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EcoTrec—A Novel VANET-Based Approach to Reducing Vehicle Emissions

Ronan Doolan and Gabriel-Miro Muntean, *Member, IEEE*

***Abstract*—There are interdependent increases in vehicle numbers, vehicular traffic congestion, and carbon emissions that cause major problems worldwide. These problems include direct negative influences on people's health, adverse economic effects, negative social impacts, local environmental damage, and risk of catastrophic global climate change. There is a drastic need to develop ways to reduce these emissions and EcoTrec, presented in this paper, is one of these innovative approaches. EcoTrec is a vehicular ad hoc network-based vehicle routing solution designed to reduce vehicle carbon emissions without significantly affecting the travel times of vehicles. The vehicles exchange messages related to traffic and road conditions, such as average speed on the road, road gradient, and surface condition. This information is used to build a fuel efficiency model of the routes, based on which the vehicles are recommended to take more efficient routes. By routing vehicles more efficiently, the greenhouse emissions are reduced while also maintaining low traffic congestion levels. This paper presents results of extensive simulations, which show how EcoTrec outperforms other state-of-the-art solutions with different number of vehicles, vehicle penetration, and compliance rates, and when considering different real world road maps from Dublin and Koln.**

***Index Terms*—Ad hoc networks, routing, vehicle communications, wireless LAN, road traffic.**

I. INTRODUCTION

CURRENTLY, human-induced climate change is a critical issue. In order to help mitigate the magnitude of climate change, severely reducing greenhouse gases in all economic domains is imperative. The transport sector, as an important contributor to global gas emissions, should follow the same approach.

For instance in the United States (US) transportation sector's greenhouse gas emissions are expected to grow by about 10 percent by 2035, when they will account for 25% of the global emissions [1]. In 2011 the US road vehicles' CO2 emissions share was 27.5% [2]. Another study showed that there were 2.9 billion gallons of fuel wasted during congestion in US urban areas in 2011 alone [3]. In the same period in Canada emissions for the transportation sector accounted for 24% of greenhouse gas emissions [4].

Traffic congestion contributes to pollution in built-up areas: a specialist report showed that children who live in high traffic areas are six times more likely to develop leukemia and other cancers [5]. The constant low-level noise created by traffic was also shown to negatively affect children's blood pressure.

Traffic congestion also causes a lot of time-related stress for people who waste time in traffic. Studies have shown a correlation between increased time behind the wheel and high blood pressure [6] and likelihood of obesity [7]. Another report revealed that carbon monoxide levels are 10 times higher inside a car, so therefore large amounts of time stuck in traffic will negatively affect a person's health [5]. Gwilliam *et al.* [8] states that in the developing world vehicles emit about 6% of particulate matter emissions (PM). Yet because this is at ground level in urban areas, vehicles account for 32% of PM population exposure.

There are many negative economic effects associated with traffic congestion; one example is the downtime for trucks and other commercial vehicles. Employing innovative communication-based solutions, such as those making use of Vehicular Ad-hoc Networks (VANET), which give real-time traffic congestion, as mentioned by Taleb *et al.* [9], and wirelessly monitoring vehicle performance, could reduce the downtime for commercial vehicles, as stated in Ko *et al.* [10].

These technologies which can provide a huge increase in Floating Car Data (FCD) have the potential to enable innovative techniques to predict traffic and enhance traffic management systems.

This paper presents **EcoTrec, a novel eco-friendly routing algorithm for vehicular traffic which balances, in a smart manner the need for reduction in both travel-time and gas emissions along the vehicle's route**. Load balancing is used when recommending routes for vehicles in order not to create flash crowds on certain roads. EcoTrec relies on vehicles collecting and periodically sending out information on road characteristics and traffic conditions on the route segments they are on. Vehicles exchange this information using VANET communications and based on it they are recommended routes to take in order to reduce gas emissions without compromising greatly on travel time [11].

Simulation-based testing compared the proposed solution with different penetration and compliance rates against real vehicular traffic data from cities of Dublin and Koln, and algorithms proposed by Dijkstra and Sommer. In terms of the percentage of vehicles which reached their destinations, EcoTrec outperformed the real-life situation and Sommer algorithm by 15% and 17% respectively, and was very similar in performance to applying the Dijkstra shortest path solution.

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In terms of emissions, EcoTrec outperformed the real-life case, Dijkstra and Sommer algorithms by 21%, 19%, and 12%, respectively.

The paper is structured as follows: Section II discusses the related works, Section III presents the system architecture and Section IV introduces the proposed algorithm. Modeling, simulation details and testing scenarios are introduced in Section V and the results are discussed in Section VI. Performance analysis, conclusions and future work directions are presented in the final sections of the paper.

II. RELATED WORKS

This section discusses several related works relevant to the proposed EcoTrec algorithm [11]. These related works were divided into several areas discussing: routing solutions, eco-routing solutions, penetration rate, compliance rate, and vehicular road maps. The penetration rate, compliance rate and map types influence the performance of VANET-based solutions and so will be discussed next.

A. *Penetration Rate*

An important variable for VANET communication-based routing is the penetration rate. Penetration rate refers to the percentage of vehicles which are VANET communications-enabled. In the initial stages of any VANET-based solution deployment, the penetration will be quite low, but its increase in time will determine performance improvements. This section examines papers which addressed the low penetration problem. Three possible methods for addressing low penetration rate were increasing transmission power [12], using the store and carry approach [14] or using Road-Side Units (RSU) [17] to cover greater distances for messages. However, each of these approaches has limitations. RSUs are a very expensive way to improve connectivity, using the store and carry approach is slow for messages to reach all the vehicles and increasing the transmission power will improve the connectivity slightly only and scaling is very limited. These methods can also be used to cope with network fragmentation even when there is 100% penetration rates [15].

There are a number of applications for which determining penetration rates is important, such as sending vehicular traffic information [12], average road travel times [13] or finding parking places [17].

B. *Different Routing Techniques*

Various solutions are proposed such as that of Sommer *et al.* [18] which employ VANET-based systems to send vehicles along alternative routes when the roads they are on are congested. This approach was focused on reducing travel time and did not include any environmental metrics.

Wu *et al.* [19] proposed several Dynamic Navigation Algorithm (DNA) flavors which consider as parameters average speed, inter-vehicle distance, road type and length and recommend better routes. An obvious limitation is that DNA does not consider road length over road speed in order to get the time vehicles take to traverse a road segment.

Several approaches used swarm algorithms [20]–[22]. Reference [20] and [21] introduced ant-colony based swarm algorithms, whereas [22] proposed an intelligent water drop algorithm.

Doolan *et al.* [20] developed *Time-Ants*, an algorithm which uses an ant-colony optimization approach in both time and spatial domains in order to send vehicles along certain routes when these paths are non-congested. However this approach requires access to historical traffic data, which may not be available in some scenarios.

Cong *et al.* [21] considered a centralized dynamic ant-based routing algorithm. The ants are given different colors for different destinations and they only pay attention to pheromones left by ants of the same color. A network pruning step is used to reduce the complexity, so a color can be applied to a particular area only. Load balancing is applied to avoid flash crowding.

Sur *et al.* [22] designed the *Intelligent Water Drop* algorithm which uses a water droplet falling principle when dealing with routing vehicles on a congested road network. The algorithm can determine and route vehicles to all the under-utilized roads within a network. The author states the confliction between the fastest route and the number of vehicles going on this route as a key problem that is addressed by this algorithm.

