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TRADER:Traffic Light Phases Aware Driving for Reduced Traffic Congestion in Smart Cities

Cullen Rhodes and Soufiene Djahel
School of Computing, Mathematics and Digital Technologies, Manchester Metropolitan University, UK
{cullen.rhodes@stu.mmu.ac.uk, s.djahel@mmu.ac.uk}

***Abstract*—Despite the significant research efforts and resources spent to alleviate the impact of road traffic congestion on economy, environment and road safety, it is still one of the major unsolved problems of the 21st century. The emergence of smart self-driving vehicles promises a dramatic change in the way road traffic congestion is controlled and mitigated. This can be achieved by enabling efficient communication between these vehicles and modern road infrastructure such as smart traffic lights controllers. This paper, therefore, proposes a simple yet efficient mechanism named (TRADER: TRaffic Light Phases Aware Driving for REduced tRaffic Congestion) in order to reduce the overall vehicles' travel time in smart cities. TRADER has been implemented and extensively evaluated under several scenarios using SUMO and TraCI. The obtained simulation results, using a set of typical road networks, have demonstrated the effectiveness of TRADER in terms of the significant reduction of travel time, up to 31.44% in a random road network topology.**

***Keywords* – Smart Transportation, Smart Cities, Road Traffic Congestion, SUMO, TraCI.**

I. Introduction

Road traffic congestion is a major problem faced by many cities that occurs when the traffic demand approaches or exceeds the available capacity of the road network. Congestion is distinguished by two types, recurrent and non-recurrent. Recurrent congestion occurs when there are more vehicles than available road space. This form of congestion is typically found in urban cities at peak times such as 9am and 5pm throughout the week. Non-recurrent congestion is caused by temporary disruptions such as road works and traffic accidents.

The impact of road traffic congestion on the economy is significant. A report from the Texas Transportation Institute estimated that, in 2014, the economic loss caused by road traffic congestion in terms of extra travel delay and fuel consumption was $160 billion [1]. During this period, Americans travelled an extra 6.9 billion hours and purchased an additional 3.1 billion gallons of fuel because of traffic congestion. A study conducted in the United Kingdom by INRIX, a leading provider of real-time traffic information and transportation analytics, estimates that the annual cost of congestion will be £21.4 billion by 2030. This study found that between 2013 and 2030, the total cumulative cost of congestion to the UK economy is estimated to be £307 billion [2]. It is clear from the above data that advanced technical solutions to road traffic congestion problem are becoming increasingly important. Attempts at mitigating the environmental effects of road traffic congestion can already be seen. The development of systems such as start-stop [3] are one example of this. The aim of start-stop is to reduce fuel consumption and emissions by disabling the internal combustion engine when a vehicle comes to a stop.

The advent of mobile phones has also led to the development of solutions aiming to alleviate the effects of road traffic congestion. A notable example of this is Google Maps service which provides navigation through a mobile application available on most platforms. Real-time traffic data provided by Google Traffic is used in the route planner to navigate users around congested areas to reduce their journey time. This is achieved by analysing the locations transmitted to Google by a large number of mobile devices using GPS technology. Traffic and incident data, such as accident reports, are incorporated into Google Maps from another popular GPS mapping application called Waze. Waze relies on its users to report incidents such as traffic jams and accidents. This crowd-sourcing of traffic data has proven useful in helping users overcome some of the problems traffic congestion creates. Community-based traffic applications such as Waze can also have a positive effect on the environment by reducing journey times and thus reducing fuel consumption. Applications such as Google Maps are undoubtedly useful tools that can help reduce road traffic congestion, however they are used by a limited subset of road network users. Furthermore, they do not integrate with the infrastructure in any meaningful manner. To reduce road traffic congestion more advanced traffic monitoring and control tools need to be developed and implemented [4].

The aim of this paper is to investigate the efficiency of V2X communication technologies in reducing travel time in smart cities. Specifically, we aim to develop a solution using Vehicle to Infrastructure (V2I), a practical technology leveraging the existing road-side infrastructure, and Vehicle to Vehicle (V2V) communication technologies. To achieve this, a simple yet efficient solution dubbed (**TRADER**: **TR**affic Light Phases **A**ware **D**riving for **RE**duced t**R**affic Congestion) is designed and implemented in SUMO and TraCI. The ultimate goal is to improve commuters' journey time by having traffic light controllers communicate the remaining time for the green traffic light phase to the approaching vehicles. Using this information, vehicles will be able to determine an optimal speed that will allow them to pass the traffic light before it turns red, thus minimizing the number of stoppages and reducing their travel time. Compared to the work presented in [5], TRADER is a simpler solution with much lower communication overhead.

