A Vehicle Route Management Solution Enabled by Wireless Vehicular Networks

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***Abstract*— Traffic Congestion is a very serious problem which is growing worse as the number of cars on the road continues to increase, out-pacing the provision of road capacity. This paper presents a novel vehicle routing algorithm for TraffCon - an innovative Traffic Management System for Wireless Vehicular Networks. The algorithm tackles the traffic congestion problem by seeking to optimize the usage of the existing road capacity, reduce vehicle trip times and decrease fuel consumption and the consequent gas emissions. Results demonstrate that the algorithm significantly reduces congestion, journey times and fuel consumption and emissions in comparison with an existing approach.**

I. Introduction

Vehicular traffic is one of the biggest issues faced by cities worldwide; in urban areas commuters can spend large portions of their days stuck in traffic. The traffic congestion cost to the UK economy was £20bn (US$38bn) for 2006 alone [1] and it has been estimated that this cost to the US economy will exceed $90bn per year by 2009 [2]. These are huge monetary costs based on lost productivity and wasted fuel. There is also the environmental cost; in Europe in 2004 road transport accounted for 19.5% of greenhouse gas emissions [3]. Alarmingly there is a worsening trend as the growth in the number of vehicles on the road outpaces growth in road capacity worldwide.

Since the first traffic lights were installed there has been a continued effort to find solutions to traffic-related problems. These solutions can be broadly categorized into three areas depending on their focus: increasing road system capacity, controlling the demand for travel and improving vehicular transport efficiency.

Increasing capacity involves building new roads, expanding and/or re-organizing the existing ones. Most research in this area is done by urban planners and solutions aim at building multi-level and multi-lane roads and at performing static or dynamic lane allocation. The latest research proposes the use of contra-flow and reversible lanes to alleviate traffic problems[4], [5], [6]. Solutions in this category are very effective, but highly expensive.

Controlling demand efforts aim at reducing user demand for road travel or encouraging more efficient travel (e.g. mass transit, car pooling, etc.), decreasing the number of vehicles. Much research is studying how road pricing or congestion charging discourage drivers from using certain roads unless absolutely necessary [7], [8]. In this context London has the largest implementation of congestion charging and results indicate a great success [9] in terms of controlling demand. However most of these solutions are very unpopular among the traffic system users and therefore authorities have difficulties to deploy them.

Improving efficiency of the existing traffic system includes work on access management, traffic signal timing and coordination, accident prevention, traffic routing and scheduling, etc. An important solution in access management is ramp metering, i.e. the use of traffic signals at motorway on-ramps to control the rate of vehicles entering the motorway and optimize the flow [10], [11]. Research on signal timing algorithms proposed among other solutions Split, Cycle and Offset Optimization Technique (SCOOT) [12] and Sydney Coordinated Adaptive Traffic System (SCATS) [13] which use real-time traffic data from mainline loop detectors for adaptive signaling.

These solutions for traffic management are in practical use. Increasing capacity may seem like a cure-all but is constrained by the available space. Other solutions solve only local problems without regard to the effect on traffic in the entirety of the road network. However the emergence of Mobile Networking for Vehicular Environments (MOVE) brings the possibility of a paradigm shift in traffic management as it opens the door to previously unavailable levels of control.

It is in this context that **TraffCon** is introduced as a novel Traffic Management System for MOVE [14]. TraffCon requires vehicles to have a GPS receiver (enabling location awareness) connected to a wireless enabled computing device with an interface capable of conveying information to the driver. The system aims to exert greater influence over the transportation system by allowing direct communication with individual vehicles.

There are many aspects of vehicle or infrastructure behaviour such a system could attempt to affect in order to alter traffic conditions such as: a vehicle's route, lane or speed and traffic lights or any other variable road side infrastructure (e.g. adjustable speed limit signs). This paper focuses on the management of vehicle routes. The proposed route management solution based on a novel Best Route Selection Algorithm improves Quality of Driving Experience (QDE) by reducing journey time, fuel consumption, gas emissions and cost.