C. *Eco-Routing Solutions*

Eco-routing solutions refer to vehicle routing techniques specifically designed to reduce fuel consumption when applied to vehicles on a real road network. As this is a very recent area of interest, very few solutions have been proposed to date. This section discusses some of these eco-routing proposals.

There were a number of ways of doing this such as gathering information from previous trips, or traffic data from different sources [23], such as induction loops and traffic cameras, and factoring in turning and acceleration [26]. For instance information from induction loops is prone to errors as noted by Abuelela *et al.* [24] which among other aspects stated that over 50% of induction loops are defective. The paper [26] which considered turning and acceleration had no testing.

Anderson *et al.* [25] developed a tool called EcoTour which recommends a route to other drivers based on how much fuel is used on the road segments. However, no attempt is made to determine why certain segments used more fuel than others. For instance a road might be smoother and flatter than another road, and the drivers of high powered vehicles choose to go on this road. This would make the flat road appear less efficient than the other even if the flat road would have been the efficient choice due to road-related parameters.

More recent research has proposed innovative eco-routing solutions for combustion engine vehicles [51], electric vehicles [52] and electric bicycles [53], [54].

D. *Compliance Rate*

Assume all the vehicles have network connectivity, can forward VANET vehicular routing algorithm messages, and can receive algorithm recommendations. Yet some vehicles choose not to follow the advices. The compliance rate is the

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percentage of vehicles which follow the recommendations and is an important factor in any algorithm's performance.

Oh *et al.* [27] have analyzed the effect of different rates of compliance. This study showed that routing schemes aimed at improving overall system performance may perform worse than selfish algorithms, as drivers may not follow them. Ma *et al.* [28] looked at issues of trust when determining the compliance rate and their study illustrated that trust dropped rapidly with the number of mistakes.

Leontiadis *et al.* [29] stated that suboptimal routing where every vehicle follows one route may be better than none.

Schaub *et al.* [30] considered receiving information on traffic over FM radio and inspected existing flaws in navigation systems and ways of addressing them. The paper discussed issues such as gullibility errors where the driver follows the automotive navigation's directions even when they do not make sense. Also it noted that drivers do not always follow the advice of the navigation system. The paper suggests giving the driver a number of choices and indicating the advantages of each choice. This is a good idea as machines are not always capable of judging the advantages of some concepts and different users will have different preferences, e.g. some drivers may not like driving a certain roads.

Schakel *et al.* [31] introduced a lane-changing advice system and looked at how this system was affected by the compliance rate, by varying it from 0% to 100%. A small rate of compliance was shown to improve traffic flow with a greater amount at higher rates. This study only focuses on inter-vehicle coordination and does not consider vehicle routing.

Yamashita *et al.* [32] simulated different compliance rates for the algorithm developed. The average travel time of all users decreased as the compliance rate increased. However, real traffic data was not used.

E. Different Maps

There are several types of maps which can be identified. Urban maps contain a dense of number of roads and traffic, and rural maps often have long empty roads. There are also grid maps, where most roads intersect at 90 degrees to each other and non-grid maps, where this is not the case. Map type matters, as some protocols are designed to best work for certain map types only. This was noted by Djahel *et al.* [33] which discussed the different scenarios VANET routing protocols are designed for. Some protocols outperform others in scenarios with various map types; this means that VANET schemes should be tested on different map types.

III. ARCHITECTURE

Fig. 1 illustrates the EcoTrec architecture, whose major components are a *Vehicle Model*, a *Road Model* and a *Traffic Model*. The vehicle model is built and updated by each individual vehicle, using information from the GPS sensors, speedometer and accelerometer. The vehicle's local traffic conditions are used to create and maintain the *Traffic Model*. The Road Model is maintained at a central *Server* and is updated with information on the nearby roads. The data is exchanged using IEEE 802.11p [34].

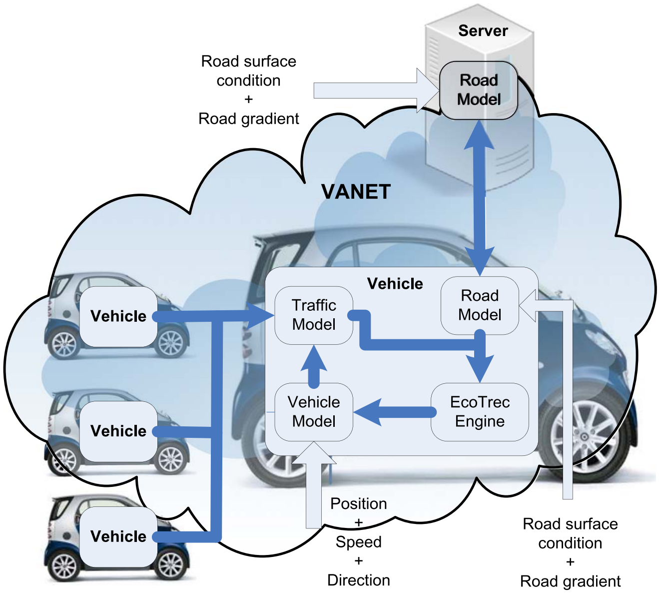

Fig. 1. EcoTrec system architecture.

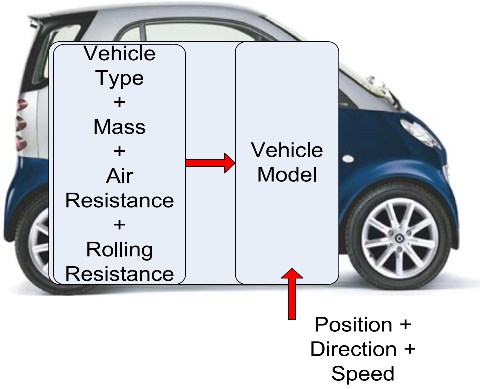

Fig. 2. Vehicle Model.

A. The Vehicle Model

The *Vehicle Model* (see Fig. 2) models the characteristics of individual vehicles. The vehicle parameters such as type of vehicle, mass, air resistance and rolling resistances are placed in the model when it is initialized. The other inputs are data from the GPS sensors on the vehicle which determine position, direction and velocity. These inputs are provided regularly. The outputs of the model are: vehicle emissions (which are determined regularly) and position information (which is sent to other vehicles).

The purpose of the *Vehicle Model* is to accurately represent the important characteristics of each vehicle in order to simulate emissions and traffic dynamics. Each vehicle sends its position and speed to the *Traffic Model* and to other vehicles' traffic models, embedded in VANET messages.

B. The Road Model

The *Road Model* (see Fig. 3) includes a representation for each individual road section in terms of its characteristics.

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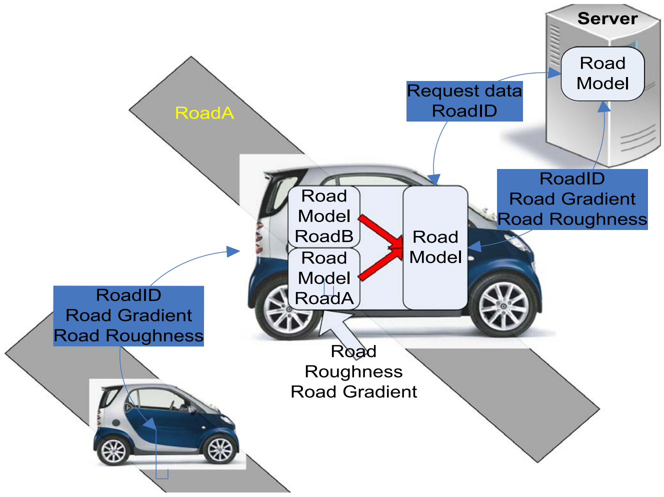

Fig. 3. Road Model.

