# An Adaptive Vehicle Route Management Solution Enabled by Wireless Vehicular Networks

Kevin Collins, Gabriel-Miro Muntean
*Performance Engineering Laboratory, School of Electronic Engineering,*
*Dublin City University, Dublin, Ireland*
{collinsk, munteang}@eeng.dcu.ie

*Abstract*— **In order to accommodate the constantly growing number of vehicles on the road with which infrastructure provision is failing to cope, new means of optimizing the available road space are required. This paper presents a novel adaptive vehicle routing algorithm for TraffCon - an innovative Traffic Management System enabled by wireless vehicular networks. The algorithm combats the vehicular traffic congestion problem by seeking to optimize the usage of existing road capacity, while also minimising vehicle fuel consumption and emissions. Results demonstrate that the algorithm significantly increases road utilisation, reduces congestion, average journey times and fuel consumption in comparison with existing approaches.**

## I. Introduction

Wireless vehicular networks have attracted significant research in recent times. The development of standards which enable inter-vehicle and infrastructure-to-vehicle communications which underpin wireless vehicular networks - be they mesh or ad hoc - is well underway (e.g. IEEE1609 Wireless Access in Vehicular Environments (WAVE) [1], [2], [3], [4], [5]). The biggest remaining obstacle for this technology is the emergence of a killer application to drive market introduction and widespread success.

The search for this application has caught the imagination of researchers and many groups are studying feasible use cases for wireless vehicular networks. Safety applications have proved especially popular [6], [7], [8], [9]. One use case with vast potential is the alleviation of vehicular traffic problems.

Vehicular traffic is one of the most critical concerns for a modern society where cities are ever-growing. In 2008, for the first time, more than half of the world‘s population lives in urban areas and the balance of people continues to shift to the cities [10]. It is well known that in urban areas commuters can spend a large percentage of their day stuck in traffic. It has been estimated that traffic congestion will cost the US economy over $90bn per year by 2009 [11] and the EU economy approximately 1% of its GDP by 2010 [12]. There is also the environmental cost. In Europe in 2004 road transport accounted for 19.5% of greenhouse gas emissions [13]. Alarmingly there is a worsening trend as the growth in the number of vehicles on the road outpaces growth in road capacity worldwide and the construction of new roads is ultimately constrained by space.

In this context **TraffCon** is proposed as a novel Traffic Management System enabled by wireless vehicular networks [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 a many aspects of vehicle or infrastructure behaviour such a system could attempt to affect in order to alter traffic conditions: vehicles' route, lane or speed, traffic lights or any other variable road side infrastructure (e.g. adjustable speed limit signs).

This paper focuses on the management of vehicle routes and as a novelty aspect, it proposes an adaptive vehicle routing algorithm which improves Quality of Driving Experience (QDE) by reducing journey time, fuel consumption and gas emissions.

## II. Related Work

There are many research groups exploring use cases for wireless vehicular networks 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.

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 asynchronously in order to support two main functions: information gathering and traffic management as shown in figure 1. Communication between client and server is achieved via a mesh network.

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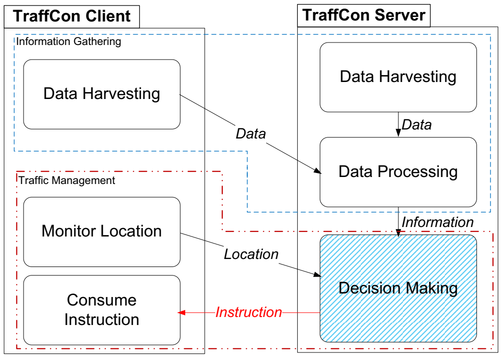



Fig. 1. TraffCon system architecture

### A. Information Gathering

With information gathering all nodes in the system collect useful temporal and spatially referenced traffic data e.g. speed, acceleration (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, some threshold on the age of the information is 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 vehicular network. In this case the decision making block is comprised of a 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 as an adaptive vehicle routing algorithm. 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. This fitness function which considers overall road congestion, vehicle journey times and fuel consumption is presented in the next section (eq. 4).

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

(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 cache of $k$ shortest paths is created using the generalised Floyd Shortest-Path algorithm [23]. 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. The parameter was introduced to reduce the complexity of the solution space and speed up the solution finding process.

Other well known $k$ shortest path algorithms exist including the double sweep algorithm and the generalized Dantzig algorithm [23]. However the double sweep algorithm is better suited to finding the k shortest paths between a specified vertex and all other vertices, while both Floyd and Dantzig algorithms are suited to finding the $k$ shortest paths between every pair of vertices, as required. These two algorithms are of the same order of complexity so the choice for the Floyd algorithm does not influence system performance. The complexity of the proposed algorithm is discussed further in [24]

## V. Fitness Function

### A. Preliminaries

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

Equation (1) can be used to estimate the value of the fuel consumed (ml), $\Delta F$, during a time interval of duration $\Delta t$ seconds [25] by a vehicle travelling with an instantaneous speed $s$ and acceleration $a$. The total tractive force $R_T$ and vehicle mass $M_v$ are constant and $\alpha$, $\beta_1$, $\beta_2$ 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 $\alpha$, $\beta_1$, $\beta_2$ are simply replaced by appropriate alternatives.