The remainder of this paper is organized as follows. In Section II, we present the literature followed by a description of our proposed system in Section III. Section IVpresents the detailed implementation of TRADER, its evaluation metrics and scenarios and provides critical analysis of the obtained simulation results. Section V concludes the paper and presents some directions for its improvement.

II. Related Work

In this section, a few significant works proposed in the literature to deal with the road traffic congestion problem will be discussed.

The authors of [6] studied the consequences of road traffic congestion on the emergency services and proposed solutions that would enable them to continue being effective in growing cities. Human lives depend on the efficient and timely response of emergency services such as ambulances, fire and rescue operations, and police intervention. Another concern is accidents involving emergency vehicles, according to statistics cited in this paper, crashes involving emergency vehicles using signals such as sirens led to 60 deaths and 918 total injuries in the USA in 2009. To mitigate these issues they proposed a new framework that involves adaptive Traffic Management Systems (TMS) communicating with the appropriate authorities, roadside infrastructure, and vehicles. Emergency response vehicles would be safely routed to incidents as traffic lights dynamically adjust and citizens on the road network are notified about incidents such that they can adjust their behaviour accordingly. The system proposed in this paper could be effective in assisting emergency response services, however it is only a proposal and the authors have not conducted experiments to test its effectiveness.

The study conducted in [7] looked at the Red Light Running phenomenon (RLR), which can cause fatal accidents, and proposed a dynamic TMS based on WSNs (Wireless Sensor Networks) technology to reduce vehicles' waiting times at intersections, and as a consequence reduce the occurrence of this phenomenon. A major goal of smart transportation is to reduce the number of accidents occurring on road networks, however the majority of traffic lights in use today operate in fixed cycles or are manually controlled by a human operator who has the potential to make mistakes. The authors present a system that dynamically manages traffic light cycles using data obtained from a WSN deployed at a traffic light junction. By evaluating real time traffic flows the traffic light cycle can be dynamically adjusted based on the queue length. The road with the longest queue length would be assigned a greater green time, allowing more vehicles to pass the signal. As a result, overall waiting times are reduced and the occurrence of the RLR phenomenon is decreased. The performance of the proposed solution was evaluated by simulating a 4 way junction in Enna, Italy, using both fixed and dynamic traffic light cycles. The obtained results show that this solution has the potential to reduce the occurrence of the RLR phenomenon in certain scenarios. However, it is difficult to advocate the proposed system because the authors did not conduct a thorough analysis of the system with varying scenarios. Moreover, it is possible that dynamically adjusting the traffic light cycle will worsen the average waiting time and only be beneficial to a subset of road users.

Today's road users are becoming more reliant on driver assistance systems (DAS) to increase their safety on the road. DASs incorporate a variety of tools to assist in tasks such as automatic parking, traffic sign recognition, and collision detection. In [8], the authors discussed the benefits of context-awareness and collaborative approaches in DASs. The current approaches involving tasks like traffic sign recognition are specialised and do not represent a general context awareness. The context for a DAS is defined as several sub-contexts, this includes the environment in which the vehicle is operating, the driver, the vehicle, and the national traffic regulations. This paper successfully highlights the importance of context-awareness and collaboration in developing intelligent DASs. Nevertheless, we believe it is difficult to make a conclusion given the lack of data supporting their ideas. Furthermore, the economic implications of implementing such systems are unclear, equipping vehicles with such technology may be cost prohibitive. Therefore, a more cost-effective solution will be proposed in the rest of this paper.

The EU-funded Compass4D project [13], [14] proposed the so-called Energy Efficient Intersection service in order to optimise the way vehicles cross an intersection. It aims to reduce energy consumptions and emissions by avoiding any unnecessary acceleration or braking by the drivers. Compared to Compass4D, TRADER focuses on self-driving cars only and aims to optimize the throughput at every intersection through inter-vehicle coordination using V2V technology. This is achieved by the altruistic operation mode in which every vehicle tries to help the vehicle(s) behind it as well, as opposed to Compass4D where the aim is to adapt the driving behavior of every driver according to the information received form the TLC, to cross the intersection without stopping, whenever possible.

