Optimisation of geofencing for mobility solutions in smart cities

Peter Fussey  
Technical Authority, Controls  
Ricardo  
Shoreham-by-Sea, UK  
peter.fussey@ricardo.com

Josh Dalby  
Chief Engineer  
Ricardo  
Shoreham-by-Sea, UK  
joshua.dalby@ricardo.com

Abstract – Mobility solutions are increasingly aware of their location and can be considered as elements within a connected transport system. In this context, geofencing refers to the use of a vehicle position to change its behaviour to improve the overall environment for the whole transport system. In this paper, we start with advances in simulation tools for optimizing the use of geofences for both existing and new vehicles, covering both vehicle performance and the overall impact on air quality. The results of the simulations have been demonstrated in a connected city environment resulting in significant reductions in emissions and energy consumption for two applications; a geofence enabled bus and a fleet of existing hybrid electric vehicles using a smartphone app to enable geofence zones.

Keywords – Geofencing, Air quality, Emissions, Fuel consumption, Hybrid Electric Vehicle

I. INTRODUCTION

Mobility and transport systems are undergoing rapid changes to heavily reduce CO2 emissions whilst also reducing their contribution to air pollution that is linked to human health impacts including lung disease and premature mortality, [1]. The drive to zero emissions is focussed on the development of new electric and hydrogen-based vehicles (fuel cell and internal combustion). These new vehicles will be introduced progressively over the coming years. In the meantime, there are many hybrid electric vehicles (HEVs), with combustion engines, deployed in cities for many years to come before they reach end-of-life. Cities around the world are considering implementing zero emissions zones, for example [2] and [3]. Vehicle manufacturers are adapting their HEVs to charge up before entering the zone, for example [4].

This paper considers how both existing and new mobility solutions can use the knowledge of their location to optimise the local or regional air quality through reduced emissions, considering CO2, noxious and particulate emissions.

Mobility solutions are increasingly aware of their location, with this information either built into the vehicles or in the driver’s smartphone location. This paper considers examples of both applications, Figure 1. The smartphone approach has the significant advantage in being applicable to vehicles that are currently operating on the road and so can have an immediate impact.

The paper is structured as follows; Section II introduces the simulation toolchain used to assess the impact of optimised geofencing solutions. Section III covers the demonstration of an optimised geofence vehicle, Section IV covers the demonstration of an optimised geofence using existing vehicles and a smartphone app and Section V concludes the paper.

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The detailed models are ‘driven’ by a traffic simulation. In this case based on the SUMO open source, microscopic, mesoscopic and intermodal traffic modelling tool, [5]. The traffic can be modelled at a microscopic level considering individual vehicle models, and at a mesoscopic level considering traffic movements with queues. The traffic model was configured for the city of Brighton and Hove (subsequently referred to Brighton) in the UK, Figure 2. This involved setting up traffic flows such as bus routes and general vehicle movements together with the infrastructure such as traffic lights and bus stops. The model was calibrated to replicate the measured average daily vehicle counts and validated according to the criteria in [6]:

Where

\[ GEH = \frac{2(M-C)^2}{N+C}, \]

M is hourly traffic volume from a traffic simulation and C is the real world, hourly vehicle count, sourced from the UK’s Department for Transport data.

The locations for the vehicle counts are shown in Figure 3. The target of over 85% accuracy was achieved for all criteria.

The optimisation of bus geofence zones

Initial implementations of geofenced, series hybrid buses have used fixed geographical zones to trigger the electric only operation. In the case of buses in Brighton, the electric only operation is requested in the AQMA. The bus operation was updated to reflect this strategy and there was an improvement in air quality through the main East/West route through the city.

The optimisation of hybrid bus operation considered in this paper maintains the vehicles following their standard routes with variations in the use of electric mode for differing levels of traffic and passenger loading. The geofences can also be divided by direction of travel, for example going East across the city is a different use case to going West.

