Route-based Vehicular Traffic Management for Wireless Access in Vehicular Environments

Kevin Collins and Gabriel-Miro Muntean

Performance Engineering Laboratory, RINCE,
School of Electronic Engineering, Dublin City University,
Dublin, Ireland
{kevin.collins, munteang}@eeng.dcu.ie

***Abstract*— Traffic congestion is a very serious problem which is becoming ever worse as the growth in the number of cars on the road significantly out-paces the provision of road capacity. This paper presents a novel vehicle routing algorithm for TraffCon - an innovative Traffic Management System for wireless vehicular networks - and discusses its complexity. The algorithm combats 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 increases road capacity utilisation and consequently reduces traffic congestion in comparison with an existing approach.**

I. Introduction

Wireless Access in Vehicular Environments (WAVE) has attracted significant interest and has seen increasing activity in recent years. As the standardization of WAVE under IEEE 802.11p is ongoing [1], [2], [3], [4], [5], it is clear that there is a need for research and development which would support and implement a new set of WAVE-based applications in the vehicular realm.

There are many research groups exploring feasible use-cases for WAVE and much of the early focus has been on making vehicles safer. The Vehicle Safety Communications Consortium has compiled a listing of distinct use-cases and ranked them by benefit [6]. Starting from these use-cases or from similar scenarios, many groups worldwide are researching or developing vehicular safety applications [7], [8], [9], [10].

More recently academics have pursued other avenues for WAVE by proposing for example a remote diagnostics application [11], a mobile surveillance platform for national security which uses vehicles as sensors [12] and a solution for free parking space discovery [13].

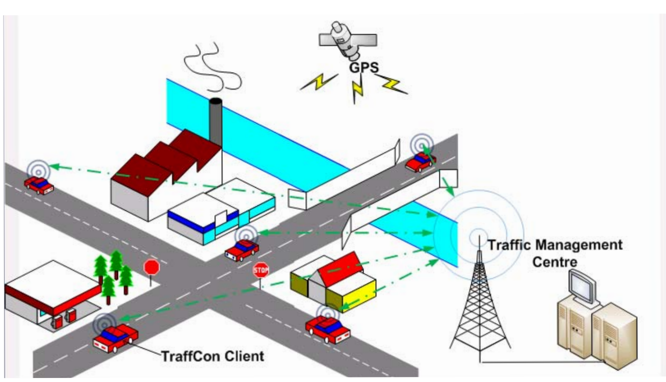

Fig. 1. Traffic Management System (TMS) for WAVE

One use-case for WAVE which has enormous potential is traffic management (figure 1). Vehicular traffic is one of the biggest problems faced by cities around the globe; in urban areas commuters can spend large portions of their days stuck in traffic. It has been estimated by the Texas Traffic Institute that traffic congestion will cost the US over $90bn per year by 2009 [14] and the UK Treasury put the cost to its country's economy at £20bn (US$38bn) for 2006 alone [15]. These are huge monetary costs based on lost productivity and wasted fuel. However there is also the environmental cost to consider. For example in Europe in 2004 road transport accounted for 19.5% of greenhouse gas emissions [16].

On top of the existing problems there is a worsening trend. The growth in the number of vehicles on the road outpaces growth in road capacity worldwide. From 1982 to 2002, the total number of vehicles in the US grew by 36% and vehicle miles travelled - by 72%, while road capacity increased by less than 5%. Between 1990 and 2004 the number of cars in the 25 EU member states rose by over 40% and continues to rise. Meanwhile the total length of motorways in the EU grew by 28% between 1990 and 1998 and has remained roughly stagnant since then [14], [15]. Also in spite of more fuel efficient vehicles being produced, emissions from road transport are expected to further increase due to the rise in traffic volumes [16].

In this context **TraffCon**, a novel Traffic Management System for WAVE [17] is introduced. TraffCon requires vehicles to have a GPS receiver (for 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.

This paper focuses on TraffCon management of vehicle routes by proposing the Best Route Selection Algorithm and discusses its complexity and benefits. This novel route management algorithm improves Quality of Driving Experience (QDE) by reducing journey time, fuel consumption and gas emissions.

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II. Related Works

There are many research groups exploring use cases for WAVE which improve QDE by influencing vehicle routes. These can be loosely divided into three main categories Traffic Information/Advisory Systems (TIS), Autonomous Vehicle Systems and Traffic Management Systems (TMS).