The Carbon Dioxide ($CO_2$) emissions are estimated directly from fuel consumption by using equation (2):

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

where,

$\Delta F$ = 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 $R_T$, $M_v$, $\alpha$, $\beta_1$, $\beta_2$ and $f_{CO_2}$ remain constant for all routes and may not be included.

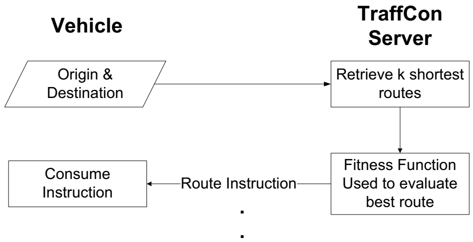



Fig. 2. One Iteration of TraffCon's best route selection algorithm

The values of $s$ 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.

As a direct consequence, the Fuel Consumption and Emissions Cost for a road segment $n$ can be calculated as the summation of the instantaneous velocity ($s$), plus the instantaneous acceleration ($a$) squared by the instantaneous velocity divided by 1000, all multiplied by the time interval duration ($\Delta t$), for all the time intervals along the given road segment from its origin (O) to destination (D).

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

The fitness function presented in equation (4) is proposed to choose a vehicle's route so that journey time, road congestion, 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 $w_i$ which obey equation (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 $R_{nv}$.

$$R_{nv} = w_1 T_{nv} + w_2 C_{nv} + w_3 F_{nv} \tag{4}$$

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

$$\sum_{i=1}^{3} w_i = 1 \tag{5}$$

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

### B. 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. Each cost function generates a cost score between 0 and 1. These individual cost scores are calculated as follows.

*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 from the $k$ possible routes $t_{maxv}$ (see equation 6).

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

*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).

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

*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).

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

## VI. Testing

In order to evaluate the proposed route management solution simulations are performed with the Scalable Wireless Ad Hoc Network Simulator (SWANS) [26]. 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 as highlighted in figure 3.

### A. Simulation-based Testing

In order to evaluate the efficiency of the proposed solution the following experiment was performed examining four different scenarios, which involved four competing approaches, including TraffCon with static and dynamic route adaptation, respectively. 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.

Case (1): before each vehicle embarks on its journey it selects a shortest route using the A* shortest path algorithm [27]. The vehicle does not deviate from this route. The shortest


Fig. 3. Subnetwork of Boston road network used highlighted

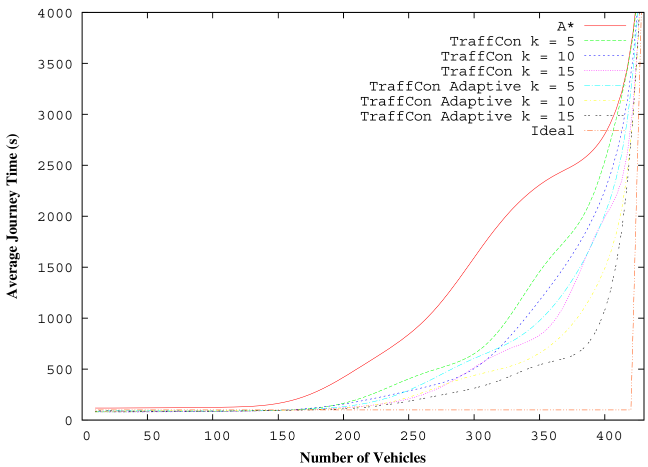



Fig. 4. Average Journey Time(s) against Number of Vehicles in the Network

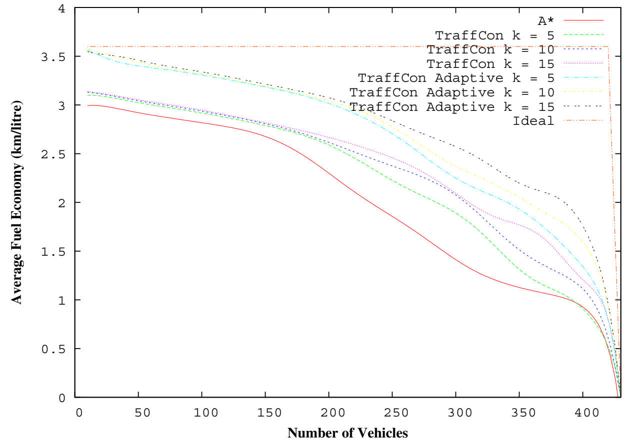
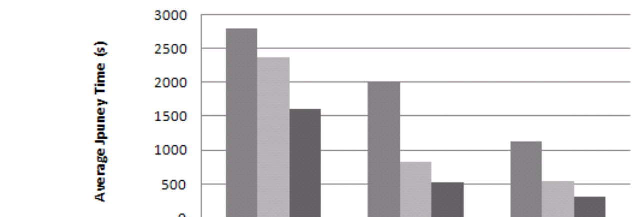