From these use cases, the following approach for optimising the geofence boundaries was developed:

1. Parameterise the bus routes with zones defined by variables such as start point, length and split distance.

2. Use a design of experiments approach to take different combinations of the discretised geofence variable space and feed into the bus/traffic and battery models to obtain responses for quantities such as NOx emissions and battery capacity fade.

3. Use the data points to create continuous response surface models for optimisation.

The optimisation provides a trade-off between reduction in emissions versus impact on battery life. The emissions data has been assessed considering both the total emissions over the route and emissions in the central air quality management area, which is the area of historical poor air quality. It is important to consider both since just improving the air quality in the AQMA could move the emissions to other areas.

The varying of weightings on air quality and battery life leads to a pareto surface for each route and from this an optimum geofence can be selected. An example pareto surface is presented in Figure 5 which shows the original baseline (black), with no geofencing applied, the baseline with a static
geofence (orange), the pareto surface showing the best trade-off between emissions and battery life and the confirmation runs (grey) which take the parameters from the continuous response surface and re-run through the detailed simulation. Point #1 was selected as offered a significant reduction in emissions whilst also improving battery life compared to the baseline with a static geofence zone.

Figure 5: Pareto analysis of geofence optimization showing total NOx emissions along the route versus the time before 70% state of health, which is an indicator of battery ageing – a shorter time indicates a shorter battery life.

An example of the final optimised geofence zone is presented in Figure 6, where the new geofence zone is highlighted in red, the AQMA zone is in black and the bus route is multicoloured with colour indicating elevation.

Figure 6: Example of optimised geofence zone.

III. DEMONSTRATION OF OPTIMISED GEOFENCE VEHICLE

A. Vehicle implementation

The optimised geofence zone was evaluated using a bus equipped with a dynamic geofence, where the geofence can be updated, and a portable emissions measuring system (PEMS) for recording the impact on tailpipe emissions.

The bus was tested on a single bus route travelling in two directions; eastward (E) and westward (W). The route incorporates significant variations in topology with steep gradients and varying levels of traffic. Testing was carried out during peak and non-peak traffic conditions, 30% laden and no passenger conditions (using ballast) to highlight the impact of additional passenger loading.

The dynamic geofence zones were optimised for the different testcases meaning for example, that the buses used different geofence zones when going east or west, due to the difference in topology.

B. Test results

The results are summarised in Figure 8, which shows the benefit from introducing geofence buses with a fixed zone is a 23% reduction from the baseline conventional buses. The optimised geofence with dynamic geofence zones reduced the emissions by a further 8%. At the same time, the fuel consumption was reduced by 7% and the reduction of battery life has been estimated to be less than 2%.

C. Total cost of ownership

The wider impact of the optimised geofence was studied in a total cost of ownership assessment which is critical for a fleet of buses.

The cost of ownership can be divided into capital investment and running costs. The series hybrid buses represent a significant capital investment, and a major part of the investment is for the battery. The revised geofences have an impact on battery life which is estimated from the revised vehicle operating schedules. The running costs are affected by the impact of the geofence zones on the fuel economy.

Across a fleet of 54 geofence enabled buses, the update from a static geofence zone to dynamic geofences would save over £1.5 million over the life of the fleet whilst also improving the local air quality.
IV. DEMONSTRATION OF GEOFENCE VIA SMARTPHONE

A. Network architecture

A cloud-based network architecture was configured that was centred around a smartphone which had the following features:

- A hybrid vehicle with an Electric Vehicle (EV) mode,
- Location of the vehicle from GPS,
- Access to a cloud server for uploading vehicle performance data and downloading optimised geofences,
- Access to the vehicle OBD port to check if the vehicle is operating in electric only mode.

The smartphone has an app which accesses the latest geofence zone and provides an alert to the driver when the vehicle passes into the zone. The audio signal prompts the driver to press the EV button on the dashboard to select electric only operation. The app can then check if the engine is off through communications with the OBD port.

