ENVIRONMENTAL IMPACT OF COMBINED ITS TRAFFIC MANAGEMENT STRATEGIES

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Introduction

Transport was responsible for 20% of the total greenhouse gas emissions in Europe during 2011 (European Environmental Agency 2013) with road transport being the key contributor. To tackle this, targets have been established in Europe and worldwide to curb transport emissions. This poses a significant challenge on Local Government and transport operators who need to identify a set of effective measures to reduce the environmental impact of road transport and at the same time keep the traffic smooth. Of the road transport pollutants, this paper considers NO_x, CO_2 and black carbon (BC). A particular focus is put on black carbon, which is formed through incomplete combustion of carboneous materials, as it has a significant impact on the Earth's climate system. It absorbs solar radiation, influences cloud processes, and alters the melting of snow and ice cover (Bond et al. 2013). BC also causes serious health concerns: black carbon is associated with asthma and other respiratory problems, heart attacks and lung cancer (Sharma 2010; United States Environmental Protection Agency 2012).

Since BC emissions are mainly produced during the decelerating and accelerating phases (Zhang et al. 2009), ITS actions able to reduce stop&go phases have the potential to reduce BC emissions. This paper investigates the effectiveness of combined ITS actions in urban context in reducing CO_2 and BC emissions and improving traffic conditions.

State of the art

The ITS actions considered in this study are Traffic Signal Control (TSC) and Variable Message Sign (VMS). This section provides a literature review of the environmental impact of these actions.

Significant research effort has been dedicated so far to the assessment of the impact of traffic signal control on emissions. Isolated junctions were investigated to study the effect of cycle length on emissions (Chen and Yu 2007), to identify the relationship between delay, number of stops and emissions (Ntziachristos 2009) and to explore the impact of optimisation of phase ordering (Allsop and Charlesworth 1977). Increasing green time to the main traffic direction by 5% resulted in a reduction of CO, HC and NO_x emissions in the range of respectively 7.21%, 4.54% and 2.63% (Webster 1958). Traffic signal coordination has also the potential to reduce the impact of traffic on HC, NO_x, CO and CO_2 emissions. Various studies show that the extent of this reduction has been found to be up to 40% (Zhang et al. 2009; De Coensel et al. 2012; Lv and Zhang 2012). However these studies do not assess the impact of traffic signal control on BC emissions.

The research undertaken on VMS so far has encompassed different work streams: estimation of the compliance rates (Ramsey and Luk 1997; Chatterjee et al. 2002; Hoye 2011; Kattan et al. 2011), impact on traffic performance (Lam and Chan 1991; Mammar et al. 1996; Chatterjee et al. 2002; Chen S. 2008; Wei et al. 2009), credibility and understanding of VMS messages (Cummings 1994; Chatterjee et al. 2002), and safety hazard associated to VMS (Hoye 2011). Few studies have analysed the impact of VMS on emissions and the majority of these (Dia and

Cottman 2006; Schlaich 2010; Hoye 2011) have focused on VMS as a tool to manage incidents. These studies show the potential of VMS to reduce emissions during non-recurrent events. The actual emission reduction is dependent on the compliance rate as emissions network-wide tend to increase when the alternative route becomes congested (Kottapalli et al. 2003).

The literature review reveals a lack of research into the potential for VMS to be used as a tool for sustainable traffic management in urban areas with recurrent congestion. Existing studies also fail to consider black carbon emissions in this context. This study will assess the effectiveness of traffic signal control and VMS rerouting, in isolation and combined, in reducing BC and CO_2 emissions in an urban area experiencing recurrent congestion. In this study the compliance rate is considered to be an exogenous variable and different rates are defined based on the outcomes of the literature review (see scenario section for references).

This study has been undertaken within the FP7 CARBOTRAF project (grant agreement n° 28786), which aims to support traffic operators in real-time when choosing the most effective ITS action to reduce CO_2 and BC emissions. The project includes on-line and off-line modules: the on-line module is comprised of a decision support system and real time traffic and environmental data monitoring; the off-line module is formed by a database (Look-up-Table, or LUT), where all the simulation results are stored. The decision support system uses the data in the LUT to recommend the best action based on the current traffic conditions. The CARBOTRAF system is implemented in two test sites: Glasgow and Graz. This paper presents the simulation results for Glasgow. The focus of the study is the West End, including Byres Road, an area that has been declared an air quality management area due to critical pollution levels.

