Quantifying the Impact of a Real World Cooperative-ITS Deployment across Multiple Cities

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Abstract

Cooperative Intelligent Transport Systems (C-ITS) - Connected Vehicle Technology in the USA - where vehicle and roadside infrastructure communicates to deliver more intelligent traffic management, is one of a range of ITS technologies emerging as a key component in pursuit of the wider objectives of improved urban mobility. This paper presents the Compass4D project, which deployed a C-ITS system in seven European cities and coordinated the common evaluation of the technology for three services focusing specifically on safety and environmental objectives under real-world driving conditions.

The significance of the Compass4D deployments and results provides some of the first evidence of the effectiveness of C-ITS in real world conditions. Both light and heavy vehicles showed efficiency savings of 2-6%. Equipped buses exhibited a variety of results with one pilot site showing a reduction of greater than 200gCO_2 per bus route per trip whilst other buses showed an increase in total emissions.

The paper presents results from both field trials and microscopic simulation studies (to understand the network- or city-wide impacts of the technology). It discusses the results in detail before outlining the system's potential for further deployment in terms of its impact on energy efficiency and environmental objectives. Government and road operators will benefit from the results to gain an understanding of the potential impact of services given specific deployment characteristics.

Keywords:

- Cooperative
- Environment
- Policy
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- Safety

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1. Introduction

Cities in both the developed and developing worlds are under pressure to balance public and private demand for mobility against finite spatial, financial and infrastructural resources, whilst ensuring safety and environmental targets are met.

In the EU-28, passenger transport (passenger km) has grown at 1.0% per annum since 1995, whilst freight transport (tonne km) has grown at 1.1% per annum. Trends in road fatalities are downwards (c.f. 57,000 in 2000 vs. 25,500 in 2016), but the vision of a further 50% reduction in fatalities over 2009 levels by 2020 (EC, 2010) is challenging. Similarly, whilst CO_2 emissions are declining (c.f. 5.1GT CO_2e in 2000 vs, 4.5GT CO_2e in 2013) (EC, 2015), the aim of a further 60% reduction in transport greenhouse gas emissions by 2050 (EC, 2011) is ambitious. Health Issues surrounding continued exposure to local air quality problems and noise have also come to the fore, with nitrogen dioxide levels in urban areas a particular cause for concern (Moldanova *et al*, 2011).

Amelioration of safety and environmental concerns in road transport can be partially achieved through provision of new, or expansion of existing, infrastructure. However, these are expensive solutions. Attention has turned to Cooperative Intelligent Transport Systems (C-ITS), which offer the potential to increase the efficiency of existing urban infrastructure by improving network capacity, whilst simultaneously providing safety and environmental benefits, and reducing fuel and energy demand (Jandrisits *et al*, 2015). The 2008 'Action Plan for the Deployment of Intelligent Transport Systems in Europe' (EC, 2008) and subsequent Directive on ITS deployment (OJEU, 2010) recognise the role C-ITS systems have to play in overcoming the limitations of traditional infrastructure, and seek to ensure their coordinated and consistent deployment.

Through targeted C-ITS measures aimed at specific users or vehicles, cities can potentially achieve policy targets, adding value to the road network, whilst reinforcing or encouraging desired behaviours amongst both motorised and non-motorised users. Packages of measures allow a city to become smarter in its overall provision of mobility services.

In this paper, selected findings from the European Commission's Compass4D ("*Cooperative Mobility Pilot on Safety and Sustainability Services for Deployment*") project are presented. Compass4D deployed C-ITS in real-world urban environments and quantified the impacts. Through the results and key findings, it is possible to determine how urban mobility policy could benefit from either selective or wide-scale deployment.

1.1 Background to C-ITS

C-ITS enable direct communication between vehicles, roadside infrastructure and traffic control centres (Jandrisits *et al*, 2015). The technology, which can communicate vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) - collectively known as V2X (vehicle-to-anything) – enables traffic management centres to receive precise and comprehensive information from vehicles about traffic situations. This allows a targeted approach to managing flows through a network, for example the ability to deliver signal priority for different types of vehicle. Furthermore, C-ITS can inform drivers about traffic events, such as traffic light phases, current traffic situations and danger zones (Jandrisits *et al*, 2015; Katsaros *et al*, 2011), enabling drivers to make informed route choices and implement more efficient driving behaviour. This can potentially result in safety benefits, greater energy efficiency, and a decrease in CO_2 emissions. Drivers not equipped with C-ITS systems may also potentially benefit from its effects, by experiencing fewer unnecessary changes in speed, or a reduction in start-up delays at junctions (Preuk *et al*, 2016). Conversely, non-equipped drivers may also be disturbed by 'out-of-the-ordinary' behaviour of equipped vehicles in certain circumstances, e.g. long, slow coasting to traffic signals (Rittger *et al*, 2015).

Early C-ITS research took place in laboratory conditions using traffic micro-simulation and concentrated on algorithmic development (e.g. Tielert *et al.*, 2010; Katsaros *et al*, 2011; Guler *et al*, 2014; Kamalanathsharma and Rakha, 2014). Although much simulation work has been performed in isolation, micro-simulation studies have also played a role in setting bounds on the expected impacts of C-ITS systems, as well as ascertaining network-wide effects or critical threshold penetration rates of equipment.