Fig. 5. Avg. Fuel Economy (km/litre) against Number of Vehicles




| No. of Vehicles | 400 | 350 | 300 |
|---|---|---|---|
| A* | 2810 | 2020 | 1130 |
| TraffCon k=15 | 2370 | 835 | 555 |
| TraffCon Adaptive k=15 | 1610 | 540 | 315 |

Fig. 6. Avg. journey times(s) at selected vehicle numbers

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 but without adaptation during the journey. The weights of the fitness function described in equation (4) are set at $w_1$ = 0.5, $w_2$ = 0.5 and $w_3$ = 0. Different values of k (5, 10 and 15) are tested.

Case (3):each vehicle drives to its own destination according to the route management solution with dynamic adaptation during the journey. The weights of the fitness function are set at $w_1$ = 0.5, $w_2$ = 0.5 and $w_3$ = 0 and different values of k (5, 10 and 15) are considered.

Case (4): 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 on the road was varied and average journey time and fuel economy was measured.

### *B. Results*

The results for average journey times (expressed in seconds) are compiled in figure 4. As the number of vehicles travelling on the road network is increased for each solution, eventually average journey time begins to increase noticeably as the system becomes congested. At some point average journey time begins to climb steeply and the system is effectively gridlocked. The best performing non-adaptive TraffCon solution shown (k = 15) performs 44% better than the shortest path method as their gridlock points are approximately 250 and 360 vehicles respectively. The best performing adaptive TraffCon solution shown (k = 15) performs a further 9.7% better as it does not become gridlocked till there are 395 vehicles in the system. This is only 6.3% off the unachievable "ideal" solution which becomes gridlocked at 420 vehicles.

In figure 6 the performance of the shortest path solution and the best performing adaptive and non-adaptive TraffCon solutions (k=15) are examined in the portion of the graph where congestion is apparent by inspecting average journey time values when the number of vehicles in the system is 400, 350 and 300, respectively. Both the table and bar chart clearly show how the shortest path solution A* is improved upon by the non-adaptive TraffCon which is in turn further improved upon by the adaptive TraffCon 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 figure 5. 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 and vehicles are burning fuel but going nowhere. This gridlock point for a solution is reached when the average fuel economy begins to descend steeply. The best performing non-adaptive and adaptive TraffCon solution shown are when k = 15. Non-adaptive TraffCon performs 32.7% better than the shortest path method as their gridlock points are approximately 245 and 325 vehicles respectively. Adaptive TraffCon performs a further 20% better as its gridlock point is approximately 390 vehicles. This is 7.7% off the unachievable "ideal" solution which has a gridlock point of 420 vehicles.

It can be seen in figures 4 and 5 that the significant improvements made by TraffCon over the shortest path solution occur over a wider range for fuel economy than journey time. This is because fuel consumption depends not only on journey time but also on velocity and acceleration associated with the route. The tested implementation reduces the "stop-startiness" which occurs when vehicles impede one another and reduces fuel consumption by evenly distributing the density of vehicles on individual road segments. It is also clear from these figures that the performance of the TraffCon solution improves as the value of $k$ is increased in both the non-adaptive and adaptive cases. Finally testing the effect of reductions in penetration rate of the TraffCon technology to its effectiveness are in progress and, initial results show a promising resistance to disimprovements.

## VII. Conclusion and Future Works

This paper has proposed an adaptive best route selection algorithm for use in the TraffCon traffic management system. The algorithm has been implemented and tested. Test results show that the algorithm gives shorter journey times, improved fuel economy and consequently lower harmful fuel emissions, while journey cost is also reduced in comparison with an existing scheme. It is also significant to note that these results are only 8% adrift from an unachievable ideal solution. In summary TraffCon's benefits are varied: social, economic and environmental i.e. shorter journey times, financial savings, potential increased productivity for commuters and professional drivers and a reduction in vehicle gas emissions.

Future works will include fine-tuning the weights in the fitness function as this has proven to be significant for the algorithm. Reducing the load placed on the network by communications for the traffic management phase of the system will be a major aspect of future work. One option is to not always attempt to adapt the route if a vehicle is obeying its initial route, removing the need for that vehicle to communicate.

## Acknowledgments

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