Methodology

This paper aim to assess the environmental impact of combined measures of VMS routeing and traffic signal coordination on CO_2 and BC emissions with varying levels demand and compliance rates. In order to address this research aim, this study has proposed the methodology shown in

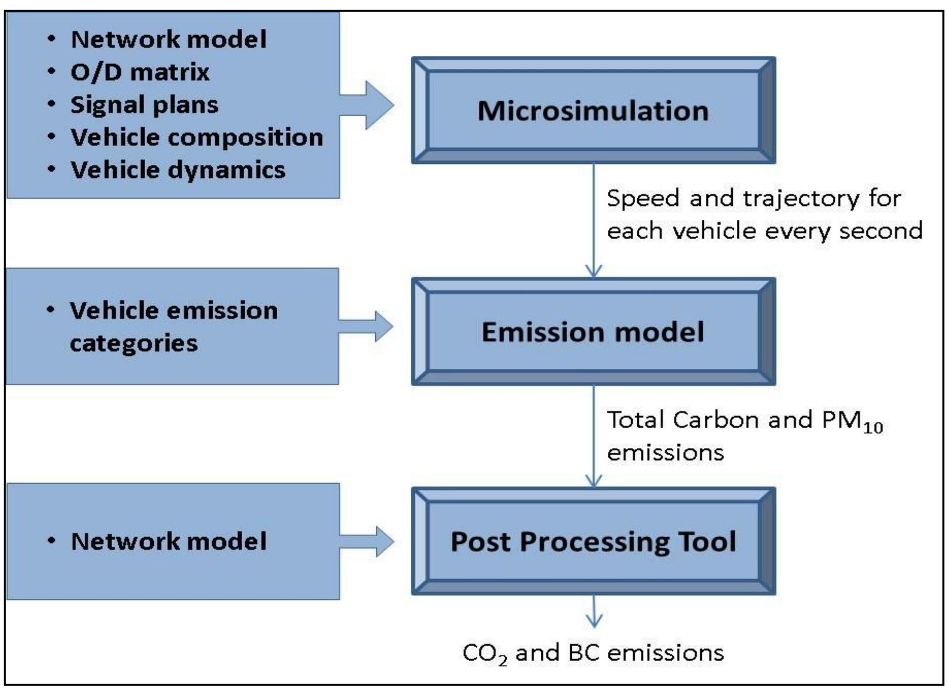

Figure 1: Methodology overview.

The analysis used the following tools:

- S-Paramics for traffic microsimulation
- AIRE (Analysis of Instantaneous Road Emissions) for emissions modelling (Barlow 2007).

AIRE incorporates an Instantaneous Emission Modelling (IEM) table which was derived from PHEM (Passenger Car and Heavy Duty Emission Model). PHEM was developed by the Technical University of Graz and enables emissions to be output for various engine speeds and engine loads. The model effectively combines the PHEM emissions database and estimation methods with a development of the emissions grid methodology employed in MODEM. Local variations in fleet composition can be reflected through direct editing of the fleet composition files. The combination of microsimulation traffic modelling and AIRE provides significantly more disaggregate and detailed emission estimates compared with traditional, average speed-based methods (Transport Scotland 2011).

In the scope of this study, the estimation of Black Carbon emissions is achieved through applying the conversion factor from COPERT IV model. Within COPERT, PM is apportioned between elemental Carbon (EC) and organic mass (OM) in the emission inventory. These factors are expressed as a proportion of $PM_{2.5}$ emissions. COPERT also contains emission factors representing the apportionment between $PM_{2.5}$ and PM_{10} (the $PM_{2.5}/PM_{10}$ ratio) for different environments. These factors permit the estimation of the EC fraction of PM_{10} exhaust emissions. For the purposes of assessing road vehicle emissions it is also assumed that EC is equivalent to BC due to the nature of the combustion processes found in road vehicles. This combination of assumptions and emission apportionment factors then provides a feasible methodology for estimating BC emissions within this study.