With the majority of the enabling technology already standardised in Europe by ETSI TC ITS (vehicle), CEN TC 278 WG16 (roadside infrastructure), and IEEE 802.11 p/ITS G5 (communications) (Festag, 2014; Lonc and Cincilla, 2016), field operational tests (FOTs) can be implemented to test C-ITS in real-world conditions (Barnard *et al*, 2011; Barnard *et al*, 2015). A FOT is "a study undertaken to evaluate a function, or functions, under normal operating conditions in road traffic environments typically encountered by the participants using study design so as to identify real world effect and benefits" (FOT-NET, 2015). Thus, drivers use their vehicles under normal conditions with data collected concerning the behaviour of the vehicle, the system, and the drivers themselves, as well as the interactions between them.

A major planned deployment is the European C-ITS corridor, a smart-road deployment project involving road authorities in The Netherlands, Germany, and Austria (Katsaros *et al*, 2011; Guler *et al*, 2014). However, the Compass4D FOT deployments (2013-15) provided an early indication of the potential impact of C-ITS technology in real-world driving conditions, and these are the focus of this paper.

1.2 Previous studies

The services offered by Compass4D build on a pedigree of C-ITS studies from Europe, the United States and Japan (Table (1)). These have examined the impacts of C-ITS through limited FOTs or simulation studies. Studies have focused on particular types of vehicle or operations using those vehicles on sections of road, typically urban highways. Work has targeted either technology demonstrations of V2X communication, or applications addressing a single policy goal, such as improving safety or increasing energy efficiency, but not necessarily both.

Previous studies have reported Green Light Optimal Speed Advisory (GLOSA) in isolation as being able to reduce CO_2 emissions and fuel consumption by approximately 13% (Eckhoff *et al*, 2013). Very similar results were reported for the adoption of a dynamic eco-driving system for highway traffic (Barth and Boriboonsomsin, 2009). These values are also in line with the identified benefits from the C-ITS systems in Table (1) for the FREILOT (Blanco *et al*, 2012) and COSMO (Volvo Group, 2013) project applications.

It is noted that suggested benefits from simulations, studies limited to few vehicles, or on a particular type of road (e.g. highways), may indicate greater efficiency results than those achievable across a real-world urban network (Tielert *et al.*, 2010; Schuricht *et al*, 2011; Xia *et al*, 2013). It is also considered unlikely that a combined C-ITS system, such as Compass4D, will yield benefits that are precisely a linear combination of the benefits as suggested for individual components. Nor might it be expected that all vehicle types would share similar benefits in all conditions. Such considerations helped inform the methodology applied in the Compass4D FOTs.

CVIS	Design, development and testing of V2X technologies and architectures (Ernst, 2006). 'Priority Intersection' application yielded a travel time saving of between 16% and 38% (CVIS, 2009).
COOPERS	Demonstrated the dissemination of infrastructure status and road hazard warning (RHW) information via dedicated I2V communication. The system was acceptable to drivers, did not cause undue distraction, enhanced compliance with traffic rules and had a positive impact on safety.
SAFESPOT	Examined cooperative vehicle highways systems (CVHS) to improve road safety (Andreone *et al*, 2010). Red light violation warning (RLVW) and RHW were later adapted in Compass4D. The socio-economic analysis of Geissler *et al.* (2011) emphasised the dominant cost of RSU infrastructure over in-vehicle systems (the on-board unit - OBU). Systems based on V2V are more cost-effective than V2I, if a 'critical mass threshold' of equipped vehicles exists.
DRIVE C2X	Complete penetration rates of In-Vehicle Signage (IVS) systems providing speed limit information could decrease fatalities by 23% and injuries by 13%. Further provision of adverse Weather Warning (WW), Road Works Warning (RWW), Emergency Brake Light Warning (EBLW) and Traffic Jam Ahead Warning (TJAW) could reduce fatalities by 6%, 3%, 2% and 2% respectively. However, complete penetration was not assumed possible until beyond 2030 (DRIVE C2X, 2014).
FREILOT	Sought to improve the efficiency of freight movements in urban areas, with focus on energy efficiency at intersections, behaviour of accelerating vehicles, adaptive speed limitation, 'eco-driving' support and fleet-management, real-time loading and delivery space booking (Gonzalez-Feliu *et al*, 2013). Field operational trials at the Dutch Integrated Test site for Cooperative Mobility (DITCM) in Helmond-Eindhoven yielded a 13% reduction in fuel consumption and CO_2 emissions with intersection priority and speed advice alone (Blanco *et al*, 2012).
COSMO	Reported a 13% fuel consumption reduction as well as a 6.4% increase in average speed for seven equipped buses in Gothenburg following time-to-green speed advice at intersections, bay-entry, and queue-avoidance advice at stops.
SmartWay (Japan)	A next generation road system that incorporated existing services such as Vehicle Information and Communication System (VICS) and Electronic Toll Collection System (ETC), as well as other services using advanced ITS technology (Kanazawa and Suzuki, 2016). Set standards and specifications for OBUs and RSUs, and performed system functions through on-road trials. Deployed nationwide services to provide dynamic route guidance and assisted safe driving through provision of road hazard alerts, including congestion, to drivers.

Table (1) Summary of key projects

1.3 An overview of Compass4D and its services

Compass4D collaborated with European cities to facilitate the sustainable deployment of C-ITS. Engaging directly with road operators, vehicle fleet operators and other local road transport stakeholders, it focused on road safety, energy efficiency and traffic congestion, and the significant potential of C-ITS to address these challenges.