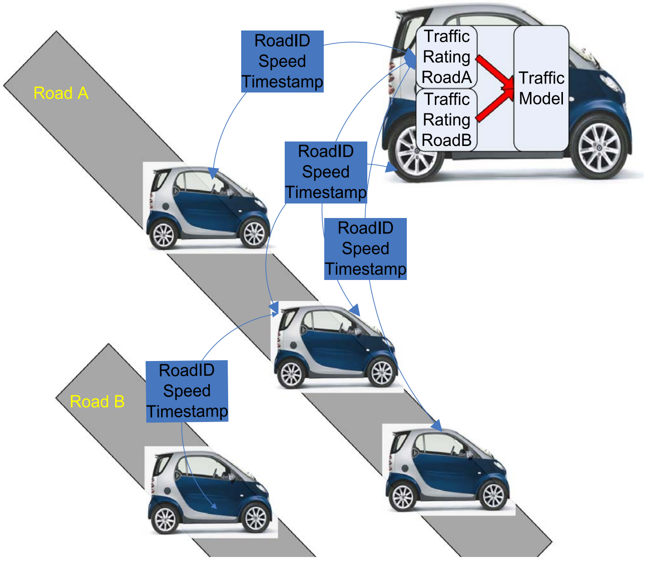

Fig. 4. Traffic Model.

The road's roughness values International Roughness Index (IRI) [35] and Mean Depth Profile (MPD) [36], the road's ID, the maximum speed, length, as well as road gradient are the inputs to the *Road Model*. The overall *Road Model* is stored on a central *Server*. The vehicles are equipped with accelerometers and tilt sensors to detect the road surface conditions and the road gradient. Information collected by these pieces of equipment is used to update the *Road Model*.

The function of the road model is to allow the vehicles to query or update the road characteristics of each individual road segment.

When a vehicle requires road-related information, it sends a request message with *roadID* as a parameter to retrieve the road's roughness and gradient. The server-vehicle communications are also performed using IEEE 802.11p via the use of RSUs. Storing information on the central *Server* is important as the road gradient should be constant, provided there are no errors and the road surface conditions change gradually over time. The different values recorded are stored in a sliding window and then an average is computed by adding all the values in the window and dividing the sum by the number of readings.

The vehicle takes the road roughness and road gradient values from the *Road Model* and inputs them into the EcoTrec algorithm to allow the vehicle to calculate the optimum route.

C. The Traffic Model

The *Traffic Model* (see Fig. 4) models the full traffic conditions of an area. Its purpose is to allow the vehicles to query real-time traffic conditions on each individual road segment. The inputs to the *Traffic Model* are *roadID*-s, as well as the traffic congestion rating for the corresponding road section. The traffic congestion rating is calculated by comparing the average speed of cars along that road with the speed limit, as indicated by eq. (3) in Section IV.

The vehicles exchange messages detailing information relating to traffic conditions. The messages contain the *roadID* of the road they are on, their current speed and a timestamp. The speed of the different vehicles on a particular road at a certain time is averaged. The average speed is used as the congestion rating for that road. The vehicles build and maintain the *Traffic Model* from the congestion information they receive. This model describes the congestion of the roads in an area of the map. Again the messages are exchanged between vehicles using IEEE 802.11p.

The vehicle takes traffic condition values from the Traffic Model and inputs them into the EcoTrec algorithm.

IV. ECOTREC ALGORITHM

The aim of the EcoTrec algorithm is to calculate the most fuel efficient route by looking at the efficiency of using individual road segments when considering a number of factors. These factors are: road condition, reflected in the road condition rating (R) and traffic condition, reflected in the traffic condition rating (T). The multiplicative utility function presented in eq. (1) relates the two parameters to determine the value associated with a road segment. T is meant to reflect the level of congestion on the road segment with effects on both travel time on the route and fuel consumption/gas emissions. The goal is to best avail from the potential of each road segment, so the closer T is to 1, the better in terms of the travel time. T having values close to zero is considered a sign of congestion and the vehicles will avoid that road segment, if possible. EcoTrec does not simply calculate the emissions due to road conditions, as it must balance relevant factors such as travel time, road congestion level and gas emissions. It uses a weight W_T which tunes the relative contribution travel time and gas emissions have in the EcoTrec algorithm and was introduced to allow for greater algorithm flexibility. As a balanced approach was preferred, for the testing in this paper, W_T was set to 1. The rationale behind using a multiplicative utility function is that a very good road would be useless to the driver if there was a serious traffic jam on it, due to an accident or road works.

$$U = \frac{R}{(T^{W_T})} \tag{1}$$

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Making use of the novel utility function described in eq. (1), the vehicles are then routed according to an improved shortest path algorithm [37], which also includes basic load balancing. In order to avoid the most popular roads become congested, not the best route is recommended to all vehicles all the time. Instead the second best solution is advised to some vehicles with certain level of randomness. Additionally, this approach also prevents the vehicles travelling from the same or similar origin to the same or similar destination picking the exact same route and thereby reduces the flash crowding effect on the common road segments. For instance for every N road segments considered, the second best road segment in the recommended route is used instead of the best. The value of N balances the size of area to be covered and the need to find the best results. The testing-based simulations in this paper have used $N = 9$, which supports the need for a very good routing solution, and prevents flash crowding, even in increased traffic scenarios.

Each time a vehicle receives new information via VANET messages, the utility function is recomputed, updating the optimum route. The VANET messages are described in the next section. Each vehicle sends and forwards messages concerning the road it is travelling on with frequency ϕ. Sending frequent messages is necessary in order to have real-time or near real-time traffic information. *MaxHopCount* is the number of hops over which the messages are sent. This has to be balanced in order to keep the information local, make sure vehicles receive necessary information and make sure the overhead is not too high. For instance in this paper an inter-message transmission interval $(1/\phi)$ of one second (minimum possible in iTETRIS) and a *MaxHopCount* value of ten are considered.

The road condition rating R is calculated based on eq. (2) and is derived from the Handbook Emission Factors for Road Transport (HBEFA) formula [40]. R is normalized by making use of a value for the most emission intensive route $(R_{\max})$.

$$R = A \cdot RR \cdot v + B \cdot RR \cdot v^2 + C \cdot v^3 + m \cdot g \cdot RG + m \cdot a \cdot v \quad (2)$$

In eq. (2), RR is the road roughness-dependent coefficient which accounts for the increase in emissions due to the surface conditions; RG—road gradient, g—gravitational acceleration, v—velocity, m—vehicle mass, a—acceleration, A—rolling resistance for the vehicle, B—rotating resistance coefficient and C—air resistance for the vehicle. C is dependent on the frontal area, which is measured in meters squared. A and B are friction coefficients and RG is a ratio of height over distance and they do not have units. Acceleration and gravitational acceleration are recorded in meters per second squared, velocity is measured in meters per second, and mass—in kilos.