A post-processing tool written in Python language was developed to estimate CO_2 and BC emissions at link level from the total carbon and PM_{10} emissions estimated by AIRE. The post-processing tool is based on the following assumptions:

- The estimation of CO_2 generated is derived from the Total Carbon by using the atomic weights of Carbon and Oxygen to generate a factor of 44/12 (i.e. one molecule CO_2 weighs 44, one atom carbon weighs 12).
- The estimation of Black Carbon is based upon the predicted PM_{10} emission rates, using the COPERT IV methodology for conversion (D. Gkatzoflias 2006).
- The PM_{10} value estimated using the emission model only includes exhaust emissions.
- All exhaust PM10 ≈ PM2.5; (D. Gkatzoflias 2006).
- EC ≈ BC (Ntziachristos 2009).

This methodology allows estimating the impact of ITS actions on CO_2 and BC emissions per link.

The microsimulation traffic model developed for the West End of Glasgow represents the existing scenario for the base year of the study (2012) during the AM peak (08:00-09:00). The base model has been calibrated and validated against existing traffic flows from detectors and counts from surveys. The validation results show that at least 85% of the modelled traffic flows are within the acceptable tolerance (5 GEH) of the observed traffic flows in line with the Design Manual for Roads and Bridges (Highways Agency 2014).

The model adopts a vehicle fleet composition based on the Annual Average Daily Flow (AADF) data for Glasgow city from the Department for Transport from 2000 to 2010. Seven vehicle types are defined in the model and their equivalent Passenger Car Unit (PCU) is computed based on Transport for London's traffic modelling guidelines (TfL 2010).

Vehicle/driver behaviour characteristics are represented by aggression and awareness factors in S-Paramics. These factors influence a driver's gap acceptance, car following and lane changing characteristics. The default normal distribution of behaviour is assumed for the current model.

Scenarios

Building on the base model, five different scenarios have been generated to take into account the variability in demand during different days of the week (Monday – Thursday). Based on processed historical data from the loop detectors, five boundary conditions have been identified to represent demand increase from different directions into the network. Boundary conditions 1, 3 and 5 present different levels of increased demand from the West and the North. While boundary conditions 2 and 4 present an increased demand from the South.

The range of compliance rates for VMS has been identified from the literature. In the last decades many researchers have attempted to estimate the compliance to VMS using different methods: observations from traffic counts and loop detectors (Ramsey and Luk 1997; Chatterjee et al. 2002; Erke et al. 2007), surveying drivers (Cummings 1994; Lee et al. 2004; Chen S. 2008; Zhao and Shao 2010; Hoye 2011; Kattan et al. 2011) and virtual driving simulators (Brocken and Van der Vlist 1991). However there is no agreement in the compliance rates found in the different studies due to different application contexts and message displayed on the VMS (Ramsay and Luk (1997), Yim and Ygnace (1996)). The literature review shows that the average range of compliance rate is [11-29%]. Therefore the following levels of compliance have been used for this paper: 10%, 20%, and 30%.

ITS actions with the potential to reduce CO_2 and BC emissions while maintaining smooth traffic on Byres Road, the focus of the study, have been identified. The following ITS actions have been simulated:

- Traffic Signal Control (TSC): a new traffic signal plan is proposed at the junction Byres Road /University Avenue which maintains signal coordination with the adjacent junction using a constant offset. The proposed plan reduces the green time from the West and the North arms at the benefit of the traffic approaching the junction from the South and the East.

- Variable Message Sign (VMS): the VMS is located on Beith Street, upstream of Byres Road going Northbound. The aim is to reroute drivers away from Byres Road. The text displayed on the VMS is: "Congestion on Byres Road, take alternative routes". The main alternative route to the city centre is shown in the figure below.

- Combination of TSC and VMS: both the above actions are simulated at the same time with the aim to further smooth traffic flow on Byres Road and reduce emissions.

The location of the ITS actions and the alternative route (Dumbarton/Kelvin Way) is shown as a continuous blue line in Figure 2.