III. TRADER design overview

This Section presents the key principle of our proposed solution (**TRADER**: **TR**affic Light Phases **A**ware **D**riving for **RE**duced t**R**affic Congestion) and illustrates its expected impact through a realistic scenario.

The solution we propose in this paper to reduce traffic congestion consists in leveraging V2X communication technology to allow smart traffic light controllers to regularly communicate traffic signal phase information to approaching smart cars in order to prevent the delay induced by cars stopping at intersections waiting for the next green phase.

In this work, we assume that the road infrastructure is dotted with next generation TLCs (Traffic Light Controllers), deployed at intersections, capable of regularly communicating the remaining time of the green phase to incoming vehicles on the road segments that they control. Such TLCs could be equipped with IEEE802.11p wireless cards similar to those used by smart cars. We assume also that all vehicles regularly (at least 10 times per second [10]) generate IEEE802.11p beacons to ensure high awareness level among them. TLC beacons, however, are transmitted during regular intervals as defined in the following equation:

$$TLC_{BI} = \frac{(\frac{RS_{length}}{Speed_{limit}})}{R} \tag{1}$$

where TLC_{BI} is the TLC beacon transmission interval, RS_{length} refers to road segment length and $Speed_{limit}$ denotes the maximum allowed speed on this road segment. R (i.e. rate) is an integer value that represents the minimum number of times the TLC beacon is broadcasted while a car moving at the maximum allowed speed is crossing this road segment. This interval is well tuned and adapted to the characteristics of road segments controlled by the TLC in terms of their length and average speed of vehicles. This ensures that each vehicle will receive a TLC beacon at least R times before it reaches the intersection. R should be set to a value greater than 1 in order to account for the potential collisions due to beacons congestion if a single radio transceiver is used by the vehicles. In case of multi-radio transceivers, the TLC beacon can be transmitted on a service channel (SCH) instead of the control channel (CCH) to prevent the collision with regular beacons sent by the vehicles.

In the implementation of TRADER, a beacon will be emitted from the TLC to the approaching vehicles at regular intervals, containing the remaining time for the current traffic light cycle. Subsequently, the receiver vehicles will use this information to calculate the optimal speed which allows them to cross the intersection without stopping. There are four scenarios for a given vehicle:

1) It cannot transit the traffic light without exceeding the speed limit.
2) It can maintain its current speed and transit the traffic light.
3) It can increase its speed whilst remaining within the speed limit and transit the traffic light.
4) It can increase its speed to assist preceding vehicles in transiting the traffic light.

Each of these cases will be considered in TRADER. The flow diagram in Figure 1 illustrates the process from the perspective of an individual vehicle. According to a recent article published in theguardian [12] on January 2017, Tesla Motors owners will be able to break the speed limit by up to five miles per hour on non-divided roads. Therefore, for Tesla cars the speed limit is always increased by 5 miles when using TRADER to select the best actions to take at intersections.

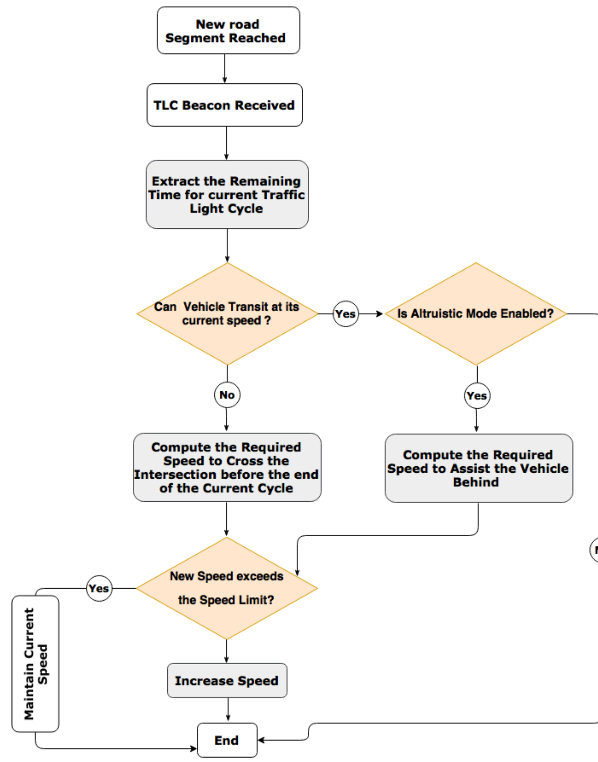

Figure 1: Flow diagram describing TRADER algorithm

A. *TRADER: operating modes*

TRADER can run under two different operating modes: selfish and altruistic. Selfish mode in which every vehicle exploits the information received from the TLC to serve its own needs only (i.e., to avoid stopping at the intersection whenever possible), which reflects to some extent the real behaviour of most of drivers on the road. The second mode, however, reflects a typical behaviour of autonomous vehicles which tend to cooperate to achieve a global objective, which is in this context a reduction of the average travel time, rather than an individual benefit. Since TRADER is mainly designed to serve autonomous vehicles then its default operation mode will be set to altruistic.