FOTs took place in seven European cities based around real-world deployment of C-ITS technology: Bordeaux, Copenhagen, Helmond, Newcastle upon Tyne, Thessaloniki, Verona and Vigo (Mitsakis *et al*, 2014). The FOTs combined both pre-market and established technologies to demonstrate three services reliant on real-time, two-way communication between vehicles equipped with on board units (OBU) and roadside units (RSU) connected to network infrastructure, enabling both V2I and I2V communications:

1. *Red Light Violation Warning (RLVW)*, to increase driver awareness near signalised intersections, and to warn the driver of the possibility of an unsafe situation involving a signal violation. Such situations include violation of a red signal by the driver's own vehicle, probable violation of a red light by another vehicle on approach to the intersection, or emergency vehicle presence at or near the intersection. Further extensions of the RLVW service include turning warnings, for example the presence of oncoming traffic acting on a green light, or the presence of vulnerable road users;
2. *Road Hazard Warning (RHW)*, to raise driver awareness of potential incidents, and to inform drivers of appropriate behaviour in relation to any hazards faced. Hazards themselves may be static, with fixed spatial and temporal properties (e.g. planned road works) or dynamic (e.g. traffic incidents and collisions, evolving traffic queues, weather-based restrictions, etc.);
3. *Energy Efficient Intersection (EEIS)*, to reduce fuel consumption and energy use at intersections, implementing three sub-services through the provision of 'signal phase and timing' (SPaT) information to a vehicle:
   - 'Green Light Optimal Speed Advisory' (GLOSA) information provided to the driver, allowing a fuel-optimal trajectory to the signals (either deceleration to a stop, or progression through the lights).
   - 'Time-to-green' information provided to vehicles to allow engine idling stop support and to limit start-up delay losses.
   - 'Green priority' extending an existing green signal phase, or hurrying a future phase for the vehicle. With multiple intersections equipped with RSUs in an urban area, the potential exists for the system to allow the 'natural' formation of 'green waves' for equipped vehicles.

The three selected services were viewed as the most promising services in terms of sustainability beyond the project timeframe, and matched those services selected by the United States cooperative systems initiative.

The OBUs consisted of a processing unit, a radio system, a GNSS (Global Navigation Satellite System) receiver and a display. Off-the-shelf smartphone or tablet technologies running Compass4D applications delivered the required functionality for service provision to drivers. Additional logging capabilities came via a separate unit for evaluation. The RSUs consisted of a processor unit, a radio system, a GNSS receiver and a mobile or wired network connection. RSUs connected directly to traffic signalling or other sensor infrastructure, with the network connection enabling operational management and 'back-office' data collection (Hill and Edwards, 2016).

Communications between RSU and OBUs utilised both short-range wireless communication (ETSI 5G, derived from the wireless 802.11p protocol) and cellular communications (3G/LTE), following ETSI TC ITS (European Telecommunications Standards Institute) standards (ETSI, 2016). Whilst the precise architecture of implementation and communications technologies varied by site and service, the demonstration of vehicle interoperability between sites was possible (Hill and Edwards, 2016). Standardisation, interoperability and certification of C-ITS systems was promoted through cooperation with bodies such as ETSI and CEN, whilst high importance was attached to collaboration with other European projects and initiatives, and with counterparts from the United States and Japan. A final important element of the project (not covered in this paper) was development of business models, cost benefit analysis and exploitation plans to provide decision- and policy-makers clear and realistic insights into the real-world viability of C-ITS (Barmpas, 2016).

This paper focuses on the results of the data analysis from the *Energy Efficient Intersection Service (EEIS)*, in particular GLOSA and green priority. The EEIS was the only service deployed in FOTs in all seven cities, whilst full analysis of the road safety services (RHW/ RLVW) was constrained because accident data analysis requires a longer timeframe for observation and data collection than the twelve months available.

2. Methodology

The evaluation for the Compass4D project embraced both real-world data collection and desktop simulation with analysis of services taking place at both the individual vehicle and network-wide levels (Mitzakis *et al.*, 2014). For the real-world trials the results are purely concerned with the equipped vehicles due to the lack of any effective testing mechanism for non-equipped vehicles. In the simulation it was possible to assess the impact of the EEIS on both equipped and non-equipped vehicles.

2.1 Field Operational Trials

FOTs in Compass4D were aligned to the FESTA V methodology (FOT-NET, 2015). FOTs are an evaluation methodology used to test intelligent transport systems (ITS), specifically their ability to deliver real-world impacts and benefits. To achieve this, studies should be designed to evaluate a function, or functions, under normal operating conditions in road traffic environments. The study is normally conducted over a long period of time, at least several weeks. 'Normal operating conditions' implies that the participants use the functions during their daily routines, that data logging takes place autonomously and that the participants do not receive special instructions about how and where to drive.

The precise implementations of the EEIS services in Compass4D varied from city-to-city, due to the diverse nature of the existing infrastructures, and transit goals of the individual partners. For example, the Newcastle UK system added priority and GLOSA to a system of semi-adaptive controls (where signal lengths may change, but not the order of signals), based on both Vehicle Actuated (VA) and Microprocessor-Optimised Vehicle Actuation (MOVA) signals (Vincent and Peirce, 1988). Fully adaptive signals, able to change signal orders, present a greater challenge for effective GLOSA algorithms, as the dynamic nature of the changes makes effective trajectory prediction problematic (Bodenheimer *et al.*, 2014). Failure to include accurate estimates of queue lengths at intersections leads to sub-optimal trajectories being provided to vehicles (Schuricht *et al*, 2011).