This paper is structured as follows. Related works are

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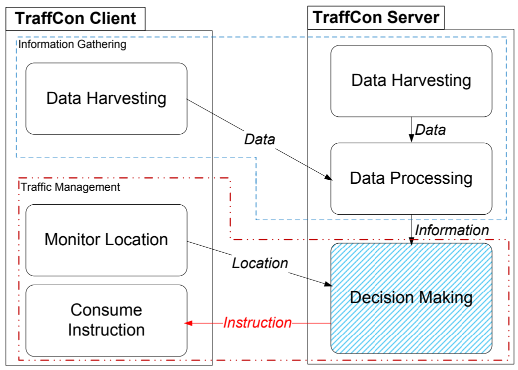

Fig. 1. TraffCon System Architecture

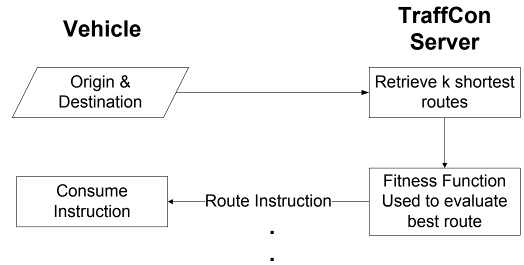

Fig. 2. One Iteration of TraffCon's Best Route Selection Algorithm

presented and commented on in the next section. Section three describes TraffCon's system architecture at block level, section four details the proposed Best Route Selection Algorithm and the fitness function this algorithm uses is presented in section five. The simulation-based testing setup, scenarios and results are presented and analysed in the penultimate section and the paper finishes with conclusions and future work in the final section.

II. Related Work

There are many research groups exploring use cases for MOVE which improve QDE by influencing vehicle routes.

A number of Traffic Information Systems have been developed i.e. systems which gather traffic data and disseminate traffic information to users, so they can make better informed decisions regarding their route [15], [16], [17], [18]. While these systems do keep drivers better informed about traffic conditions, there is no telling how the driver will interpret the information given. Consequently there is no guarantee such systems lead to more beneficial or optimal route decisions. If such systems were to become ubiquitous, they would likely cause a "flash crowd" effect making traffic worse. In [19] Inoue et al present a system designed to overcome the "flash crowd" problem but results show minimal improvement over existing shortest path navigation techniques.

Much work has also been done on the Data Harvesting and Information Dissemination schemes needed to support these type of applications [20], [21], [22].

III. TraffCon: System Architecture

TraffCon has a client-server architecture. Vehicles act as client nodes and communicate with the server in two asynchronous modes i.e. information gathering and traffic management as shown in fig. 1. Communication between client and server is achieved via a mesh network.

A. Information Gathering

With information gathering all nodes in the system collect useful traffic data (i.e. Data Harvesting). This data is filtered, aggregated and refined to generate precise information regarding the state of the traffic network (i.e. Data Processing). This communication is not time critical as traffic information does not need to be up to the second; however there will be some threshold on the age of the information required by the traffic management. In this phase inter vehicle communication may be used to employ techniques such as data aggregation in order to reduce the load on the mesh network.

B. Traffic Management

In order to facilitate traffic management vehicles keep the server informed of their location and the server disseminates traffic instructions. The instructions are generated by a decision making process which uses the location information and the traffic network information provided by the sensor network. In this case the decision making block is comprised of a novel Best Route Selection Algorithm examined in detail in Section IV. These communications are time sensitive as instructions will only be valid within a certain time frame.

IV. Best Route Selection Algorithm

The Best Route Selection Algorithm (summarised in fig. 2) is employed by TraffCon in its decision making process. A new decision making process starts when a vehicle begins a journey by sending its origin and desired destination to the server. The steps listed next are followed:

(1) Retrieve the k shortest routes from origin to destination. This is done by querying a cache of k-shortest paths using the origin and destination. It is possible to cache the paths as road layout changes infrequently relative to traffic conditions.

(2) A fitness function (4) is evaluated for each route, resulting in an associated fitness score. The novel fitness function used is presented in the next section.

(3) The best route is selected based on fitness scores. The fitness function is the sum of weighted cost functions so the route with the lowest score is the winning solution.

(4) The user is given an instruction on what to do at the next junction to follow the chosen route. After passing through a junction and onto a new road segment, the journey origin is updated to that position and the algorithm is repeated. In this way the route instructions remain valid even if the user does not obey all instructions, and the route may also be altered if changes in traffic conditions mean a better route now exists.