B. *TRADER: illustrative scenario*

To highlight the importance of TRADER let us consider the scenario shown in Figure 2 which depicts how traffic conditions evolve on two multi-lane road segments controlled by traffic lights during the last 30 seconds of a traffic cycle (the first traffic light is green while the second one is red). In this scenario TRADER is disabled and therefore we can see that when the traffic light controlling the second junction switches into green (and the first one controlling the first junction into red) the capacity of road segment 2 is not fully used, meaning that some vehicles stopped at junction 1 will experience longer delay in their journey due to the extra waiting time. In contrast, as shown in Figure 3, by enabling TRADER vehicles on road segment 1 will become aware of the remaining time in the green cycle and perform the actions highlighted in Figure 1 to cross the junction before the expiration of the 30 seconds, whenever possible, leading to a better usage of the road infrastructure capacity and lowering their journey time. Of course, the gain in delay strongly depend on the number of junctions on the vehicle route as well as the length of the road segments.

IV. Performance Evaluation

In this Section we will present in detail the implementation of TRADER in SUMO and TraCI, along with the simulation results obtained.

A. TRADER Architecture

The system architecture for TRADER is described in Figure 4, which highlights the exchange between the Python client utilising TraCI and the SUMO traffic simulator as a timeline diagram.

The diagram shows the exchange of several TraCI messages that interact and retrieve information from the simulator, this is indicative of what the architecture will look like in the implementation.

B. Evaluation Scenarios and Metrics

The metrics used to evaluate the performance of TRADER are Average Travel Time (ATT) and Travel Time Index (TTI). The ATT is the mean travel time of all vehicle trips, it is a useful metric for determining the overall status of the road network [9]. The travel time (TT) is the time taken for a vehicle to complete the route. ATT is calculated as described in Eq. 2, where *n* is the total number of vehicles and *TT* is the travel time.

$$TT_{\text{average}} = \sum_{i=1}^{n} TTi \tag{2}$$

TTI is the ratio of the TT during peak hours compared to the free flow TT [11]. Free flow TT is the time needed for vehicle to traverse a road during ideal conditions, i.e. at the maximum permitted speed with no traffic. TTI is sometimes referred to as the congestion index [9] as it is a useful metric for measuring congestion levels in a given road network, it is calculated as described in equations 3 and 4.

$$TT_{\text{freeflow}} = TT_{\text{average}} - timeloss \tag{3}$$

$$TTI = \frac{TT_{\text{average}}}{TT_{\text{freeflow}}} >= 1 \tag{4}$$

where $timeloss$ refers to the time lost due to driving below the ideal speed.

Before the performance could be evaluated, a baseline was generated containing statistics for the simulation without the algorithm. All simulations were run three times with a different random seed to get statistically meaningful results that are reproducible.

*1) **Pedestrian Crossing scenario**:* Pedestrian Crossing scenario is an example available in SUMO package which contains a dual carriageway running from east to west with a pedestrian crossing intersecting the centre from north to south.The results obtained for this scenario are summarised in Table I with the discussed metrics. The improvement is not significant for this scenario, although the algorithm is having an effect.

ATT % Improvement	TTI % Improvement
3.39%	3.66%

Table I: TRADER performance for pedestrian crossing scenario

The results plotted in Figures 5 and 6 reveal that TARDER didn't achieve significant improvement in this scenario since the incoming road segments are only 100m leaving little time for improvement. Furthermore, the trips generated by the flow are simplistic, each vehicle has a depart speed of zero, contributing to the issue of the algorithm having little time to respond. It could be worth investigating the performance for this scenario with trips generated by the Random Trips, however given the simplicity of the scenario it is unlikely this would yield much better results. Therefore, TRADER's performance will be evaluated by testing two further scenarios.