The traffic condition rating T defined in eq. (3) is obtained by gathering information on the speeds of the vehicles on a stretch of road. The traffic condition rating is obtained by normalizing the average speed of the vehicles by considering the maximum speed (the speed limit) on that road. This information is then distributed to other vehicles via VANET.

$$T = \frac{AS}{MS} \quad (3)$$

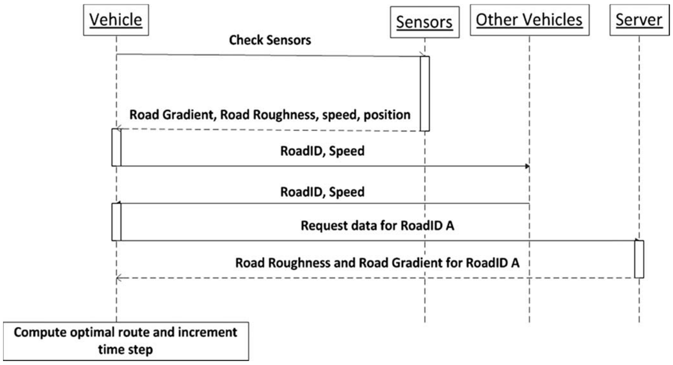

Fig. 5. UML sequence diagram of EcoTrec message exchange.

In eq. (3), $AS =$ Average Speed and $MS =$ Maximum Speed (the speed limit) of vehicles on a road segment, both measured in m/s.

When a vehicle receives a message from another vehicle, it checks the time-stamp and the *roadID* of the message. If the message is newer than the data stored for that road, the traffic congestion rating of the message is stored. If they relate to the same time interval, the values of the message and the value stored on the vehicle are averaged. This is done by incrementally considering the contribution of the new values and taking into account the number of readings in the same time interval. If the message is older, it is discarded. The vehicle now forwards this value as the traffic congestion rating on that road. This accomplishes the calculation of the average speed on a road in an entirely decentralized manner. The maximum speed is stored in the *Road Model*.

Each time a vehicle receives new information, it runs the EcoTrec algorithm to update its fuel efficient route. The sequence diagram of the model information gathering and exchange is illustrated in Fig. 5. The vehicle receives the information on its position, speed, direction and the road roughness and road gradient from its sensors. The vehicle then identifies the road that it is on from the position information and the map. Next it sends its speed and the ID of the road that it is on to the other vehicles and then receives the other vehicle messages regarding their speed and location. Next it updates the traffic model from the information it has received and then it requests road data from the Server. When this has been received, it calculates the optimal route using EcoTrec.

The GeoRouting protocol (GRP) [39] is used to route the VANET messages. GRP uses the fact that all nodes are aware of their location to route messages. Using beaconing and listening to the channel, the node is able to create a table of nearby nodes. The messages are sent using the topology-based broadcast TopoBroadcast GeoRouting scheme. TopoBroadcast sends messages to all vehicles within certain number of hops. The hop number is up-bounded by *MaxHopCount*.

This was done for a number of reasons in order to: localize message exchange, not to load the VANET unnecessarily, minimize the number of U values which must be calculated in real-time and to avail from high throughput (which decreases with the number of hops). The IEEE 802.11p data channel is used to exchange the messages, but the control channel may be used if the VANET network is congested.

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SenderID	messageType	messageID	RoadID	message	timestamp	Sequence Number

Fig. 6. Message data fields.

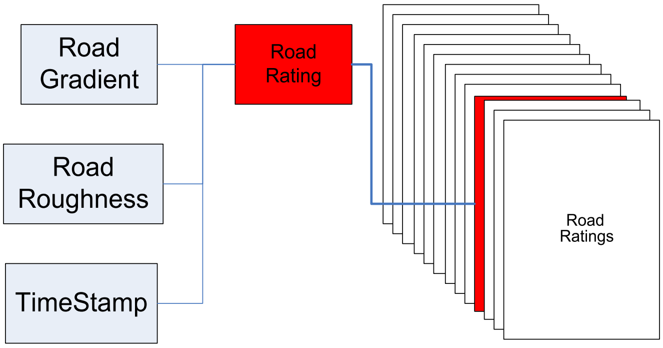

Fig. 7. Contents of the road rating link list.

The VANET message structure used by EcoTrec is displayed in Fig. 6.

The messages sent between the vehicles contain the senderID, which is stored as a string. Next the message type is stored. This can be a broadcast message or a unicast message. The road the sender is on, is stored as a string. This field is obviously quite important for determining either the traffic conditions or road conditions on that road. The messageID is stored as an integer. This determines whether the message is to do with the average speed of vehicles on the road, the spacing between vehicles, the road gradient or the road surface conditions. The message itself is stored a float. The time-stamp is stored as an integer. Lastly there is the sequence number, which is an integer detailing the number of messages the sender has sent.

V. COMPLEXITY ANALYSIS

A. *Storing and Updating Models*

Each individual vehicle has a *Traffic Model* instance which stores the most up-to-date information on the local traffic conditions. This is being constantly updated from the messages received from other vehicles. This information is stored in a link list (see Fig. 7), in order for the data to be quickly searched for information. This information is stored in structures along with the road ID, traffic rating or road rating. This list will be $n \times m$ structures large, assuming there are n vehicles, each storing information regarding m nearby roads. This totals $52 \times n \times m$ bytes, as the structure size is 52 bytes. For $n = 1000$ and $m = 4000$, typical values in an area of a European city like Dublin (described in scenario 2 in Section VI), this data size is 200 Megabytes, easily stored given today technology and economic development level.

B. *Communication Messages*

As already mentioned, each VANET message contains the fields illustrated in Fig. 6. This message is used to carry useful information and is roughly of size = 300 bytes.

According to Han *et al.* [40], IEEE 802.11p has a data rate of between 3–27 Mb/s, with a commonly assumed default of 6 Mb/s. For a number of vehicles n, this data is size $* n$ bytes.

For a message exchange frequency of ϕ, z hops and y maximum one-hop neighbors, there are a maximum of $z * \phi * y$ messages per second being exchanged which totals $z * \phi * y *$ size bytes. For a message exchange frequency ϕ set in simulations to one Hz, a number of hops z used in the multi-hop communication set to 10, and y equals 20, the amount of data exchanged was 60 kilobytes per second, which gives a maximum of 1% use of the bandwidth.

Bilstrup *et al.* [41] ran testing on the amount of packet drops in a scenario involving a similar amount of vehicles to this paper over a 10,000 m stretch of highway, they estimated 0% packet drops for 300 byte messages, at 5 Hz frequency and a range of 1,000 m. Considering the simulations in this scenario are at 1 Hz there should be very few packet drops.

VI. SIMULATION-BASED TESTING SETUP

A. *Simulation Environment*

The EcoTrec algorithm was modeled and tested on the iTETRIS simulator [42]. iTETRIS is an open source simulator designed to test inter-vehicle communication solutions and its development was funded by the European FP7 programme. iTETRIS creates a bridge between the network simulator (NS-3) [43] and the traffic simulator SUMO [44]. It was designed to be flexible, scalable and accurate and was coded in C++. SUMO is an open source microscopic traffic simulator meaning it simulates each individual vehicle as opposed to just traffic flows. NS-3 is an open-source discrete event network simulator and allows for the simulation of both wired and wireless networks. For this research SUMO was extended to include data about road conditions, such as IRI and MPD, and gradient. For emission calculation the additional acceleration required to overcome gravity on a slope was added to the vehicles' acceleration to determine the fuel used on that route. SUMO has a function to enable the computation of vehicle CO2 emissions in each second of simulation. SUMO has several ICE emissions models which are based on the HBEFA study [44]; the light passenger vehicle model was used in all testing in this paper. The overall emission was computed by summation. The simulations started with all the roads empty for all the tested algorithms.