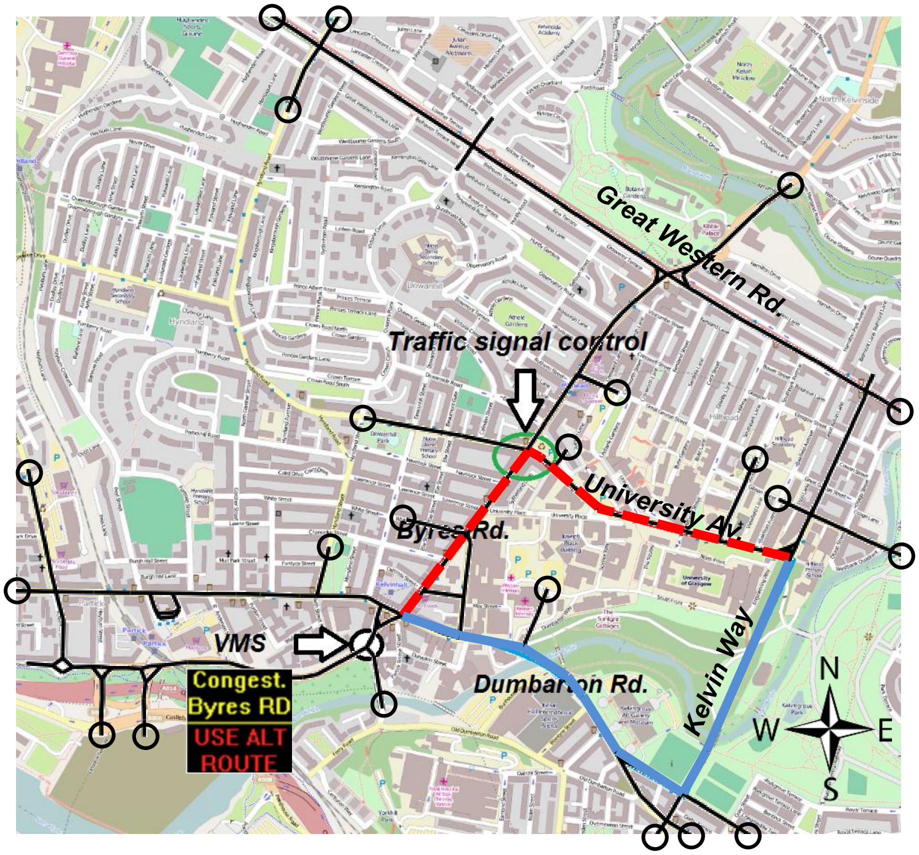

Figure 2: Test site, ITS actions and relevant corridors.

The ITS action scenarios simulated are compared against the baseline scenario in order to assess the effectiveness of the proposed measures. A number of Key Performance Indicators (KPIs) have been calculated to support the analysis:

- Travel time, speed and delay from a traffic perspective;
- Black carbon, CO_2, NO_x emissions;

These KPIs have been estimated at the network, junction and corridor levels. Several corridors have been considered in the analysis to ensure any other localised effect of the ITS actions was captured. The two corridors most often referred to here, are also used in the graphical user interface (GUI) for the traffic operators within the CARBOTRAF project. These corridors are:

- GUI_Byres_University (indicated in dotted red in Figure 2)
- GUI_Dumbarton_Kelvin (indicated in continuous blue in Figure 2)

All the scenarios have been simulated for the 5 boundary conditions. The simulations have been run using 25 random seeds for each boundary condition and the results have been averaged.

All results presented in this paper are statistically significant with confidence level (CL) of at least 90%.

Analysis of results

This section reports the simulation results for the Glasgow network to assess the impact of the ITS actions on traffic and emissions. The results are discussed for the different ITS actions simulated:

- Traffic Signal Control (TSC)
- Variable Message Sign (VMS)
- Combined TSC and VMS.

5.1 Traffic Signal Control

This subsection presents simulation results for the TSC scenario where a new traffic signal plan is proposed at the junction Byres Road /University Avenue. The signal plan also coordinates with the adjacent junction through a fixed offset. The proposed plan keeps the existing cycle time while reducing the green time from North and West and extending the green time for the traffic approaching the junction from the South and the East.

