapt the signal program to assign an absolute priority green light to the non-conflicting signal phase regarding the route of the approaching EV. This green light will stay active until the EV has passed the intersection. When the EV passes the controlled intersection, the algorithm for the return of rescheduled time will start.

B. Fuzzy logic based preemption

The basic idea of fuzzy logic control is to model the control law on the basis of human expertise and knowledge rather than on the basis of a precise modeling of the process itself [13]. Fuzzy controller observes the current condition of traffic and changes the phase duration based on actual conditions of queues on all intersection approaches.

The main difference in relation to the first approach is that the signal control problem is solved using fuzzy logic decision rules. In this control approach, there are no fixed parameters for extending the green phase on the EV route. The fuzzy logic approach gives a more adequate signal program depending on the measured traffic situation. Decision making in this fuzzy controller is based upon the multiple input single output theory. In the developed fuzzy controller there is a set of 81 rules implemented in the fuzzy inference system.

Mentioned fuzzy decision rules are taking the value of the distance of the EV from the controlled intersection, vehicle occupancy on the entire EV route before the intersection, and queue lengths on intersection approaches presented as vehicle occupancy in the road segment 100 m in front of the intersection. Each of these four inputs is represented with three Gaussian membership functions corresponding to human perceptive linguistic terms. For EV distance, terms are close, middle, and far away. For the rest three occupancy based inputs, terms are low, medium, and high as shown in Fig. 1. Membership functions are shown only for one input variable as an example because of the lack of space. Other input variables have similar membership functions. The output of this fuzzy system is the percentage extension of the green non-conflicting phase ranging from zero to twenty percent. When the EV is very close to the intersection, the absolute priority will be assigned until the EV exits the intersection followed

TABLE I. SELECTED FUZZY RULES USED IN FUZZY LOGIC PREEMPTION APPROACH

	EV distance		Queue EV approach		Queue secondary		Occupancy EV approach		Green Extension
IF	Close	AND	High	AND	Middle	AND	High	THEN	High
IF	Medium	AND	Middle	AND	Low	AND	Low	THEN	Medium
IF	Medium	AND	Middle	AND	High	AND	Low	THEN	Low
IF	Far away	AND	Low	AND	Middle	AND	Middle	THEN	Low
IF	Far away	AND	High	AND	Low	AND	Middle	THEN	Medium

by immediate activation of the algorithm for the return of rescheduled time same as in the first approach.

The fuzzy logic controller is designed with rule base using IF-AND-THEN conditions. Some of the rules are presented in table I while the rest follow a similar approach as explained in [14].

C. Return of rescheduled time

In both compared approaches it is necessary to return the traffic to the state before the algorithms for preemptive traffic light control were activated. This is achieved by the algorithm for the return of rescheduled time in order to alleviate possible congestion that was the result of the influence of preemption algorithms. In [9], it is shown that by returning the rescheduled time it is possible to further improve the EV travel time results mostly due to the alleviation of congestion before the EV return trip. Especially, if the EV uses the same route for its return trip. A similar algorithm was shown in [10] but without taking into consideration the ratio of durations of conflicting, and the non-conflicting phase. In this paper, the algorithm from [9] is used for the return of rescheduled time in both compared approaches.

III. VISSIM-MATLAB SIMULATION FRAMEWORK

In order to create an appropriate simulation network, the microscopic simulator PTV-VISSIM [15] was used in conjunction with the MATLAB software package [16]. VISSIM was used to simulate the intersection, and to simulate the behavior of all vehicles including the EV on the microscopic level in order to provide a realistic traffic model, as well as to simulate the GNSS data needed for EV tracking [17], [18]. Connected to VISSIM by a Component Object Model (COM) interface MATLAB is used for the implementation, and execution of control algorithms for both compared approaches for preemptive traffic light control. By using the COM interface, all relevant data can be exchanged between VISSIM, and MATLAB.

In order to enable an easier manipulation of signal programs, the National Electrical Manufacturers Associations (NEMA) ring structure is used as a template for the design of the signal program definition in MATLAB [19], [20]. Using the NEMA ring structure enables also an easier manipulation of signal programs related to signalized intersections in a larger urban traffic network with MATLAB [20].

In order to track the EV during simulation, EV position data were simulated in VISSIM. The EV position was calculated as the distance of the EV from the intersection using the sum of lengths of the respective road links on the EV route and the distance from the beginning of the road link where the EV is currently traveling. More details can be found in [9].