Single simulation runs were performed for each scenario/map and routing strategy. All t-tests are paired t-test and have been performed for each simulation run considering pairs of routing strategies.

B. *Simulation-Based Modeling*

The proposed EcoTrec routing algorithm was compared against three alternative approaches: the routing algorithm described in Sommer *et al.* [18], Dijkstra shortest path algorithm, commonly used by GPS road guidance systems [45], and the real-life routes taken by the vehicles, as recorded in the TAPASCologne dataset [46]. Both EcoTrec and Sommer algorithms consider real-time traffic conditions in the routing

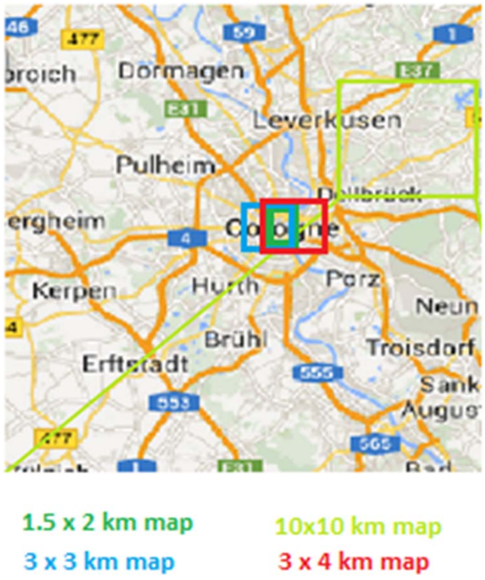

Fig. 8. Approximate areas of Köln used for simulations (data for the maps were obtained from TAPASCologne [48]).

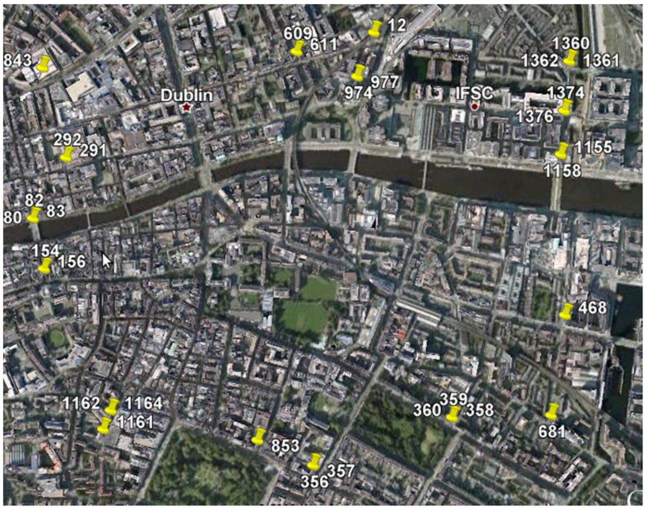

Fig. 9. Location of induction loops, which generated the vehicle counts used for the simulation of Dublin City Center.

process, whereas Dijkstra and TAPASCologne do not. The TAPASCologne project was taken as it includes the routes the cars took if they had no intelligent routing information.

Dijkstra's shortest path algorithm uses a graph search to find the shortest paths based on certain metrics. To simulate the Dijkstra routing algorithm a travel time function available SUMO was used. The Sommer algorithm implementation involved assigning roads with heavy traffic a high edge weight so the vehicles avoid these routes. To implement the EcoTrec algorithm the edge weight was calculated according to eq. (1) using the information on that route. If no traffic data was available for the route or the most recent traffic data was too old (over 20 seconds), the route was assumed to be free of traffic, leaving a T value of 1. In this paper W_T from eq. (1) was set to 2 in order to give traffic a relatively high importance and *MaxHopCount* was set to 10 in order to make sure the overhead did not run too high. Future works will include a sensitivity analysis to determine optimum values for parameters such as: W_T.

C. Scenarios

1) Scenario 1—Compliance and Penetration Rates Influence: The time of day was varied in Scenario 1 to see the effect of this metric on the system. The penetration rate and compliance rate are also varied to note their effects.

The map used for the testing scenario in this paper was taken from the TAPASCologne project [46]. The map was cut in order to reduce the simulation time and the area considered in the simulations is represented in Fig. 8. The new map is 2000 m × 3000 m in size and is at the location 50.924043, 6.93643 to 50.950456, 6.96611 (Koln2 × 3).This map contained 2557 road segments.

The gradients for the roads in the map were obtained using Google-Earth [47]. The heights of all road segment ends on the map were retrieved using the Google map APIs and stored in a .cvs file. A Python script was then run which took the length of the individual road segments and the heights of the start and end points of the road segment, and used to these to calculate the gradients. These were then stored in the maps xml file.

Two vehicle traces, one of 900 vehicles and the other of 1100 vehicles, were obtained from the TAPASCologne website. The vehicles were considered light passenger vehicles (these had engines between 1.4 and 2 liters in the Sumo simulations). The two vehicle traces consider the situation in the German city of Koln from 6:00 A.M. to 6:15 A.M. and 6:15 A.M. to 6:30 A.M., respectively. These times were chosen as they are busy traffic times in Germany.

In order to test the effects of compliance and penetration rates a number of extra simulations were run for the first vehicle trace. These consisted of running the simulations at varying compliance rates: 0%, 25%, 50%, 75%, and 100%. Another set of simulations varied the penetration rates: 0%, 25%, 50%, 75%, and 100%.

2) Scenario 2—Influence of Different Traffic Sets: The purpose of scenario 2 is to test the system on different data sets, and note the effects in similar, but different days.

For the second testing scenario a map of Dublin (see Fig. 10) was obtained from the OpenStreetMap website [48]. The map size is 1500 m by 2000 m and the coordinates are 53.333274, −6.291900 to 53.356862, −6.202507. This map contained 4111 road segments.

The vehicle traces were constructed from vehicle counts available from the Dublin City Council website [49].

The data collected from the website included traffic counts at major junctions which are shown in yellow in Fig. 9. A Python script was written to determine the number of vehicles entering and exiting the map from the induction loops at the edge of the area of interest. The number entering was slightly higher than the ones exiting, so some vehicles finished their journey within the area. The others were randomly assigned an exit. This was done as the induction traffic counts give the number of vehicles which crossed the monitoring point over a 5 minute interval only, no individual vehicles could be identified and so there was no way to tell where exactly vehicles have exited. Although not highly accurate, this method gives a good representation of

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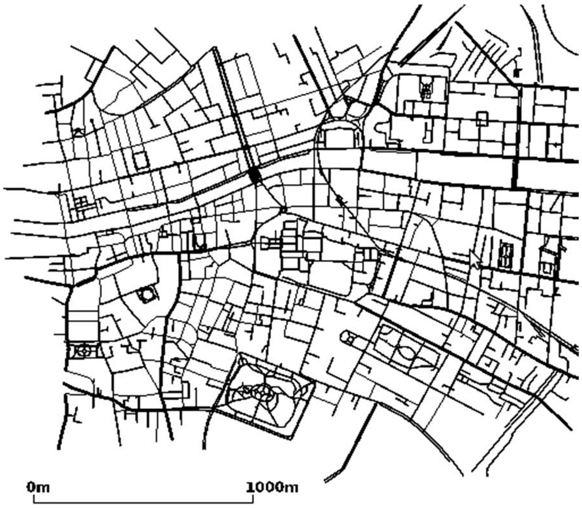

Fig. 10. Map of Dublin used for simulations.