*2) **8x8 Grid Network scenario**:* Now, the performance of TRADER will be evaluated using an 8x8 grid network. Grid topologies are commonly found in metropolitan areas, most notably New York city. Recall that the grid number specifies the number of junctions in both directions, for an 8x8 grid the value for this parameter is 8. The trip data was generated by Random Trips and several simulations were run with varying traffic density. Each simulation was run 3 times with a different seed for SUMO and Random Trips. The vehicle density does not increase in regular intervals, as a subset of the trips generated by Random Trips are not valid and are removed with the validate parameter. For the first simulation 1000 vehicles was specified but only 790 of the trips were valid and the others were removed.

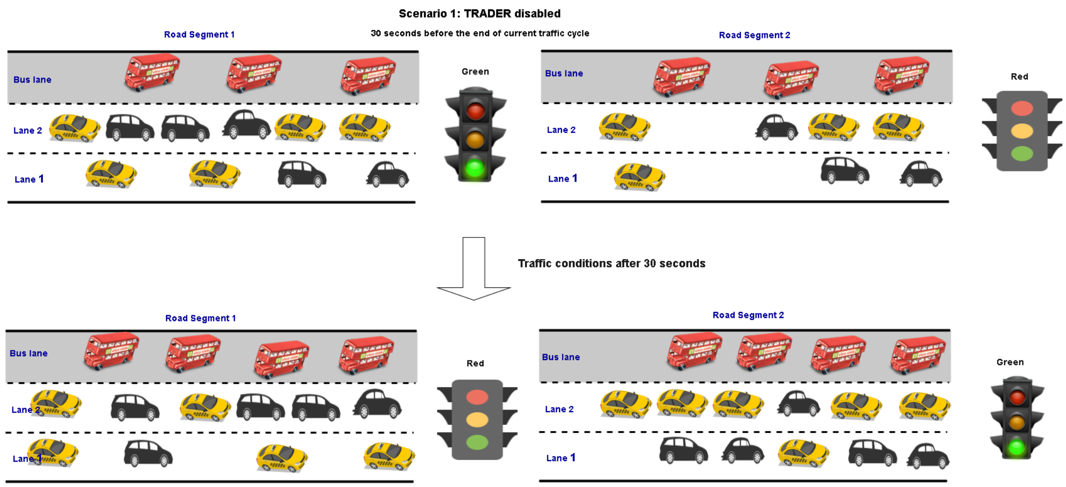

Figure 2: Example showing how traffic conditions evolve when TRADER is not used

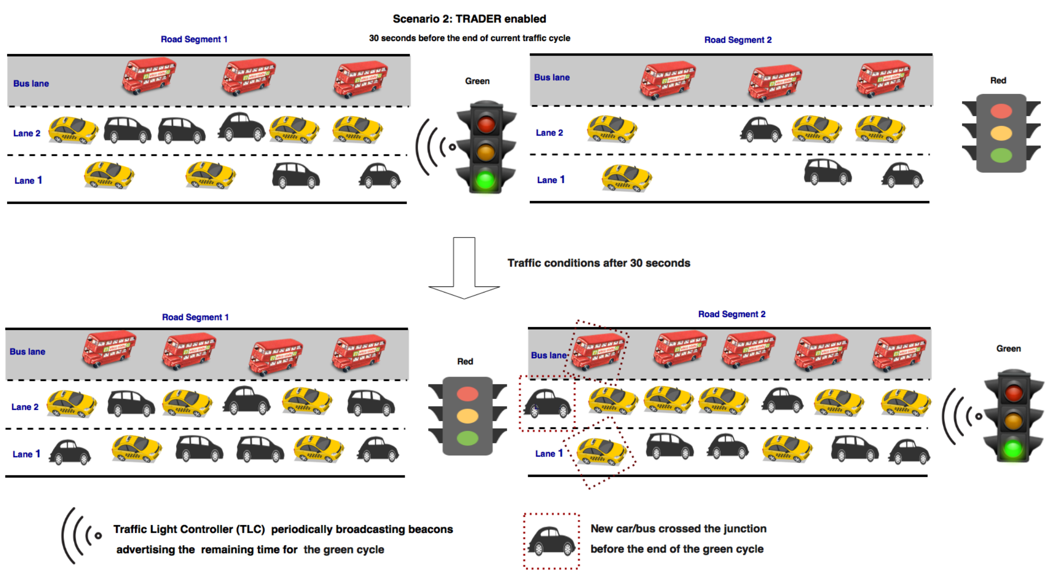

Figure 3: Example showing how traffic conditions evolve when TRADER is enabled

Table I presents a summary of the results obtained, and Figure 7 contains a bar chart visualising the percentage improvement for ATT. The TTI bar chart is identical and has therefore been left out.