A. Traffic Information/Advisory Systems

A number of TISs 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. Examples of this include a traffic information system utilising vehicular mesh networks [18], a system which presents time-sensitive information about traffic conditions and roadside services [19], StreetSmart: a system which identifies and disseminates traffic patterns to users [20] and SOTIS: a system which distributes up-to-date travel and traffic information pertinent to a vehicles locale [21].

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.

B. Autonomous Vehicle Systems

Autonomous vehicle systems can provide traffic control solutions by fully automating vehicles and thereby removing user responsibility for driving. There has been and continues to be a wealth of research in this area, the most celebrated of which feeds into the DARPA Urban Challenge Autonomous Vehicle Competition (and previously the DARPA Grand Challenge [22]). Some notable recent work includes a system to keep autonomous vehicles in the correct lane using inter-vehicle communication [23], a and a system capable of avoiding complex obstacle filled environments to complete a journey described by a simple set of waypoints [24].

However at present such solutions are prohibitively expensive for large scale deployment and must also overcome the challenge of user resistance to automation.

C. Traffic Management Systems

Systems which actively control aspects of the traffic network in order to force member nodes into a behaviour which has some benefit to the system as a whole can be classified as Traffic Management Systems. Current work in this area includes a system where users can reserve a slot on a high-priority highway lane by paying a premium [25], a vehicular ad-hoc networks (VANET) approach to traffic management in emergency and evacuation scenarios [26] traffic adaptive traffic lights for improved traffic co-ordination at intersections [27] and train - vehicle communications to manage their interactions at road and rail intersections [28]. These solutions micro manage distinct scenarios to provide some benefit but do not examine the effect on traffic in the entirety of the road network. In [29] Inoue et al present a route based vehicle control method designed to alleviate traffic congestion but results show minimal improvement over existing shortest path navigation techniques.

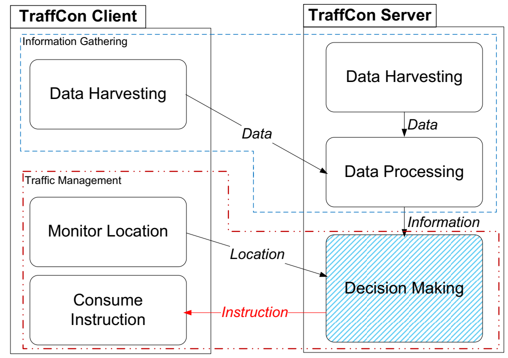

Fig. 2. TraffCon Architecture with Server Side Decision Making for Instruction Dissemination

III. System Architecture

TraffCon has a client-server architecture. Vehicles act as client nodes and communicate with the server which is responsible for traffic management. The system's functional blocks are divided between client and server as shown in figure 2. Server side decision making means instructions are disseminated and consumed by the clients.

For TraffCon's server side decision making, the overall situation is of paramount importance and vehicles are given route instructions designed to benefit both the individual and the overall system. Additionally TraffCon is readily enhanced to consider new parameters in order to generate environmental or social system-level benefits.

The system is comprised of four main functional blocks:

1) Data Harvesting - all nodes in the system gather useful temporal and spatially referenced traffic data e.g. vehicle velocity, acceleration etc.
2) Data Processing - the data is filtered, aggregated and refined to generate precise information regarding the state of the traffic network. In this instance the data processing results in road segments being assigned the metrics required by the cost equations discussed in Section V
3) Decision Making - the traffic network information is used in a decision making process which generates a route instruction which if followed has a benefit over the other route choices available e.g. improved traffic flow, a reduction in fuel consumption. In this case the decision making block is comprised of a Best Route Selection Algorithm examined in detail in Section IV.
4) Instruction Consumption - the instruction is consumed i.e. it is followed or ignored.

The functional block - Monitor Location also present in figure 2 simply highlights the fact that the system is by necessity location aware.

IV. Best Route Selection Algorithm

A. Overview

The proposed Best Route Selection Algorithm 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 is evaluated for each route, resulting in an associated fitness score. The fitness function is presented in the next section (see equation (1)).

(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.

B. Complexity

In a network such as a wireless vehicular network where communication delays may be substantial it is important that delays introduced into any communication sequence by processing are kept to an absolute minimum. It was for this reason that the k parameter was introduced.