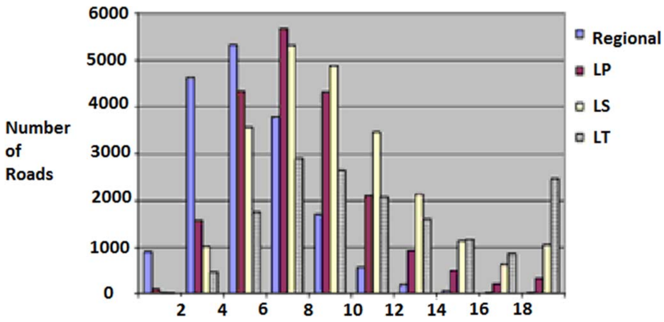

Fig. 11. Cumulative frequency graph of IRI values on Irish roads [52].

the traffic density in the area. Four traces of different Monday mornings in the month of January were made with the vehicles travelling at 6:00–6:15. These traces contained approximately 450 vehicles each. Again the vehicles considered were light passenger vehicles.

The road gradients were obtained from Google-Earth, using the same method described in scenario 1. The road roughness was obtained from Dublin City Council and included IRI and MPD values. These were used for the major roads; the smaller roads' data was estimated from statistics obtained from the National Roads Authority [50].

In Fig. 11, LP is local Primary, LS is local Secondary and LT is local Tertiary and refer to Irish road types.

3) Scenario 3—Influence of Map Size: A third set of testing considered a 3000 m × 3000 m (Koln3 × 3) and 3000 m × 4000 m (Koln3 × 4) map of the center of Koln. The coordinates are 50.923896, 6.9221 to 50.950888, 6.96349, and 50.924249, 6.93623 to 50.951759, 6.99172. These maps contained 3365 and 3885 road segments respectively. The purpose of this scenario is to note the effects of larger simulations on the algorithms.

The traces for the two maps contained 1400 and 1200 vehicles, respectively and were obtained from the TAPASCologne website. The vehicles were considered light passenger vehicles. The two vehicle traces consider the situation in the German city of Koln from 6:00 A.M. to 6:15 A.M.

TABLE I
PERCENTAGE OF VEHICLES THAT HAVE REACHED THEIR DESTINATION

	900 vehicles 6:00-6:15 (%)	Gain from baseline (%)	1100 vehicles 6:15-6:30(%)	Gain from baseline (%)
EcoTrec	65	36	60	30
Sommer	52	10	53	14
Dijkstra	54	16	52	12
TAPASCologne	47	0	46	0

Unfortunately no data on Road Roughness was available for Koln at the time of simulation. The road roughness values were generated using similar statistics from roads in Ireland.

4) Scenario 4—Influence of Map Type: The purpose of scenario 4 is to consider the effect of rural and urban maps on the solutions, respectively.

A section of road just outside Koln was used for the urban vs. rural comparison. The rural map was 10000 m × 10000 m and its coordinates are 50.97029, 7.04784 to 51.080232, 7.20403 (Koln rural). This map contained 9420 road segments. The trace for the rural map contained 370 vehicles. These traces were obtained from the TAPASCologne website. The vehicles were considered light passenger vehicles. The vehicle traces consider the situation in the area surrounding Koln from 6:00 A.M to 6:15 A.M The urban scenario uses the 6:00–6:15 trace and the 2000 m × 3000 m Koln map from scenario 1 (Koln2 × 3).

VII. TESTING RESULTS

All t-tests are paired t-test and consider each simulation run.

A. Scenario 1—Influence of Time, Compliance, and Penetration Rates

The first set of results is for the 2000 m by 3000 m map of Koln. Two traces of 900 and 1100 vehicles were simulated using the four different rerouting mechanisms indicated in Section VI-B *Simulation-based Modeling*. The tests with this scenario aim to demonstrate how in different traffic load conditions, EcoTrec performs better vehicular routing and results in both higher number of vehicles reaching their destinations and lower gas emissions.

Table I shows the percentage of vehicles which have reached their destination within the allotted time. For both vehicle traces the EcoTrec algorithm resulted in the highest number of vehicles reaching their destination.

EcoTrec outperformed the baseline, TAPASCologne, by 36% and 30% in the 900 and the 1100 vehicle traces, respectively. It also outperformed Sommer by roughly 24% and 13% in the 900 and 1100 vehicle traces, respectively. EcoTrec outperforms the other schemes because it considers the speed of the vehicles on each road in order to judge how long it will take to traverse the road infrastructure.

Fig. 12 depicts the total amount of CO_2 produced during the simulation time by all vehicles. For both vehicle traces the EcoTrec algorithm resulted in the least amount of emissions produced by the vehicles. EcoTrec outperformed the baseline, TAPASCologne, by 19% and 20% in the 900 and 1100 vehicle traces, respectively. It also outperformed Sommer solution by

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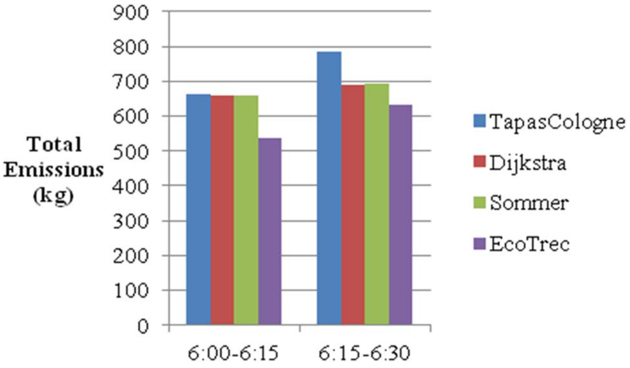

Fig. 12. CO_2 emissions generated by the vehicles between 6:00–6:15 and 6:15–6:30 for different routing solutions.

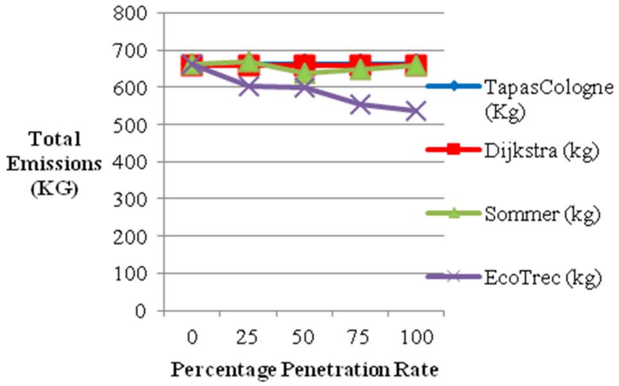

Fig. 13. Emissions generated by the vehicles for different penetration rates (the 6:00–6:15 trace was used).

roughly 18% and 9% in the two scenarios considered. T-tests were performed and confirmed that there is a significant statistical difference between EcoTrec's results and each of the other schemes results with 99% confidence interval. EcoTrec results are better than those of the other schemes, because it considers a number of factors, including the amount of emissions into the atmosphere on each road in order to decide which route to take. At the same time it also reduces the idle time by avoiding very slow roads.