# Vehicles	ATT % Improvement	TTI % Improvement
790	2.65%	2.62%
1547	3.59%	3.56%
3866	5.63%	5.62%
7766	**7.42**%	**7.42**%
11640	6.48%	6.47%

Table II: Summary of performance for 8x8 grid network

The ATT and TTI improve as the density increases from 790 to 7766 vehicles, but decline slightly with 11640 vehicles. The greatest improvement observed was a 7.42% increase over the baseline. A logical assumption as to why the performance is better with greater traffic density is the cooperation occurring between smart cars in the simulation. The opportunity to assist preceding vehicles increases with the number of vehicles in the network, although the positive effect of this will decline if the traffic density is too high and gridlocks occur, at which point TRADER will have negligible impact.

The histogram in Figure 8 comparing the trip duration of the baseline against TRADER for the simulation with 7766 vehicles is a useful depiction of our solution impact. This graph shows that the frequency of the longer trips (> 360 seconds) is reduced by TRADER and the number of short trips is increased.

3) ***Random Abstract Road Network scenario:*** In this section the performance of TRADER is evaluated using an abstract

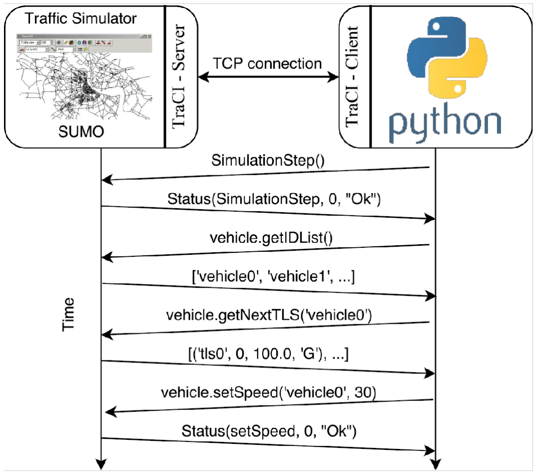

Figure 4: Timeline diagram describing TRADER implementation architecture

random network generated by NETGENERATE. The aim is to investigate the performance of TRADER in road networks that have not been designed from the ground such as in New York city. Rather, this should provide an insight into how TRADER will perform in cities such as Manchester in England or Los Angeles in the United States. Figure 9 is a screenshot of the network used for this evaluation.

Vehicle trips were generated by Random Trips and each simulation was run 3 times with a different random seed for SUMO and Random Trips as with the previous scenario. Traffic density was also varied to understand how TRADER performs under different circumstances such as rush hour where higher traffic density is expected.

The results for this scenario are summarised in Table III.

# Vehicles	ATT % Improvement	TTI % Improvement
479	1.08%	1.07%
967	1.69%	1.68%
1933	1.59%	1.57%
3463	**22.43%**	**21.80%**
4803	**31.44%**	**25.49%**

Table III: Summary of performance for random abstract network

As Figure 10 highlights, the improvement with TRADER is negligible for this scenario with lower traffic density from 0-2000 vehicles, however the improvement is significant around 3500 vehicles, where a 22.43% increase over the baseline was observed for the ATT. A notable increase of 21.80% for the TTI was also achieved, indicating that TRADER improved vehicular flow in higher density traffic.

The improvement was greater with around 5000 vehicles in the simulation, which is not too many as to cause a jam but still a significant amount of load. For a network of this size serious congestion would occur at approximately double this number of vehicles, at which point TRADER will have a limited effect.

Figure 11 shows the distribution of the trip duration for the simulation containing 4803 vehicles. The graph shows that TRADER reduced the occurrence of long trips observed in the baseline. The highest trip duration for the baseline was 93 minutes (5603s), compared to 67 minutes (4051s) with TRADER.

C. Summary

This section will serve as a summary of the results obtained for the scenarios that were used to evaluate the performance of TRADER.

In total, a deep analysis was conducted across three scenarios with different characteristics, which provided insight into the suitability of this solution for disperse geographical locations which realise these varying characteristics. Table IV provides a summary of the best results observed in each scenario.