The generalised Floyd Shortest-Path algorithm [30] is used to create the cache of paths offline, from the current roadmap. Constraint checking runs in parallel to ensure the k routes are valid i.e. no rules of the 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 by the algorithm. If a permanent change is made to the roadlayout (e.g. new road constructed) then the cache of paths is regenerated using the new roadmap. Temporary changes in the roadlayout can be accounted for by associating special fitness scores to a road segment e.g. for a road closed due to roadworks the road segment can be assigned a fitness score of infinity so it is never selected.

In terms of computational complexity the algorithm is the simple operation of choosing the smallest number from a list of size k meaning a complexity of order $O(k)$. In practice k will be a small number i.e. approximately less than or equal to 20 so processing time will be negligible.

An obvious alternative to the proposed approach is to use a shortest path algorithm with the fitness scores as edge weights. However this results in a complexity of order $O(V^2)$ where V is the number of vertices in the road network. In a large-scale real-world road network, V is a very large number and consequently the proposed solution will be considerably more efficient.

V. Fitness Function

The fitness function presented in equation (1) 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 (see eqaution (2)), 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}.

$$R_{nv} = w_1 T_{nv} + w_2 C_{nv} + w_3 F_{nv} \quad (1)$$

For a vehicle v taking route n, R_{nv} components are:

T_{nv}.............Journey Time Cost
C_{nv}.............Used Capacity Cost
F_{nv}.............Fuel Consumption and Emissions Cost
w_i...............Weighting Factors

$$\sum_{i=1}^{3} w_i = 1 \quad (2)$$

A detailed description of the individual cost components (T_{nv}, C_{nv} and F_{nv} can be found in [31]. This fitness function could be enhanced at a later date by considering additional parameters such as speed, operating cost, solution fairness, etc.

VI. Testing

In order to evaluate the proposed route management solution simulations are performed with the Scalable Wireless Ad Hoc Network Simulator (SWANS) [32]. 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, USA.

A. Simulation-based Testing

In order to evaluate the efficiency of the proposed solution the following experiment was performed examining three different scenarios, which involved three competing approaches, including Traffcon.

Case (1): before each vehicle embarks on its journey it selects a shortest route using the A* shortest path algorithm [33]. The vehicle does not deviate from this route. The shortest path algorithm factors in the speed limit and a turn penalty based on intersection type for each road segment.

Case (2): each vehicle drives to its own destination according to the route management solution. The weights of the fitness function presented in equation (1) are set at w_1 = 0.5, w_2 = 0.5 and w_3 = 0. Different values of k (5, 10, 15 and 20) are tested.