1) Penetration Rate: The penetration rate was varied from 0%, 25%, 50%, 75%, and 100%. This indicates how many vehicles were VANET equipped and so only these vehicles could send and receive messages. The non-VANET equipped vehicles did not avail from any communication and route updates and followed the predefined routes from the TAPASCologne dataset.

As can be seen from the results in Fig. 13 and Table II, EcoTrec outperforms the other VANET-based schemes on average by 25% in terms of the percentage of vehicles to reach their destination. EcoTrec outperformed the other scheme at every percentage of penetration rate tested. In terms of emissions EcoTrec outperformed the other schemes by 12% on average. T-tests were performed and these confirmed that there is a significant statistical difference between EcoTrec's results and the results from the other schemes with a 97.5% confidence interval. These results show that the vehicles are taking more efficient, but not necessarily faster routes when having more information (following increased penetration).

TABLE II
PERCENTAGE OF VEHICLES THAT HAVE REACHED THEIR DESTINATION FOR DIFFERENT PENETRATION RATES

Penetration Rate (%)	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
0	46.3	54	46.3	46.3
25	46.3	54	47.0	52.7
50	46.3	54	49.0	63.5
75	46.3	54	49.0	64.6
100	46.3	54	51.4	65.4

TABLE III
PERCENTAGE OF VEHICLES THAT HAVE REACHED THEIR DESTINATION FOR DIFFERENT COMPLIANCE RATES

Compliance Rate (%)	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
0	46.3	46	46.3	46
25	46.3	49	48.4	52
50	46.3	50	50.5	63
75	46.3	51	54.4	60
100	46.3	54	51.4	65

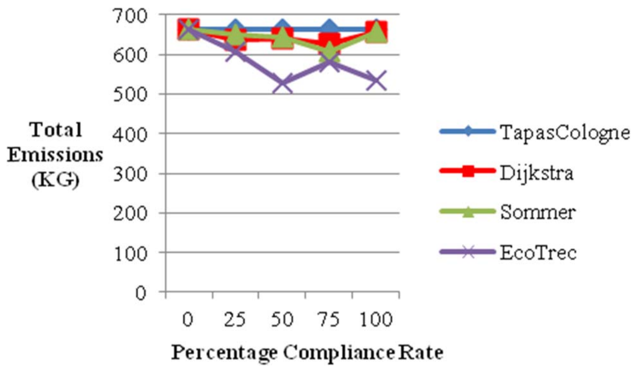

Fig. 14. CO_2 emissions generated by the vehicles for different compliance rates.

2) Compliance Rate: The compliance rate was varied from 0%, 25%, 50%, 75%, and 100% (see Table III). This means that although 100% of the vehicles in this simulation are VANET-equipped, meaning they can receive and exchange messages, only the compliant vehicles follow the routes that were recommended to them by the different schemes. The non-compliant vehicles followed the predefined routes from the TAPASCologne dataset.

EcoTrec improves in performance with greater compliance rate, both in terms of emissions and of percentage of vehicles to reach their destination (see Fig. 14).

As can be seen from these results, EcoTrec outperforms Sommer by 17% and Dijkstra by 18% on average, in terms of percentage of vehicles to reach their destination. This confirms that EcoTrec is the best scheme at different compliance rates. T-tests were performed and these confirmed that there is a significant statistical difference between the EcoTrec results and the results from the other schemes with a 97.5% confidence interval.

At 75% compliance rate we see an improvement in Sommer. This is due to the fact that load balancing is not implemented, and so 25% of vehicles not going the recommended route, results in less congestion on some roads. EcoTrec performed quite

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TABLE IV
PERCENTAGE OF VEHICLES THAT HAVE REACHED THEIR DESTINATION

	Original(%)	Dijkstra(%)	Sommer(%)	EcoTrec(%)
Dublin1	63.2	65.4	54.7	67.1
Dublin2	39.9	48.1	27.1	38.5
Dublin3	42.2	53.8	36.2	50.6
Dublin4	42.9	46.6	33.2	27.4

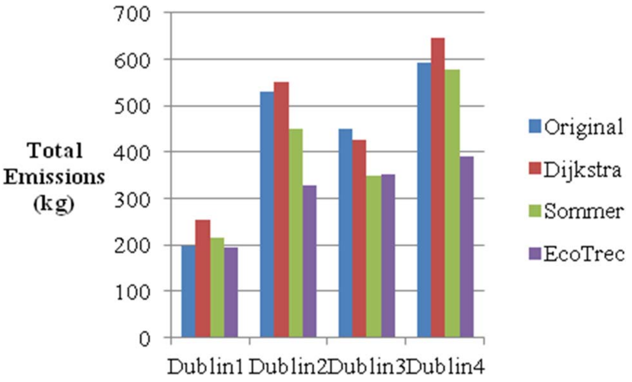

Fig. 15. CO_2 emissions generated by the vehicles.

TABLE V
PERCENTAGE OF VEHICLES THAT HAVE REACHED THEIR DESTINATION

	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
Koln3x4	40.4	46.8	46.5	55.4
Koln3x3	40.4	48.3	50.6	63.1
Koln2x3	46.7	54.0	52.0	65.3

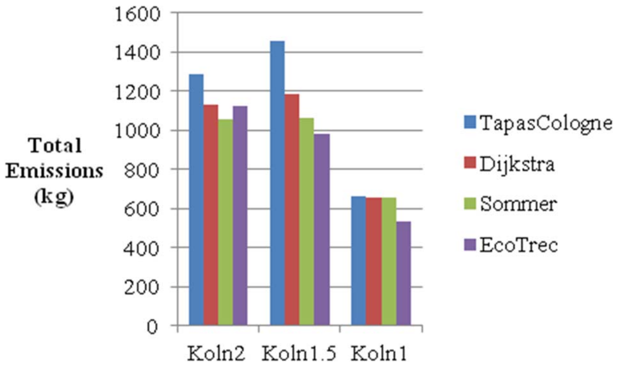

Fig. 16. Total Emissions in kilograms (the 6:00–6:15 trace was used).

poorly at this percentage too. The effects of traffic are highly variable, especially in situations when the compliance rate is lower than 100% and they can offset the benefits introduced by solutions such as EcoTrec, which do not account for compliance rate in their algorithm. Future improvements of EcoTrec should consider inclusion of penetration and compliance ratings in the algorithm.

In terms of emissions EcoTrec outperforms the other schemes by 12% on average. T-tests were performed and these confirmed that there are significant statistical differences between these results with 95% confidence interval.

B. *Scenario 2—Influence of Different Traffic Sets*

The second set of results is for the 1500 m × 2000 m map of Dublin. Four traces of approximately 450 vehicles were simulated using 4 different rerouting mechanisms.

Table IV shows the percentage of vehicles which have reached their destination within the allotted time. Apart from Dijkstra, EcoTrec outperforms all the other schemes in the first three traces in terms of percentage of vehicles which reach their destination within the time frame. EcoTrec outperforms all the schemes including Dijkstra when using trace 1. On average EcoTrec outperforms the Sommer routing scheme by 18%. On the other hand, on average, EcoTrec is outperformed by the original routes and Dijkstra routing schemes by 3% and 17% respectively.