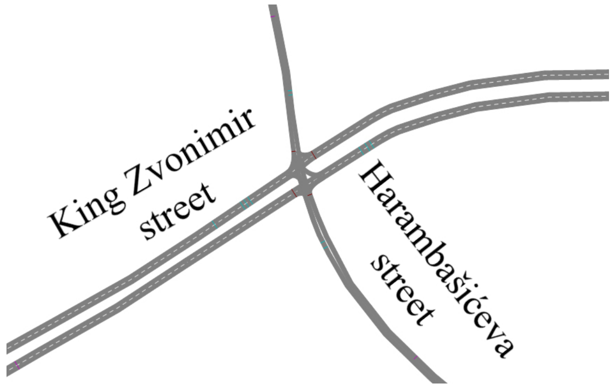

Figure 2. Configuration of the simulated intersection modelled in the microscopic traffic simulator PTV-VISSIM

IV. SIMULATION RESULTS AND EVALUATION

In this section, the results of both approaches will be analyzed in six different scenarios created in the simulation framework described above. The influence of both approaches on the simulated traffic situation is analyzed with respect to evaluation parameters related to the EV, and all other vehicles.

A. Simulation model

For the evaluation of both approaches, a simulation model of the intersection created in [9] was used with realistic traffic data from [7]. The chosen intersection is part of a green wave corridor in the city of Zagreb, Croatia. It is also prone to daily reoccurring congestion, and therefore suitable as a use case to test preemptive control. In this paper, the model is slightly changed in such a way that it no longer includes the public transport line, and the main approach is somewhat shorter to alleviate the simulation process as shown in the Fig. 2.

B. Traffic scenarios and traffic data

As mentioned, the comparison was done by using six different traffic scenarios. In the first, and second scenario, normal traffic conditions with the data obtained from [7] are simulated. The third, and fourth scenarios have an increased traffic demand (by 40%) to simulate congested traffic. In the fifth, and sixth scenario, the demand is further increased by 60% relative to the first two scenarios to simulate heavy congestion. Used traffic demand values are shown in Table II. Simulations with even higher traffic demand were attempted but such demand was far beyond the jam capacity of the

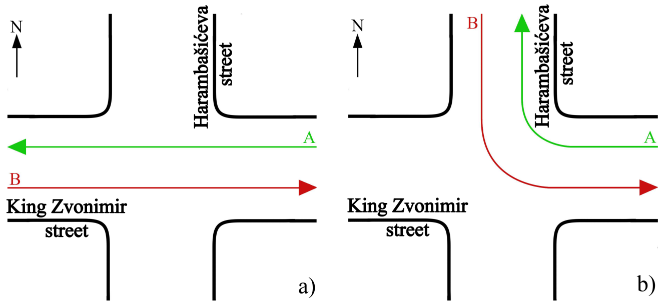

Figure 3. EV route for scenarios [9]: a) one, three, and five; and b) two, four, and six

simulated network and traffic control has no effect in such cases. It should also be noted that in odd-numbered scenarios the EV route is defined only along the main corridor, while in even numbered scenarios both the main and secondary corridors are used as shown in Fig. 3.

C. Obtained traffic parameters

Each scenario was simulated 10 times with randomized EV entry times. All simulations lasted 60 min, and there was a 15 min warm-up period during which no measurements were made. This warm-up period is used to fill the network with simulated vehicles, and to create a realistic traffic situation. The first EV was generated around the 30th simulation minute for route A, and for the return trip (route B) around the 45th simulation minute. EV entry times used the same stochastic seed regardless of the approach applied for preemptive traffic light control.

For each scenario, 10 different simulations were made for each control case (without the use of any preemption, with the use of fixed time preemption based on vehicle tracking and queue lengths, and with the fuzzy logic based preemption). For the comparative analysis the following Measures of Effectiveness (MoE) were obtained from each scenario: TT_{EV} as the Travel Time of EV; NS_{EV} as the Number of Stops of EV; LT_{EV} as the Lost Time of the EV; and TTT as the Total Travel Time of all vehicles.

D. Discussion

Results obtained for the first two non-congested scenarios are shown in Tables III and IV. Both approaches show a reduction of TT_{EV}, NS_{EV}, and LT_{EV}, with the fuzzy logic based approach showing slightly better results. The TTT barely increased due to preemptive traffic light control.

TABLE II. Traffic demand for each scenario

Scenario	Traffic demand [veh/h]			
	Harambašićeva Street		King Zvonimir Street	
	North	South	East	West
1	220	150	1100	720
2	220	150	1100	720
3	308	210	1540	1008
4	308	210	1540	1008
5	352	240	1760	1152
6	352	240	1760	1152

Tables V and VI show the results for congested scenarios three, and four. Reduction in TT_{EV} is greater than in the first two scenarios reaching a reduction of 12.98% with the use of the fuzzy logic based approach in the fourth scenario. NS_{EV} is also significantly reduced in scenario four but remains rather unchanged in scenario three. LT_{EV} shows a similar reduction as the first two scenarios. TTT is somewhat increased, most notably by 1.32% in the fourth scenario with the use of the fuzzy logic based approach. The only case with reduced TTT is scenario three when the fuzzy logic based approach is used.