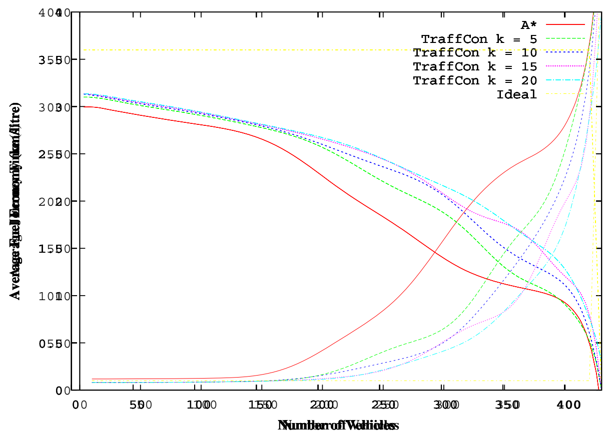

Fig. 3. Graph of Avg. Journey Time(s) against Number of Vehicles

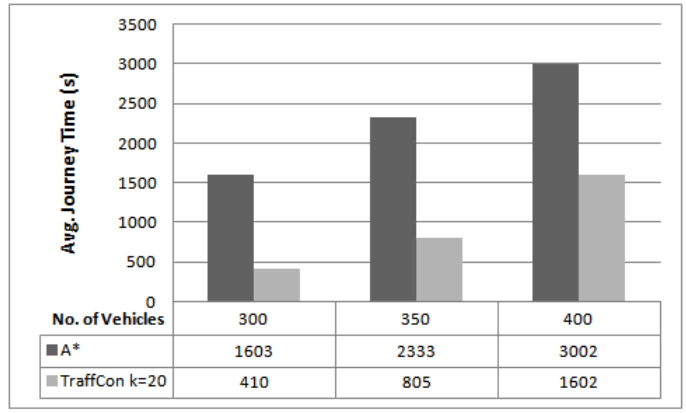

Fig. 5. Avg. journey times(s) at selected vehicle numbers

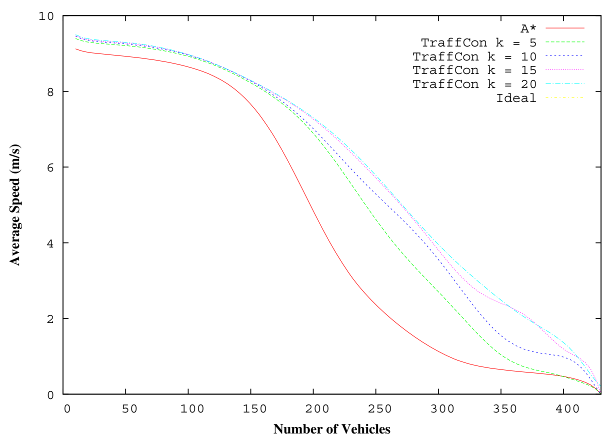

Fig. 4. Graph of Avg. Speed(m/s) against Number of Vehicles

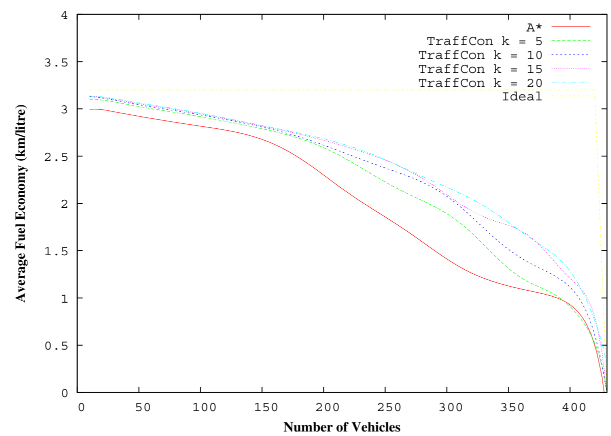

Fig. 6. Graph of Avg. Fuel Economy (km/litre) against Number of Vehicles

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

The simulation time was set at two hours. In each simulation, the number of vehicles travelling in the network was varied and average journey time, speed and fuel economy was measured. In order to reduce the influence of noise in the results, the experiments were run three times using different seeds and the results were averaged.

B. Results

The results for average journey time are compiled in figure 3. 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. In the congestion is occurring when average journey time begins to rise noticeably and gridlock when the average journey time rises steeply. It can be clearly seen by observing those characteristics in the graph that the TraffCon solution reduces traffic congestion very significantly over the shortest path solution and even comes reasonably close to the unachievable ideal solution.

In figure 5 the performance of the shortest path solution and the best performing TraffCon solution (k=20) in the portion of the graph where congestion becomes evident are scrutinized. This is done by measuring average journey time when the number of vehicles is 300, 350 and 400 respectively. The bar chart clearly shows how much the shortest path solution A* is improved upon by TraffCon e.g. with 350 vehicles: average journey times are 2333 and 805 seconds respectively a 65% reduction when using TraffCon.

The results for average vehicle speed are compiled in figure 4. As more and more vehicles are travelling on the road network it becomes increasingly congested causing the average speed to drop until the system becomes completely gridlocked and vehicles are burning not moving. This gridlock point for a solution is reached when the average fuel speed begins to descend steeply. The characteristics of this graph show that the reduction in journey time is being achieved in part by increasing the average speed over the shortest path solution as would be expected.

In figure 6 the results for average fuel economy are shown. Again it can clearly be seen that TraffCon improves over the shortest path solution. One interesting observation to be made from figures 3, 4 and 6 is that the TraffCon solution improves as k increases as would be expected. The improvement brought about by increasing k converges quickly as there is an upper bound enforced by the road network in use. This can be seen in figures 3, 4 and 6 as there is a large improvement when increasing k from 5 to 10 but progressively smaller improvements when going from 10 to 15 and then 15 to 20.

VII. Conclusion and Future Works

This paper has proposed a novel Best Route Selection Algorithm for use in the TraffCon traffic management system. TraffCon aims to overcome the multitude of problems - social, economic, environmental etc. caused by traffic congestion. The Best Route Selection Algorithm has been implemented and tested via simulation stand-alone and in comparison with an existing approach. Test results show that the algorithm alleviates the traffic congestion problem by increasing the usable road capacity. This results in shorter journey times meaning more free time for commuters and increased productivity for commercial drivers.

Future works will include an enhancement of the implementation to adapt the route over the course of a journey if a better route becomes available due to a change in road network conditions. An extension of the fitness function to include additional parameters which consider environmental and social issues is also envisaged.

Acknowledgments

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