The in-cab visualisation for the driver was a simple 'colour band' display (red = too fast, green = optimal, blue = too slow), alongside an indication as to whether the vehicle could expect priority, rather than providing a numerical target speed value. This was refreshed second-by-second in equipped vehicles, with no display provided when within a certain radius of the intersection, to avoid driver distraction (Matthias, 2015).

The EEIS was implemented and operated in real driving conditions over a 12-month period, with an initial 3-month 'baseline' phase where the system was not operating, followed by a 9-month fully operational phase, well beyond the 'several weeks' recommended as a minimum by FOT-NET. A baseline study is an important part of the methodology, as this enables the study team to compare the effects that the function has on traffic against a situation when the function is not operational.

Data from the deployments was subsequently analysed to provide insights into aspects of system performance against the baseline. Over 600 vehicles and 1200 drivers participated across the seven locations. A diverse range of vehicle types included buses, taxis, freight and emergency vehicles, as well as private cars (Hill and Edwards, 2016) (Table (2)).

City	Roadside units	Vehicles and Drivers
Bordeaux	22	60 vehicles (20 trucks; 34 cars; 6 emergency vehicles) 86 drivers
Copenhagen	21	106 vehicles (87 buses; 2 hydrogen cars; 17 trucks) 330 drivers
Helmond	24	38 vehicles (2 buses; 2 EVs; 4 cars; 8 trucks; 10 taxis; 12 emergency vehicles) 52 drivers
Newcastle upon Tyne	20	13 vehicles (2 EVs; 11 patient transfer vehicles) 20 drivers
Thessaloniki	7	351 vehicles (350 taxis; 1 car) 600 drivers
Verona	3	40 vehicles (10 buses; 30 cars) 50 drivers
Vigo	37	45 vehicles (20 buses; 13 cars; 10 taxis; 2 EVs) 77 drivers

Table (2) Site characteristics.

2.2 Data Analysis

Analysing the data from the Compass4D system required that there was both a metric to be analysed, a spatial region of interest within which to analyse that metric, and two distinct populations between which the metric could be compared, that is, the baseline and the operational phases.

For a normal trial it would be typically trivial to mark the separation between the baseline and operational phases for each of the differences. However, as this was a FOT using a system implemented on vehicles operating in the real world, simply having a distinction between the baseline and operational phases was insufficient. A vehicle approaching an intersection on one heading could not be compared to a vehicle approaching the intersection on a different heading. Each different approach towards an intersection needed to be assigned an ID so that a like-for-like comparison could be made.

Due to the size of the dataset, the IDs on each intersection were automatically assigned using a clustering algorithm. The clustering algorithm used the initial plus the final position and heading of the vehicle within the intersection to separate the data sets and “tag” the raw data with the appropriate ID. The actual clustering was accomplished using the DBSCAN (Density-Based Spatial

Clustering of Applications with Noise) algorithm (Ester *et al*, 1996). This is an algorithm which clusters together points which lie in high density regions whilst ignoring any points in a low density region. For example, on a T-Junction most vehicles would enter by one of three entrances and leave by one of the other two entrances. Hence the DBSCAN clustering algorithm would cluster the data into six separate groupings with any outliers flagged.

In addition to splitting the data by ID on each intersection, it was also necessary to split the analysis by the type of vehicle being investigated. Due to the large variety of vehicles it was decided to classify each vehicle into either a light, heavy or bus category. A light vehicle would be a typical passenger car or light van, with a heavy vehicle representing a truck, emergency vehicle or minibus.

The variation between light and heavy vehicles is simply one of scale, with heavy vehicles using more fuel generally and consumption being more sensitive to speed variations, particularly acceleration. Although there is a continuum in the classification for heavy and light vehicles, for this particular vehicle population there was a strong demarcation point with vehicles in the "heavy" category using up to five times as much fuel per km travelled.

Buses, by comparison, will use approximately the same amount of fuel over each intersection as the heavy vehicles (with the same corresponding efficiency) but they will exhibit a markedly different drive cycle due to their more frequent stops – i.e. to pick up and drop off passengers.

To harmonise analysis of the results from each of the pilot sites, a series of Performance Indicators (PI) were created that would allow similar analytical techniques to be used across each pilot site. The majority of the performance indicators were designed to highlight the proposed benefits of the EEIS system or the Speed Advice system, due to the comparative difficulty of creating performance metrics for either the RHW or the RLV use cases. The three most important performance indicators (emissions, duration and number of stops) are presented below:

- Emissions is the total (simulated) emissions across the 500 metre local region of each equipped intersection
- Duration is the total time taken to enter and exit each intersection
- Stops is the total number of separate "stopping" events. A stopping event is defined as any point where a vehicle drops below 5kmph

The spatial region of interest is defined as the subsection of the vehicle data within 250m of the Compass4D-equipped intersections with individual trips demarcated by the entry and exit timestamps within this region. As such they do not represent the change in emissions (for example) over the entirety of a vehicle's journey but rather the change in emissions within the locality of the equipped intersection. By analysing the results in this way it is possible to remove the excess variation which would be present if the full vehicle journey were to be considered.

As the only vehicles used within the Copenhagen pilot site were buses travelling a fixed route, it was possible only to extract the data for each complete bus route within the Copenhagen site and analyse the effect of multiple instrumented junctions over a single journey. In general, this led to a more consistent pattern of results as each bus would typically be affected by multiple intersections over the course of one journey, multiplying the effect of the EEIS.