Results for highly congested scenarios five, and six are shown in Tables VII and VIII. TT_{EV} is significantly reduced in scenario five regardless of the approach used while scenario six shows similar results as the previous scenarios. NS_{EV} is also significantly reduced in scenario five, and a bit less in scenario six. LT_{EV} is reduced in both scenarios with a higher reduction when the fuzzy logic based approach was used. TTT is reduced in all cases except in the scenario six when the fuzzy logic based approach is used. Higher reduction in TTT can be explained by the very high congestion on the main intersection approaches.

Average results for TT_{EV} across all scenarios are shown in Fig. 4. TT_{EV} is reduced in all scenarios with the fuzzy logic based approach producing better results for each scenario except scenario three. The maximal reduction in TT_{EV} is observed in scenario five with the fuzzy logic based approach where it reached a reduction of 24.75%.

Fig. 5 shows the average results for NS_{EV} across all scenarios. The results for the number of stops are similar to the results for the travel time of EV with the fuzzy logic based approach showing a larger reduction in all scenarios except scenario three. The largest reduction is achieved in scenario four with the fuzzy logic based approach, and a reduction of 5%.

Results for LT_{EV} across all scenarios are shown in Fig. 6. The fuzzy logic based approach shows better results in all scenarios except scenario three were it is tied with the fixed approach. The maximal reduction was achieved in scenario two with the fuzzy logic based approach reaching a reduction of 4%.

Fig. 7 shows the average results for TTT of all vehicles across all scenarios. In all scenarios, and approaches, TTT has not significantly changed. The largest increase of 1.32% is in scenario four with the use of the fuzzy logic based approach. Some minimal improvement of 0.14% is achieved in scenario five when the fuzzy logic based approach was used. Therefore, it can be concluded that the analyzed approaches for preemptive traffic light control have a minimal influence on the other vehicles.

V. Conclusion and Future Work

In this paper, two approaches for preemptive traffic light control were analyzed, and compared. The goal of both ap-

TABLE III. AVERAGE VALUES OBTAINED FOR SCENARIO 1

MoE	Scenario 1				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	196	180	-8.16	177	-9.69
NS_{EV}	1.5	0.7	-53.33	0.6	-60
LT_{EV} [s]	43	26	-39.53	24	-44.19
TTT [h]	57.70	57.76	0.10	57.71	0.02

TABLE IV. AVERAGE VALUES OBTAINED FOR SCENARIO 2

MoE	Scenario 2				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	208	188	-9.62	181	-12.98
NS_{EV}	1.6	0.9	-43.75	0.8	-50
LT_{EV} [s]	50	30	-40	23	-54
TTT [h]	57.71	57.77	0.1	57.79	0.14

TABLE V. AVERAGE VALUES OBTAINED FOR SCENARIO 3

MoE	Scenario 3				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	215	192	-10.7	193	-10.23
NS_{EV}	1.4	1.1	-21.43	1.4	0
LT_{EV} [s]	62	39	-37.1	39	-37.1
TTT [h]	89.44	89.59	0.17	89.4	-0.04

TABLE VI. AVERAGE VALUES OBTAINED FOR SCENARIO 4

MoE	Scenario 4				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	213	189	-10.39	184	-13.62
NS_{EV}	2	0.7	-65	0.5	-75
LT_{EV} [s]	54	30	-44.44	25	-53.7
TTT [h]	88.79	89.03	0.27	89.96	1.32

TABLE VII. AVERAGE VALUES OBTAINED FOR SCENARIO 5

MoE	Scenario 5				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	303	235	-22.44	228	-24.75
NS_{EV}	4.9	2.8	-42.86	2	-59.18
LT_{EV} [s]	151	81	-46.36	75	-50.33
TTT [h]	123.43	123.21	-0.18	123.26	-0.14

TABLE VIII. AVERAGE VALUES OBTAINED FOR SCENARIO 6

MoE	Scenario 6				
	No preemption	Fixed preemption		Fuzzy preemption	
		Value	Change [%]	Value	Change [%]
TT_{EV} [s]	210	192	-8.57	185	-11.9
NS_{EV}	1.2	0.9	-25	0.8	-33.33
LT_{EV} [s]	52	33	-36.54	26	-50
TTT [h]	123.07	122.91	-0.13	123.17	0.08

proaches is to reduce the travel time of EVs. The first approach uses fixed vehicle arrival threshold values while the second is fuzzy logic based. Both approaches incorporate an algorithm for the return of the rescheduled time in order to minimize the negative impact of preemptive traffic light control on other vehicles.