The generalised Floyd Shortest-Path algorithm [23] was used to create the cache of paths. Constraint checking runs in parallel to ensure the k routes are valid i.e. no rules of the

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road are broken (e.g. going the wrong way down a one way street). The value of k is important as only that number of routes will be considered as possible solutions. The parameter was introduced to reduce the complexity of the solution space and speed up the solution finding process.

V. Fitness Function

A. Preliminaries

In this subsection an equation which quantifies the effect of route on fuel consumption and gas emissions is derived, for use as part of the fitness function in the next subsection.

The following equation can be used to estimate the value of the fuel ΔF (millilitres - ml) consumed during a time interval of duration Δt (seconds - s) [24] by a vehicle travelling with an instantaneous speed v and acceleration a. The total tractive force R_T and vehicle mass M_v are constant and α, β_1, β_2 are also constants associated with individual vehicles.

$$\Delta F = [\alpha + \beta_1 R_T v + (\beta_2 M_v a^2 v/1000)_{a>0}]\Delta t \qquad (1)$$

Emissions of gases such as Carbon Monoxide (CO), Hydrocarbons (HC) and Nitrogen Oxides (NO_x) are calculated similarly; the constants α, β_1, β_2 are simply replaced by appropriate alternatives.

The Carbon Dioxide (CO_2) emissions are estimated directly from fuel consumption by using the following equation:

$$\Delta E_{CO_2} = f_{CO_2}\Delta F \qquad (2)$$

where,

ΔF = fuel consumption in ml calculated from (1) and,

f_{CO_2} = CO_2 rate in grams per millilitre of fuel (g/ml).

When comparing the fuel consumed by the same vehicle along a number of alternative routes R_T, M_v, α, β_1, β_2 and f_{CO_2} remain constant for all routes and consequently can be ignored.

The values of v and a vary based on the traffic characteristics of the individual routes and are consequently the only relevant parameters when evaluating routes in terms of fuel consumption and emissions. Therefore the cost function presented in equation (3) can be used to compare routes.

In the case where the route is simply a link (i.e. the segment of road between two junctions) the Fuel Consumption and Emissions Cost for the link n can be calculated as the summation of the instantaneous velocity (v), plus the instantaneous acceleration (a) squared by the instantaneous velocity divided by 1000, all by the time interval duration (Δt), for all the time intervals along the given link from its origin (O) to destination (D). The Fuel Consumption and Emissions Cost for a route is obtained by adding the costs of all individual links part of the route.

$$f_n = \sum_{j=O}^{D} [v_j + (a_j^2 v_j/1000)]\Delta t_j\} \qquad (3)$$

B. Fitness Function

The fitness function presented in equation (4) is proposed to choose a vehicle's route so that journey time, congestion and fuel consumption and gas emissions are minimized. It consists of weighted cost components including T which encourages a routing solution with the minimum possible user journey time, C which ensures that the solution considers the effect on congestion and F which makes sure fuel consumption and gas emissions are factored in.

Each of the components are weighted by w_i (5), to force the emphasis on a particular outcome. The more important a cost component is considered to be to the solution, the smaller the weighting factor associated with it, and therefore the stronger its contribution to the overall score R_{nv}.

$$R_{nv} = w_1 T_{nv} + w_2 C_{nv} + w_3 F_{nv} \qquad (4)$$

Given a certain vehicle v taking route n,

T_{nv}.............Journey Time Cost

C_{nv}.............Used Capacity Cost

F_{nv}.............Fuel Consumption and Emissions Cost

w_i...............Weighting Factors

$$\sum_{i=1}^{3} w_i = 1 \qquad (5)$$

This fitness function could be enhanced at a later date by considering additional parameters such as speed, operating cost, solution fairness etc.

C. Individual Cost Components

Measurements associated with road segments are made available by the information gathering process and pulled as required by the fitness function to evaluate its constituent cost functions which generate a score between 0 and 1.

Three metrics are considered: segment journey time, used capacity and fuel cost; these were chosen to reduce journey time, congestion and fuel consumption and emissions respectively. It may appear that these metrics are correlated and that time alone would suffice e.g. an increase in journey time would indicate an increase in used capacity or increased congestion and a shorter journey duration would mean reduced fuel consumption. However without considering capacity, congestion can only be identified when journey times rise which may be too late for many vehicles. By using the capacity component, congestion can be prevented without a rise in journey time. In the case of fuel consumption, the associated cost is indeed dependant on time, but also on velocity and acceleration characteristics. Consequently this component considers for example the effect of obstructions along the route which the time component alone cannot e.g. speed bumps, zebra crossings, etc.