Due to the variations in the implementation of the different system across pilot sites, such as the difference in data collection or the difference in baseline/operational phase timings (and indeed, what constitutes a baseline or operational phase), the quantitative conclusions are only valid for the particular environment within that pilot site. Results for Verona have been omitted from this paper because the unique nature of the site's objectives means that the results are not comparable to other sites.

	Priority			Speed Advice/GLOSA		
	Light	Heavy	Bus	Light	Heavy	Bus
Bordeaux				X	X	
Copenhagen			X			X
Helmond		X	X			X
Newcastle	X	X		X	X	
Thessaloniki				X		
Vigo				X		X

Table (3) Investigated use-cases for the Compass4D EEIS

In Table (3) the specific use cases investigated in each system are shown. Whether a use case was investigated depends on both the implementation of the service and whether there was enough data to adequately investigate the difference between the baseline and operational phases.

The results for light vehicles are only presented for the Bordeaux and Vigo pilot sites. Although both Thessaloniki and Newcastle possessed enough data in both the operational and baseline phase to analyse, the environment of the pilot sites themselves were deemed to be too different to warrant a combined analysis. For Thessaloniki this was due to the layout being comprised of multiple intersections within a very short distance. The short distance between intersections would not allow for the effects of one intersection to be separated and hence the results are not included here. In Newcastle the light vehicles used were electric drive train and hence would have a different response to the equivalent speed and acceleration profile for an internal combustion engine (ICE) vehicle.

The emissions for each of the vehicles were derived from an instantaneous emissions model (Panis, 2006) which allowed for the conversion of speed and acceleration into a direct second-by-second emission depending on the type of vehicle. In addition to the modelled emissions, fuel data was directly measured within the Bordeaux pilot site. Due to the linear relationship between emitted CO_2 and fuel consumption, a strong R^2 coefficient for a linear regression model constructed from the modelled emissions and the measured fuel would be a validation of the use of the Panis model.

It was observed that the R^2 coefficient typically varied between 0.6 and 0.8 for each truck indicating that although there was unexplained variation in the modelled emission, it was still possible to use it as a proxy for fuel consumption.

2.3 Simulation

Simulations of the Compass4D services were developed at six pilot sites to both expand the understanding of the FOTs and also to support future deployments of the system. The simulations concentrated on the EEIS service with a combination of GLOSA and Green Priority.

Each pilot site was responsible for developing its own methodology and tool chain for the simulation due to the difference in simulation/modelling experience within each site (Table (4)).

Pilot site	EEIS services		Simulation tools	Network		Scenarios	
	(GLOSA)	Green Priority		# Signalised Intersections	Type	High/Low demand	Penetration Rates
Bordeaux	X		Sumo + Omnet++/ Veins	4	Arterial		X
Copenhagen		X	VISSIM + EnViVer	21	Network	X	
Helmond	X	X	VISSIM + EnViVer	4	Arterial	X	X
Newcastle	X	X	VISSIM + EnvIVer	9	Arterial	X	X
Thessaloniki	X	X	AIMSUN + EnViVer	23	Network	X	X
Verona	X		Dynasim Cube	4	Arterial	X	X

Table (4) The type of simulation platforms and the scenarios tested are shown here.

In addition to the diverse modelling chains, individual sites adopted differing implementations of GLOSA, for example in Bordeaux modified algorithms from Katsaros *et al.* (2011) and Rakha and Kamalanathsharma (2011) were adopted, whilst for Newcastle and Thessaloniki the approach of Xia *et al* (2013) was used.

As a result of the wide variety of simulation methods, each model was required to produce a series of metrics that would be comparable to those produced through the real-world trials. This would enable the results from the model to be directly compared to those within the real-world trial.

Through the generation of comparable metrics it is not only possible to directly compare the simulations to the real world trials, but also to use the simulations to more easily test scenarios which could not be implemented within this trial. For example, whilst the RSU penetration, within local areas, could reach a high percentage, the penetration rate within vehicles was typically under 1%. Using simulations it was possible to test the effect of much higher vehicle penetration rates.

3. Results

In this section the results of the field operational trials (FOT) are presented in sub-sections 3.1-3.4. Sub-section 3.5 summarises the simulation results.

3.1 FOT Results: Efficiency

The effects of the Compass4D EEIS system on the average CO_2 emissions as vehicles pass through RSU equipped intersections are shown in Table (5) for five pilot sites. The emissions (and subsequent efficiencies) were modelled by the Int Panis emissions model. Note that the results for Copenhagen are the total efficiency changes over the entire bus route within the operational area of the Compass4D system.

The penetration rate for this system is considered to be 100% as it is only derived from those vehicles equipped with the Compass4D system when they are passing through an intersection equipped with the Compass4D system, with the previously noted exception of Copenhagen.

City	Type	Efficiency Change (gCO_2)	% Change	Significant?	P-Values
Bordeaux	Light	28.02 +/-4.1	9.3%	Yes	<0.001
	Heavy	37.99 +/-26.5	1.9%	No	0.153
	Heavy (fuel)*	37.34 +/-4.4	6.7%	Yes	<0.001
Copenhagen	Bus	27.64 +/-2.8	1.6%	Yes	<0.001
Helmond	Heavy	46.72 +/-9.9	4.7%	Yes	<0.001
	Bus	-59.93 +/-7.5	-4.1%	Yes	<0.001
Newcastle	Heavy	36.57 +/-16.2	3.2%	Yes	0.024
Vigo	Light	-0.04 +/-0.82	-0.5%	No	0.960
	Bus	-6.0 +/-3.3	-0.5%	No	0.069

** Heavy (Fuel) uses the direct measurements of fuel consumption for the Bordeaux Heavy Fleet.*

Table (5) FOT Results: the change in efficiencies between the baseline and operational phase is shown here where a positive change implies an improvement in efficiency. Significance is tested at the p=0.05 level.