Scenario	ATT % Improvement	TTI % Improvement
Pedestrian Crossing	3.39%	3.66%
8x8 Grid Network	7.42%	7.42%
Random Abstract Network	**31.44%**	**25.49%**

Table IV: Summary of best observed results

For all simulations, TRADER yielded an improvement over the baseline in the metrics used for evaluation. Only a minor improvement was achieved for the pedestrian crossing scenario, as the simulation was simple, containing a dual-carriageway and a single traffic light.

The performance achieved for the random abstract network simulation compared to the pedestrian crossing and grid network scenarios was significant, there are two reasons for this. Firstly, the traffic light density was greater in the abstract network, in total there were 64 traffic lights over 43.91km of road, compared to 60 traffic lights over 52.41km in the 8x8 grid network. Therefore, the traffic light density was 0.31 per km^2 in the abstract network and 0.26 per km^2 in the 8x8 grid network. We can conclude from this that TRADER performs better in higher density traffic light scenarios because the opportunity for improvement is greater.

A further distinction in the abstract network is road length. In grid networks each road has near or the same length, whereas in the random networks the distribution is greater, this is illustrated in Figure 12. TRADER performs better on shorter road segments, which seems counter-intuitive considering the TLC has less time to communicate with approaching vehicles. A logical explanation for this is vehicles on the longer road segments do not have sufficient time to transit in the remaining time communicated because the distance is too large. However,

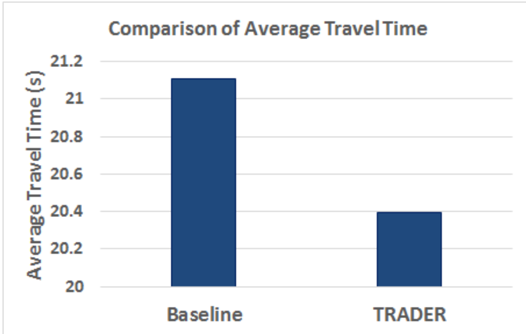

Figure 5: Pedestrian crossing scenario: Average Travel Time

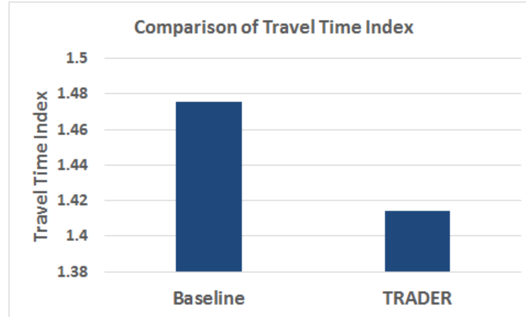

Figure 6: Pedestrian crossing scenario: Travel Time Index

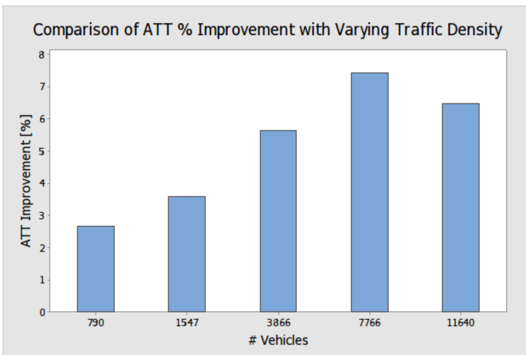

Figure 7: Percent improvement in Average Travel Time with varying traffic density

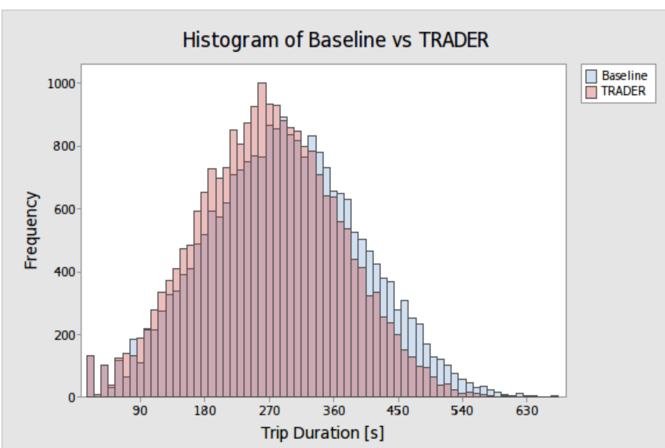

Figure 8: Histogram comparing trip duration (# vehicles=7766)