These three individual cost scores are calculated as follows.

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Fig. 3. Sub network of Boston road network used marked with dotted line

1) Journey Time Cost: The journey time cost for a vehicle v taking route n is calculated as the summation of segment times (t) from origin (O) to destination (D) along the given route over the maximum journey time for the K possible routes t_{maxv} (see equation 6).

$$T_{nv} = \sum_{j=O}^{D} t_j / t_{maxv} \tag{6}$$

This cost component function encourages the fastest route (in temporal terms) to be selected.

2) Used Capacity Cost: The used capacity cost for a vehicle v taking route n is calculated as the average of the segment length(l) adjusted used capacities (c) of all the segments from origin (O) to destination (D) along the given route over the maximum average c_{maxv}. N is the number of segments along the route (see equation 7).

$$C_{nv} = \sum_{j=O}^{D} (c_j * l_j / N) / c_{maxv} \tag{7}$$

This cost component function encourages the least congested route to be selected.

3) Fuel Consumption and Emissions Cost: The Fuel Consumption and Emissions Cost for a vehicle v taking route n can be calculated as the summation of the individual segment fuel consumption and emissions costs, for all the segments along the given route from origin (O) to destination (D) over the maximum fuel consumption and emissions cost from the K possible routes f_{maxv} (see equation 8).

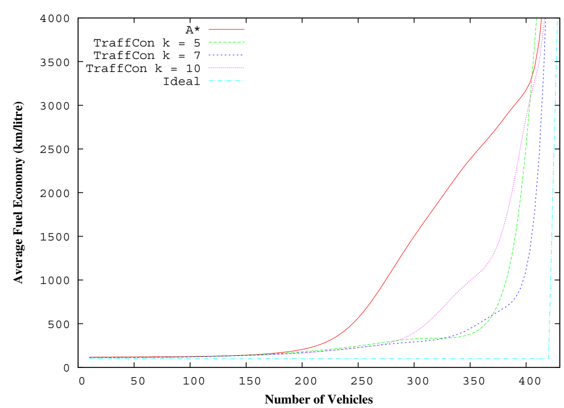

Fig. 4. Average Journey Time (s) against Number of Vehicles in the Network

$$F_{nv} = \sum_{j=O}^{D} f_j / f_{maxv} \tag{8}$$

This cost component function encourages the selection of the route which will result in the least amount of fuel being consumed and the least amount of emissions being produced.

VI. Testing

In order to evaluate the proposed TraffCon-based route management solution simulations with the Scalable Wireless Ad Hoc Network Simulator (SWANS) [25] were performed. This simulator supports realistic vehicular mobility modeling on real world roads. For testing the road network used was a subnetwork of the road network of Boston, Ma, USA as highlighted in the fig. 3.

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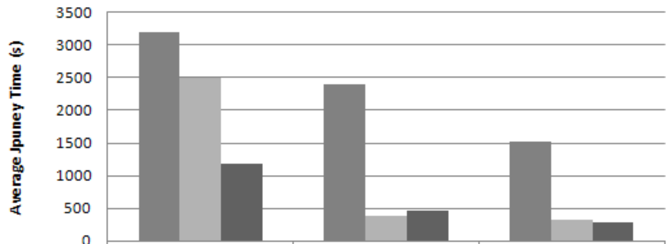

No. of Vehicles	400	350	300
A*	3200	2400	1520
TraffCon k=5	2500	380	330
TraffCon k=7	1170	460	290

Fig. 5. Average Journey Time (s) for Selected Vehicle Numbers

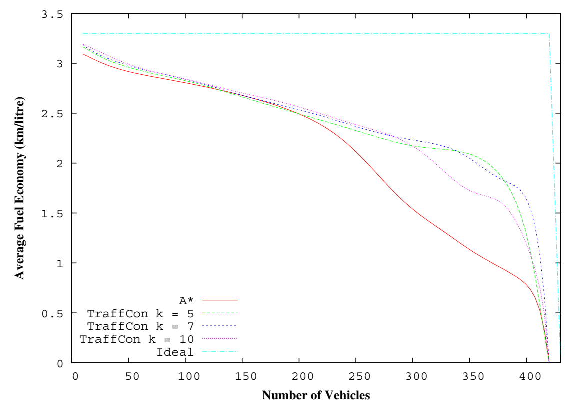

Fig. 6. Avg. Fuel Economy (km/litre) against Number of Vehicles

A. Simulation Experiment

In order to evaluate the efficiency of the route management solution the following experiment was performed. The experiment involved three different scenarios with three different traffic management solutions. This enables the various performance-related results to be compared and conclusions to be drawn in terms of these solutions' relative efficiency.