From the data here it can be seen that there appears to be two results within the Compass4D system for the light vehicles. Vigo showed no statistically significant difference for efficiency within the system, whilst Bordeaux showed a substantial improvement in efficiency (~10%). Data from Thessaloniki, whilst not directly comparable to the data shown here due to spatial characteristics of the equipped network, also demonstrated a small improvement in efficiency of 1.7gCO_2/km.

The results for the heavy vehicles appear to be more consistent in efficiency improvements with each implementation of the Compass4D system registering an improvement of between 2-5%.

For the buses there was a much greater variety in efficiency with Copenhagen showing a relatively minor (but statistically significant) improvement of 1.6%. In comparison there is a poor (and indeed negative in the case of Helmond) response to the system from buses in Vigo and Helmond.

3.2 FOT Results: Duration

The effect of the Compass4D system on the average duration of travel through RSU equipped intersections for five pilot sites is shown here.

From Table (6) it can be seen that there is a statistically significant improvement in durations for heavy vehicles in Bordeaux and Helmond, light vehicles in Vigo and buses in Copenhagen. Again, there is a negative impact on Helmond buses with an increase in time of 2.44 seconds. Bordeaux light vehicles, Newcastle heavy vehicles and buses in Vigo showed no statistically significant difference.

City	Type	Duration Change(secs)	% Change	Significant?	P-Values
Bordeaux	Light	2.7+/-1.47	4.0%	No	0.066
	Heavy	5.80+/-1.9	6.1%	Yes	0.002
Copenhagen	Bus	63.91+/-5.9	7.0%	Yes	<0.001
Helmond	Heavy	2.44+/-0.8	4.3%	Yes	0.003
	Bus	-6.75+/-0.73	-17.7%	Yes	<0.001
Newcastle	Heavy	-0.29+/-1.0	-0.6%	No	0.780
Vigo	Light	3.19+/-0.8	5.3%	Yes	<0.001
	Bus	-0.65+/-1.0	-0.5%	No	0.471

Table (6) FOT Results: the change in total duration between the baseline and operational phase is shown here, where a positive change implies an improvement in duration. Significance is tested at the p=0.05 level.

3.3 FOT Results: Number of Stops/Time Stopped

The effect of the Compass4D system on the average number of stops per vehicle associated with RSU equipped intersections was also investigated. However, it was found that there was no statistically significant effect on the number of stops with the exception of Copenhagen which was found to exhibit an average reduction of 0.7+/-0.25 stops for each single bus trip.

City	Type	Stop Change (No.)	% Change	Significant?	P-Values
Copenhagen	Bus	-0.7 ± 0.25	-5.6%	Yes	0.005

Table (7) FOT Results: Number of Stops: the result for Copenhagen is for an entire bus route rather than averaged over a single intersection. Significance is tested at the p=0.05 level.

Two separate tests were used to determine the significance of the stop numbers, a Wilcox-Test and a 2-Sample Proportion test with the “Stops” variable transformed into a binary choice of “Stopped” or “Not Stopped”. Both tests showed that there was no statistically significant difference between the Operations and Baseline phases for all sites, with the exception of Copenhagen.

The lack of statistical significance for the test is mainly due to the comparative power of tests which compare binary populations. If it is assumed that we are trying ascertain the difference between a population which stops 0.75 times per intersection versus one which stops 0.8 times per intersection (the actual mean for all sites is approximately 0.75) then we would need a sample size of >1000 to give a proportional test with a power of 0.8. This is a greater number than almost all individually assessed intersection/trajectory combinations and so is will not be possible to observe a statistically significant difference of this magnitude. However, for Copenhagen, there are more than 2000 trips in each sample segment and hence it was possible to detect a statistically significant difference (and reduction) in the number of stops.

Therefore, as a proxy for the number of stops, the total time spent stopped at each intersection was used to test for the effect of the Compass4D system (Table (8)).

City	Type	Duration Change(secs)	% Change	Significant?	P-Values
Bordeaux	Light	9.77+/-1.4	20.7%	Yes	<0.001
	Heavy	4.06+/-1.8	8.9%	Yes	0.024
Helmond	Heavy	2.73+/-0.7	17.6%	Yes	<0.001
	Bus	-2.7+/-0.6	-37.5%	Yes	<0.001
Newcastle	Heavy	-0.9+/-1.1	-2.3%	No	0.401
Vigo	Light	1.33+/-0.7	7.4%	Yes	0.047
	Bus	-1.24+/-0.9	-0.5%	No	0.152

Table (8) FOT Results: the change in total time stopped at an intersection between the baseline and operational phase is shown here. Significance is tested at the p=0.05 level.

A similar behavioural pattern is shown in Table (8), as was exhibited in the previous emissions and duration metrics, with Newcastle continuing to exhibit similar anomalous behaviour as observed in the total duration.