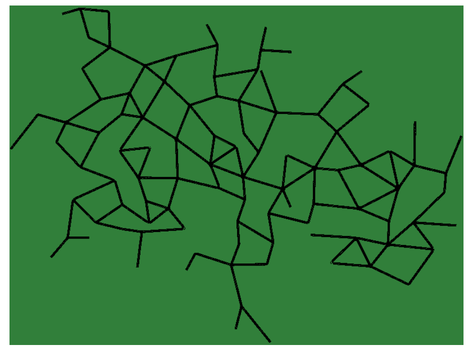

Figure 9: Random network generated by NETGENERATE

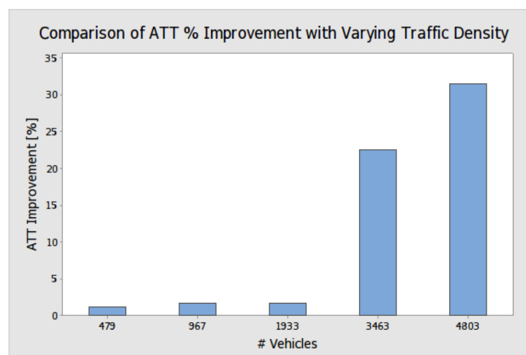

Figure 10: Percent improvement in Average Travel Time with varying traffic density

this cannot be verified without performing additional simulations on grid networks with shorter road segments.

V. CONCLUSION

Road traffic congestion is one of the great unsolved problems we face in the 21st century. Significant research is being conducted by institutes around the globe to reduce the cost and burden of this issue. It is difficult to envision at what point major breakthroughs will occur or what they shall look like, but one thing that is clear is there will be no single solution. This paper investigated the potential of V2X communication technology in reducing road traffic congestion, by enabling smart traffic light controllers to regularly communicate traffic signal phase information to smart cars in order to prevent delays induced by stopping at intersections. After designing and testing the initial implementation with a simple scenario, further tests were conducted to evaluate the performance of this approach on networks with different topologies. These scenarios shown an understanding of how TRADER would perform in disparate regions, such as New York, Manchester and Los Angeles. Furthermore, by varying traffic density we

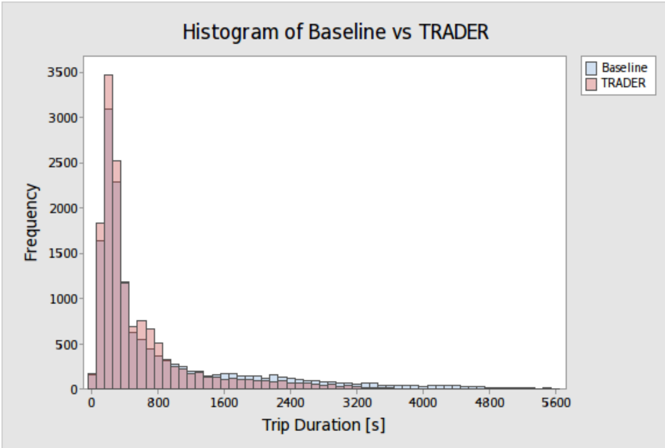

Figure 11: Histogram comparing trip duration (# vehicles=4803)

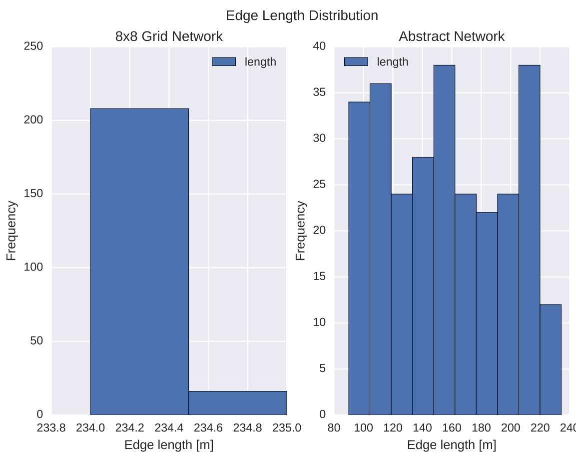

Figure 12: Comparison of edge length distribution in grid and random networks

discovered the suitability of this approach for road networks under different load. The average improvement in travel time across all scenarios was 7.94% and the greatest improvement was 31.44%, which was observed in the random topology network. The results illustrated that the performance varied considerably based on several factors, most notably network topology and traffic density. As previously mentioned, it is unlikely road traffic congestion will be solved by a single solution. Considering this, an extension of this work could be conducted to investigate how well TRADER interacts with other proposed solutions such as adaptive traffic lights systems.

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