Fig. 15 shows the total amount of CO_2 produced during the simulation. EcoTrec outperforms all the other schemes in terms of emissions except for Sommer when trace 3 is used, but Sommer outperforms EcoTrec by less than 1%.

On average EcoTrec outperforms the original routes, Dijkstra and Sommer routing schemes in terms of emissions by 24%, 33%, and 16% respectively.

In this scenario, EcoTrec did not perform as well as it did in scenario 1, in terms of the percentage of vehicles reaching their destination in the given time. Most likely this is due to the particular dynamics of the Dublin scenario. There is very heavy traffic on the roads entering the map at the start time. This prevents traffic-aware rerouting from having a more significant effect. However EcoTrec performed quite well in terms of emissions and there is an expected trade-off between speed and fuel economy.

In this scenario there was no statistical advantage for EcoTrec in terms of percentage of vehicles to reach destination. However, in terms of emissions the t-tests showed how EcoTrec was better than the original routes, Dijkstra, and Sommer with 95%, 99%, and 90% confidence intervals, respectively.

C. *Scenario 3—Influence of Map Size*

The third set of results is for three different sized maps in Koln, 2000 m × 3000 m (Koln2 × 3), 3000 m × 3000 m (Koln3 × 3) and 3000 m × 4000 m (Koln3 × 4) maps. The traces consider roughly 900, 1400, and 1200 vehicles, respectively.

Table V shows the percentage of vehicles which have reached their destination within the allotted time. On average EcoTrec outperforms the TAPASCologne, routing schemes by 31% in terms of percentage of vehicles to reach the destination within the timeframe. It also outperforms both the Dijkstra and Sommer by 19% in terms of percentage of vehicles to reach the destination within the timeframe.

Fig. 16 shows the total amount of CO_2 produced during the simulation. EcoTrec outperforms all the other schemes in terms of emissions except for Dijkstra in the Koln2 × 3 trace.

On average EcoTrec outperforms the TAPASCologne, Dijkstra and Sommer routing schemes in terms of emissions by 21%, 12%, and 7% respectively.

EcoTrec did not perform the best in terms of emissions in the 3000 m × 4000 m map. This is due to the lower vehicle density. This map had a density of 100 vehicles per square kilometer compared with the other two which had densities

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TABLE VI
PERCENTAGE OF VEHICLES WHICH REACHED THEIR DESTINATION

	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
Koln_rural	72.4	72.5	70.5	63.8
Koln_urban	46.3	54.0	51.4	65.4

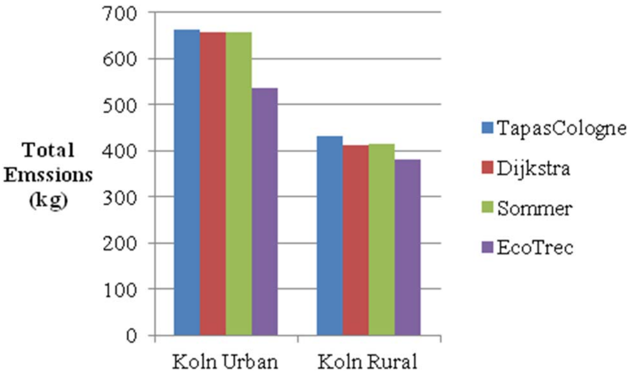

Fig. 17. CO_2 emissions generated by the vehicles.

of roughly 150 vehicles per square kilometer. T-tests were performed and they showed that in terms of the number of vehicles to reach their destination within the simulation time, EcoTrec outperformed TAPASCologne, Dijkstra and Sommer with a 95% confidence level.

D. Scenario 4—Influence of Map Type

Table VI shows the percentage of vehicles which have reached their destination within the allotted time. EcoTrec scores the worst in this scenario, but the difference between EcoTrec and the best routing scheme in this scenario is under 14%. Fig. 17 shows the total amount of CO_2 produced during the simulation. EcoTrec scores the best in this scenario.

EcoTrec outperforms the TAPASCologne, Dijkstra and Sommer routing schemes in terms of emissions by 12%, 8%, and 8% respectively in this scenario.

Over the distances in the map with the low vehicle density, vehicle to vehicle communication is very difficult if not impossible and also traffic congestion rarely occurs. False positive readings of traffic congestion might be the reason for EcoTrec not performing well in this scenario. These readings occur when vehicles detect traffic congestion, which quickly clears or when the vehicles stop at a junction or traffic lights. Note that the other VANET schemes also performed poorly.

Results suggest that load balancing may not be required in low traffic conditions, so future works will consider adjusting the load balancing dynamically with regard to traffic density.

E. Discussion

The number of messages (see Table VII) and the percentage of bandwidth used by the different schemes were looked at in the context of Scenarios 3 and 4 already described. On average the EcoTrec scheme sent approximately 300,000 messages in the 2000 m × 3000 m scenario. This corresponded to roughly 300 messages per vehicle or one message every 3 seconds. Each message is under 300 bytes. The table below shows the performance analysis. As can be seen every instance is well within the performance capabilities of IEEE 802.11p.

TABLE VII
NUMBER OF MESSAGES IN EACH SIMULATION

	Total Number of Messages	Total No. of Messages per Vehicle	Average Message Frequency (s)
Koln3x4	415000	345.8	2.6
Koln3x3	425000	303.6	3.0
Koln2x3	300000	333.3	2.7
Koln_rural	105000	262.5	3.4

The other VANET-based scheme, Sommer, sent 200,000 messages in the same scenario, which was less than EcoTrec, but the latter outperformed Sommer's solution.

Overall in terms of the percentage of vehicles which reached their destination, EcoTrec outperformed the original routes and Sommer by 15% and 17%, respectively. EcoTrec was only outperformed by Dijkstra by 0.1%, the difference between these sets of data was not statistically significant, so we can assume they are competitive with each other in this metric. Overall in terms of emissions, EcoTrec outperformed the original routes, Dijkstra and Sommer by 21%, 19%, and 11% respectively.

VIII. CONCLUSION AND FUTURE WORKS

This paper presented EcoTrec, a traffic and road characteristic aware VANET-based routing solution for reducing carbon emissions. EcoTrec was assessed in a variety of scenarios using the iTETRIS simulator. These scenarios varied the penetration rate and compliance rate, different map types including map size and urban and rural maps, and traffic traces such as different days and times of day. Testing showed how EcoTrec outperformed the other vehicle routing schemes presented in this paper in terms of fuel consumption, up to 21% was saved vs. the baseline, while maintaining a high percentage of vehicles to reach the destination with-in the timeframe (there was a 15% improvement vs. the baseline).

The proposed EcoTrec algorithm if implemented could greatly improve the environment by reducing gas emissions, and increase overall well-being in society by decreasing the time wasted due to traffic congestion.

Future work will improve the proposed EcoTrec algorithm, including by trying to better quantify its benefits. For instance research will focus on studying whether the load balancing could result in a local optimum as opposed to the global optimum, due to area of information being constrained by the maximum number of hops. Additionally future research will look at whether there are outliers, for instance most vehicles could have their journey duration reduced, but a smaller number of them could have their journey time dramatically increased. In this context, solutions to avoid having outliers will be looked at, including by regularly monitoring the standard deviation of travel times. Assessing the benefits in terms of additional metrics such as CO2 emission per vehicle-mile-traveled will be considered.

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