3.4 FOT Results: GLOSA vs. Priority

In Table (9) we can see the comparative effect of the GLOSA and Green Priority systems on total emissions across the different pilot sites. Within this diagram it can be seen that the priority system worked better than the Speed Advice/GLOSA system. It should be noted that Newcastle and Helmond also incorporated a speed advice system, however it is concluded that the effect of the priority will have a greater impact and will be the driving force behind any changes in the system. As implied by Bodenheimer *et al.* (2014) and reported by Radivojevic *et al* (2016), the effectiveness of GLOSA algorithms in relation to Green Priority in energy reduction depends on the nature of the signals infrastructure – fully adaptive signals making precise trajectory calculations more problematic than for fixed, or semi-adaptive systems.

	Priority			**Speed Advice/GLOSA**		
	Light	**Heavy**	**Bus**	**Light**	**Heavy**	**Bus**
Bordeaux				+	=	
Copenhagen			+			
Helmond		+	-			
Newcastle	+	+				
Thessaloniki				=		
Vigo				=		-

Table (9) FOT Results: a matrix showing the effect of each system.

Green indicates a positive result (+), grey a neutral (=) and red (-) a negative result

3.5 Simulation Results

Simulation results are summarised in Table (10). Vigo did not participate in the simulation activities. The speed advice simulation, which was conducted in all cities apart from Copenhagen, showed a positive effect on emissions and stops when using the GLOSA service. In general higher penetration rates showed the greatest improvements. There was a significant decrease in the number of stops across all sites implementing this simulation scenario with a concurrent decrease in emission level.

It was also observed that there was an increase in the total travel time (duration) due to vehicles typically slowing down as a result of the advice issued by the system. Whilst the increase in travel time did not result in an increase in emissions, due to the reduced number of stops, it does raise questions about whether a driver would be willing to sacrifice a delay in their journey for an unseen-at-point-of-use saving in fuel.

For Green Priority, in the cities simulating it, there was a positive effect for all vehicles equipped with the system. There was a decrease in the total emissions, a decrease in the number of stops and a reduction in total travel time. The benefits of the Green Priority system were not only observed in the equipped vehicles, they could also be seen in any vehicle travelling on the same route as the equipped vehicles.

However, the priority system could be observed to have dis-benefits in the surrounding network and side-routes which were connected to the equipped intersections. If priority was granted too often on the main equipped route then it would, by the very nature of traffic signals, be denying priority on other routes leading to a potential net increase in travel times or emissions (Hill and Edwards, 2016). The operation of GLOSA may also significantly affect traffic delay on side streets (Radivojevic *et al*, 2016).

			Emissions	Stops	Duration
Pilot Site	**Penetration**		**% Change**	**% Change**	**% Change**
Bordeaux (GLOSA)	Low	10%	-6.67%	-78.33%	0.31%
	Medium	40%	-5.29%	-83.33%	2.48%
	High	100%	-5.39%	-75.83%	2.48%
Copenhagen (priority)	Bus	100%	-2.45%	-2.00%	-2.47%
	Car	0%	-6.86%	-13.24%	-8.01%
	Truck	0%	-5.63%	-11.27%	-5.38%
Helmond (GLOSA and priority)	Low	10%	-9.10%	-1.60%	1.55%
	Medium	30%	-8.92%	-4.10%	-3.30%
	High	100%	-9.55%	-10.60%	-20.69%
Newcastle (GLOSA and priority)	Low	20%	-5.50%	-20.30%	-18.00%
	Medium	40%	-9.10%	-20.70%	-17.60%
	High	100%	-8.40%	-18.50%	-16.70%
Thessaloniki (GLOSA and priority)	Low	20%	-1.18%	-11.10%	-2.63%
	Medium	60%	-0.18%	-13.20%	5.01%
	High	100%	-0.35%	-11.28%	7.02%

Table (10) Simulation Results: the changes in the three main performance indicators are shown here.

4. Discussion

The results for emissions/efficiency (Table (5)) showed an expected result, with the heavier vehicles recording the greatest absolute benefit in emission reductions. One anomaly was in the statistically insignificant improvement in efficiency for Bordeaux. However, it was possible to measure fuel consumption directly in Bordeaux and from this it was observed that there was a statistically significant saving in the fuel consumption. As fuel consumption is linearly correlated with emissions (and hence efficiency) one could expect that the same % improvement would be observed in both data sets. The discrepancy indicates that there is a possible mismatch between the model used for calculating the emissions and the real world fuel consumption.

Light vehicles generally showed either an improvement, or no statistically significant difference, between the baseline and operational phase. Although the system does appear to work for light vehicles, the greater potential for carbon emission savings for heavy vehicles would suggest that any further implementation of the Compass4D system would show greater absolute savings if implemented on a heavy vehicle.

Bus efficiency improvements initially appear more mixed, with a low absolute improvement for Copenhagen and no improvement in Helmond or Vigo. However, the result for Copenhagen is misleading as the efficiency improvement will only occur in the region of the RSU equipped intersections whilst the total measurement of efficiency is undertaken over the entire bus route. The absolute emission savings for Copenhagen are 288 +/- 12.7 gCO_2 for each full bus route, which, when considered on a "by intersection" basis, are comparable to those seen for the heavy vehicles in other pilot sites.

Both Helmond and Vigo showed no improvement in any metric for the equipped buses. Indeed, for Helmond there was a statistically significant dis-benefit to the Compass4D system. It is believed this lack of improvement is due to a variety of factors related to the spatial distribution of the RSU compared to the bus stops within Helmond and Vigo. If a bus has a scheduled stop within a reasonable distance of an RSU, then it is unlikely that any information issued by the RSU will be usable by that vehicle as there will be limited opportunity for the vehicle to implement advice. Similarly, if a priority request is automatically issued by a bus, which then comes to a stop to allow passengers to alight, then it is likely that the delay in the bus will lead to it missing the requested priority timing. In addition, for Helmond a priority system was already in place for the buses. Attempting to implement a secondary system likely led to either conflict between the two installed systems or an initial phase that could not truly be considered baseline.