In order to evaluate each approach, an isolated intersection on a green-wave corridor in Zagreb was simulated using a VISSIM-MATLAB based simulation framework, and realistic traffic data in six different scenarios. The results show that both approaches can significantly reduce the travel time of EV with the best result being a reduction of around 25%. The influence on other vehicles was up to 1% which is very small when compared to the reduction of EV travel time. When compared, the results are slightly better when the fuzzy logic based approach is used.

Further work on this topic will include preemptive traffic light control on intersections with signal programs containing more than two phases. Algorithms will be developed to work in a coordinated network of intersections. Furthermore, the application of the genetic algorithm will be explored in order to optimize the parameters of the fuzzy logic decision rules.

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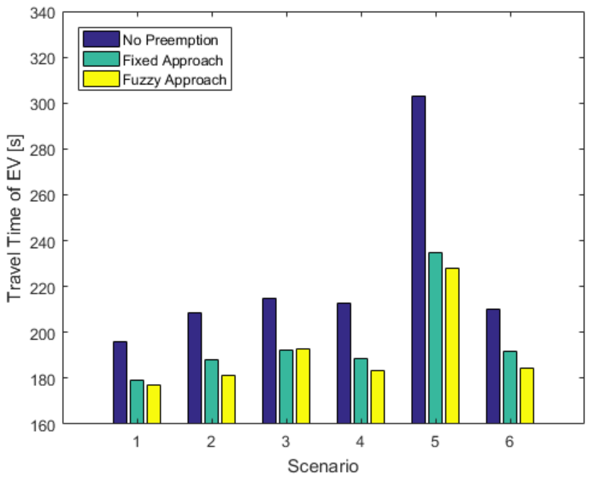

Figure 4. Average EV travel times across all scenarios

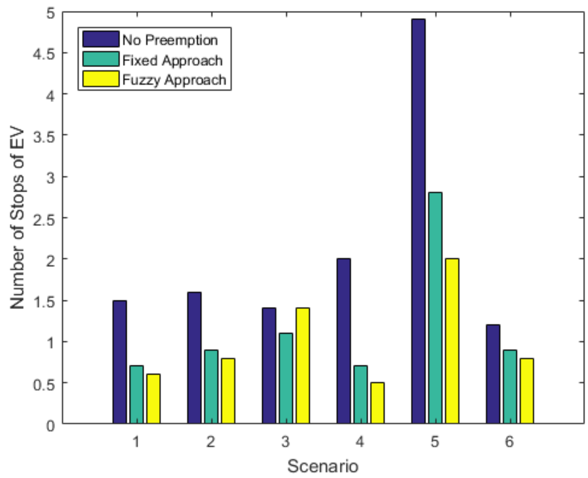

Figure 5. Average number of stops of EV across all scenarios

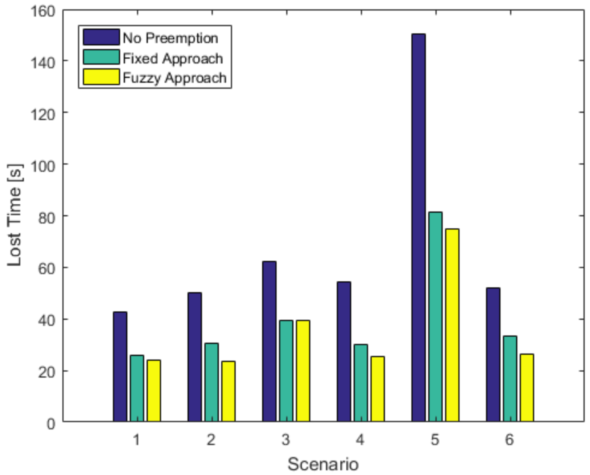

Figure 6. Average lost time of EV across all scenarios

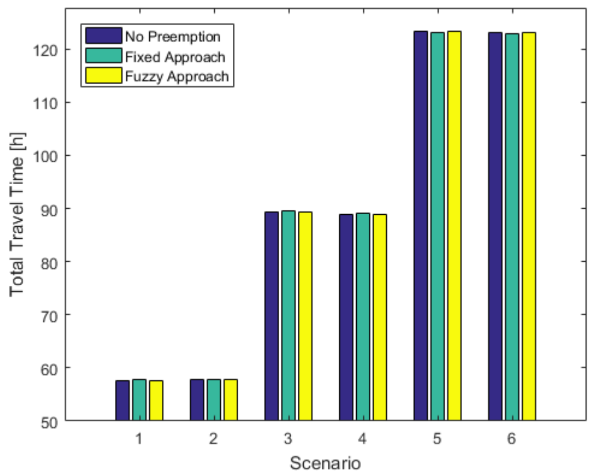

Figure 7. Average total travel times of all vehicles across all scenarios

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