Case (1): before each vehicle embarks on its journey it selects a shortest route using the A* shortest path algorithm [26]. The vehicle does not deviate from this route.

Case (2): each vehicle drives to its own destination according to the proposed TraffCon-based route management solution. The weights of the fitness function 4 are set at w_1 = 0.5, w_2 = 0.5 and w_3 = 0 and different values of k are tested.

Case (3): Results for a hypothetical "ideal" solution are derived. This solution performs well right up until the road network reaches vehicle saturation point i.e. length of available road divided by average vehicle length.

In each simulation, the number of vehicles travelling in the network was varied and the average journey time and fuel economy was measured. The simulation time was set at two hours. The origin-destination pairs are kept constant i.e. the same vehicles are attempting to complete the same journeys in all cases. Border behaviour is not an issue as journeys occur within the simulation area. Whenever a journey is completed, another vehicle commences a journey, so the number of vehicles is maintained constant during the whole simulation duration. The weight w_3 is set to zero as obstructions such as speed ramps which affect velocity and acceleration are not modeled by the simulator. The weights w_1 and w_2 were chosen to be equal in this paper; the values of these weights will be optimized via detailed experimental testing. Fuel economy is calculated using equation 1 and the values of the parameters R_T, M_v, α, β_1 and β_2 are set to the values derived for light vehicles in [24].

B. Results

The results for average journey times (s) are compiled in fig. 4. As more and more vehicles are travelling on the road network it becomes increasingly congested causing the average journey time to increase until the system becomes completely gridlocked. The saturation point for a solution is reached when average journey time begins to climb steeply. The best performing TraffCon solution shown (k = 7) performs 40% better than the shortest path method as their saturation points are approximately 250 and 350 vehicles respectively. This is only 20% off the unachievable "ideal" solution which has a saturation point of approximately 420 vehicles.

In figure 5 we more closely examine the performance of the shortest path solution and two TraffCon solutions (k set to 5 and 7) in the portion of the graph where congestion is apparent by inspecting average journey time values (s) when the number of vehicles in the system is 400, 350 and 300. Both the table and bar chart clearly show how the shortest path solution A* is improved upon by TraffCon with k set to 5 and 7 e.g. with 350 vehicles average journey times are 2370, 835 and 555 seconds respectively.

The results for average fuel economy (km/litre) are compiled in fig. 6. As more and more vehicles are travelling on the road network it becomes increasingly congested causing the average fuel economy to decrease until the system becomes completely gridlocked. The saturation point for a solution is reached when average fuel economy begins to descend steeply. The best performing TraffCon solution shown (k = 7) performs 22.4% better than the shortest path method as their saturation points are approximately 245 and 300 vehicles respectively. This is 40% off the unachievable "ideal" solution which has a saturation point of approximately 420 vehicles.

Testing of the effect of reductions in penetration rate of the TraffCon technology to its effectiveness is in progress and initial results show a promising resistance to disimprovements.

VII. Conclusion and Future Works

This paper has proposed a novel Best Route Selection Algorithm for use in the TraffCon traffic management system. This algorithm has been modeled, implemented and tested in a simulation environment. Test results show that the algorithm alleviates the traffic congestion problem by better utilising existing road capacity. This results in shorter journey times, improved fuel economy and a reduction in gas emissions. The proposed solution was tested stand-alone, in comparison with an existing approach and in comparison with an ideal solution.

Future works will include an enhancement of the implementation to adapt the route over a journey if a better route becomes available as traffic conditions change. To achieve this the "flash crowd" problem where vehicles divert to desirable segments and keep oscillating must be overcome. A solution can be built by predicting the demand. Further improvements are expected by fine-tuning the setting of the k parameter as this has proven to be very significant for the algorithm and also by optimizing the setting of the weights. The performance of the system will also be analysed in greater detail by using a wider range of metrics.

ACKNOWLEDGMENTS

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