The discrepancy between Copenhagen and Helmond, two sites that were implementing ostensibly very similar systems, shows that careful planning is needed for the implementation of any Priority system.

Improvements in time taken to cross the intersection (and number of stops within that junction) are typically expected to be of the same sign as the improvements (or not) in average emissions for a junction. If the Compass4D system is working as intended then there will be a reduction in the total number of stops and a reduction in emissions due to the lack of the more heavily polluting acceleration regimes. However, for Newcastle there was no statistically significant increase in stops or in the total time to cross an intersection plus an improvement in the efficiency. This is in contrast to other sites where the change in the number of stops was coupled with an identical change (in terms of improvement) in the change of duration. This discrepancy in Newcastle can be attributed to two individual intersections which saw a large increase in the number of stops but without the concomitant change in emission. This anomalous result was enough to skew the Newcastle data towards an overall increase in the number of stops (although not statistically significantly so) without a net increase in emissions. Again this highlights the need to view Compass4D (and co-operative ITS systems in general) as a situational and not global solution.

5. Conclusion

This paper has presented the Compass4D project, with particular reference to the Energy Efficient Intersection Service (EEIS). Results are presented and discussed relating to FOTs undertaken in real-world driving conditions, along with associated micro-simulation modelling.

The key findings are:

- Heavy vehicles showed a sustained improvement in emissions/efficiencies with savings in the region of 2-5% based on the modelled emissions. The real world fuel consumption saving was higher;
- Light vehicles showed a similar relative improvement in emissions/efficiencies but a lower absolute reduction in emissions;
- The effect on buses is highly situational with one site exhibiting a strong saving of over 200gCO_2 per bus route per trip. Other sites showed no improvement or a reduction in efficiency;
- Similarly, intersection crossing times and average stop numbers showed an improvement in most cases but with some variation due to conditions at specific pilot sites.

The results indicate that there is potential for significant contributions to environmental policy objectives given certain road configurations and for certain beneficiaries. The caveat to this is that we require a better understanding of configurations where the EEIS can be most effective, and how to optimally deploy the technology. For instance, we must balance the needs of individual users of the system against the possible impacts on the network as a whole, whilst in some locations or on some road configurations the effectiveness of the system can be quite limited. For example, network impacts would be minimal in the case of priority in the night-time economy whilst bus priority could act as a public transport incentive.

Furthermore, there is a need to investigate many other potential services (use cases) to tailor deployments to a specific set of objectives and local requirements. To date the services demonstrated for C-ITS have been quite limited and the consideration of 'what else can be done' with V2I communications integrated with traffic management needs to be explored. Even within the frame of the EEIS it may be that analysis of other pollutants, such as NOX, would deliver enhanced impact.

Despite the cautionary note implied by these results, it is clear that the demonstration and evaluation activities in C-ITS performed in the Compass4D project, along with cost benefit analysis (Barmpas, 2016), will play a major role in informing early adopters of C-ITS of the benefits and challenges of introducing the technology. What is not clear as yet, and is subject to further investigation, is at what penetration levels of equipped vehicles, and what access levels of various services, will the technology be most effective, or will the demands on the services by vehicles become greater than the optimal capacity of the system.

It is crucial that this knowledge gap is addressed as there are some major implementations of C-ITS planned across Europe, including the M2/A2 corridor in the South East of England, UK, the C-ITS Corridor (initially for roadwork warnings and traffic management) from Vienna-Frankfurt-Rotterdam, and an upscaling of deployments in the Helmond-Eindhoven-Tilburg region.

Upscaling is also planned in all the Compass4D deployment cities. In Newcastle upon Tyne, UK, expansion of the Compass4D network is progressing on a key arterial route between the suburb of

Gosforth and the city centre. The Urban Traffic Management and Control Centre (UTMC) for Tyne and Wear region, in association with regional partners and Newcastle University, have committed to develop and roll out cooperative traffic systems as part of a regional smart traffic management initiative. To part-facilitate this the UK DfT has invested in this extension in terms of the scale and location of future deployment as well as the development of new case studies, which include vulnerable road user detection (cyclists and pedestrians), bus fleet management, support for freight management and the night-time economy through late night taxi movements.

One further area where C-ITS will be considered in future is in the support for automation of vehicle functions. Here one could envisage the C-ITS system providing information to a vehicle with some automated capabilities, to set the optimum speed of the vehicle for traffic management, safety or vehicle emissions purposes, providing information on headway and possibly initiating some automated functions to assist (for example) older drivers to drive safely in the urban environment. This offers a whole array of automated services in cooperation with the infrastructure which potentially have significant benefits to urban traffic management and will be available long before fully autonomous vehicles.

Annex: Glossary of Terms

CITS	Cooperative intelligent transport system
CVHS	Cooperative vehicle highway system
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
I2V	Infrastructure to vehicle
V2X	Vehicle to anything
IVS	In- vehicle system
FOT	Field operational trial
EEIS	Energy efficient intersection service
OBU	On board unit
RLVW	Red light violation warning
RHW	Road hazard warning
RSU	Roadside unit
GLOSA	Green light optimal speed advice
SPaT	Signal phase and timing
GNSS	Global navigation satellite system

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Disclaimer:

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