The final part of the architecture is the cloud-based optimisation algorithm that updates the geofence zone based on the vehicle operation data. The cloud server also provides a dashboard summarising how the fleet of vehicles are performing, Figure 12.

B. Optimisation of a personalised geofence zone

The vehicle operation can be used to optimise the geofence zone. The zone optimisation function creates bespoke electric only geofence zones for a given driver. The function calculates the zones as a function of the driver’s GPS traces over a time period and an air quality (AQ) map. The zones are updated on a real time basis in response to the driver’s routes and as the AQ maps evolve over time.

The algorithm for updating the zones is as follows:

1. The area of interest is discretised into a grid and residency times in each sector are measured, Figure 10.
2. The air quality map is discretised over the same grid and then the two are combined with the following linear relationship

   \[ G = w_R R + w_E E + b \]

   Where \( w_R \) and \( w_E \) are scalar weighting factors to control the relative importance of the residency, \( R \), and AQ matrix, \( E \), and \( b \) is a bias term.
3. The sectors where \( G \) is above a threshold are selected
4. The selected sectors are grouped into areas to avoid the vehicle repeatedly going in and out of zones.
5. The outer vertices of the region are collected, and the resulting polygon forms the geofence zone.

An example of the updated geofence zones is presented in Figure 11.

C. Results

The geofence app was deployed across a fleet of Taxi drivers in Brighton to demonstrate the potential of this approach. A dashboard was setup for each driver to provide live feedback on the vehicle operation, Figure 13, including statistics of whether the vehicle is in a geofence zone or not, and whether the driver has switched the engine off in the geofence zone (compliance). The dashboard also has access to time histories of the vehicle to allow greater insight into the vehicle operation.

The data from the vehicle included vehicle and engine speed and load but did not include tailpipe emissions. The time series data was fed into emissions models of the vehicles which allowed an estimation of the impact of the geofence zones on tailpipe emissions.

The trial showed that NO\(_x\) emissions were reduced by approximately 10% and PM\(_x\) emissions reduced by 23% in the
geofenced zones – this is due to the impact of the app on driving style and use of electric mode.

D. Driver feedback

In addition to the reductions in emissions, the trial also had a wider impact on the driver behaviour. A survey of the driver’s experiences showed that:

1. They became more environmentally aware with the geofence zones highlighting where vehicles may be creating poor air quality,
2. They had a better understanding of their vehicle’s capabilities,
3. They changed their driving style to allow their vehicles to be in EV mode.

V. CONCLUSIONS

A. Conclusions

The two trials presented in this paper have demonstrated the potential for geofencing zones to both reduce emissions and improve fuel economy. The technologies presented here are relevant to both existing vehicles and new vehicles so have the potential to make an immediate impact on urban air quality.

The combination of vehicle, traffic and air quality simulations provides a comprehensive tool for studying the impact of geofencing and other mobility scenarios on urban air quality. Demonstrating the benefit of being able to optimise the geofence zones in simulation can be used to develop city wide plans for implementing smart transport solutions.

The cost study has shown that the optimisation can reduce the total cost of ownership whilst at the same time improving air quality.

The smartphone app presents a novel approach to implement a geofence zone for existing vehicles. Again, it is a cost-effective way of improving air quality and was found to have additional benefits by encouraging drivers to be more environmentally aware.

B. Recommendations for future work

The simulation tools provide a framework for studies of air quality. A next step may be to investigate future transport scenarios with electric vehicles and hydrogen fuelled vehicles and study how their emissions from brakes and tyres contribute to the overall urban air quality.

The smartphone app may be used by local authorities to implement clean air zones for hybrid electric vehicles. For example by providing a financial incentive to have the app running to validate the vehicle is operating in EV mode.

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REFERENCES

[7] https://www.rapidair.co.uk/
Figure 12: Smart phone geofence dashboard for fleet statistics.

Figure 13: Dashboard for individual driver.