The main benefit of TSC can be noted on the Byres corridor for all boundary conditions as the green time Northbound has been extended. The impact at local levels depends on the boundary condition. Under boundary conditions 1, 3 and 5 with increased demand from West or North the benefits of TSC are significant at all spatial levels: junction, corridor and network. The improvement on traffic conditions on Byres Road in the Southern section and the reduction of green time for the North and West arms of the junction cause only minor additional delays on these approaches.

The reduced green time for the West arm can still accommodate the demand without reaching the saturation flow under boundary conditions 1, 3 and 5. Under boundary condition 2, with moderately increased demand from the West the flow is saturated; consequently the proposed TSC signal plan causes overall minor deterioration at the junction level. When the demand from the West is substantially increased (boundary condition 4) the degradation on the West arm is critical and causes a local increase in delay by 161s on average and, at the junction level, a reduction in speed by 23% and an increase in delay by 33%.

The BC emissions are reduced on the South and East arms of the junction. This is expected due to the extension of the green time for those two arms in TSC. As a result, there is an improvement on both Byres Road and Dumbarton Road corridors in terms of BC emissions.

Figure 3 below shows the impact of TSC on traffic and emissions at the network and junction levels under boundary condition 3. The diagrams in Figure 3**Error! Reference source not found.** show the improvements in both traffic KPIs (travel time, speed, and delay) and environmental KPIs (NO_x, CO_2, and BC) by comparing the TSC case with the base case.

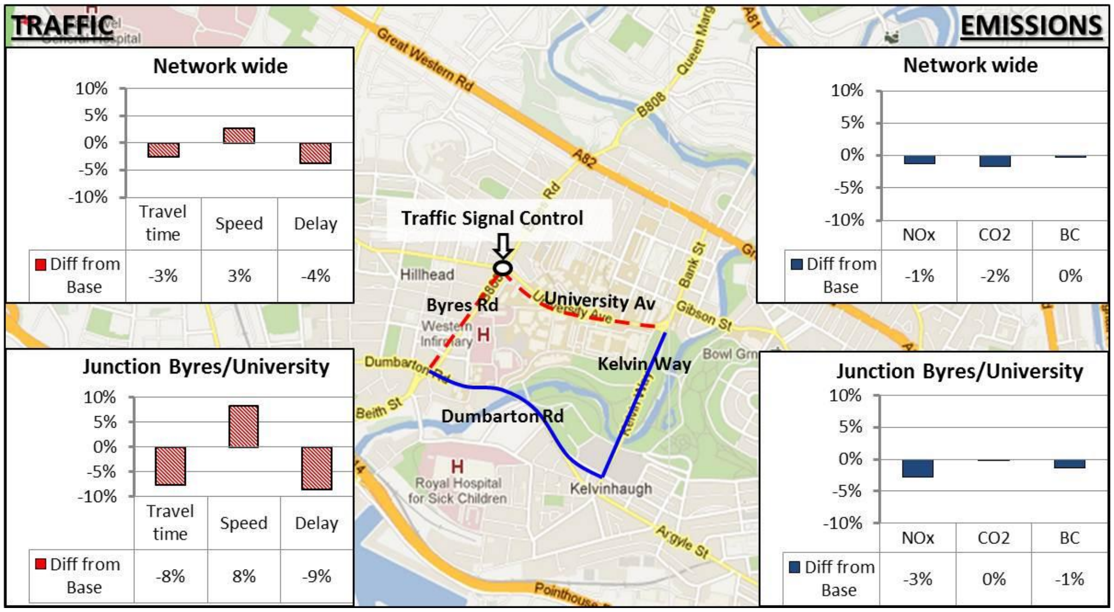

Figure 3:	Impact of TSC on traffic and emissions under boundary condition 3.

5.2 Variable Message Sign

This section provides an overview of the results from scenarios VMS10, VMS20, VMS30, which simulate the effect of a VMS located on Beith Street (South of Byres Road) with three different compliance rates: 10%, 20% and 30%.

Given that the main route to reach the city centre from South West is Byres Road and University Avenue (shown as the broken red line in Figure 2), the alternative route suggested by the VMS is Dumbarton Road and Kelvin Way (indicated as the continuous blue line in Figure 2). In order to capture the potential flow shift towards this alternative route, we first identified a set of origin destination (OD) pairs potentially affected by the VMS; then simulated a specific number of vehicles, respectively 10%, 20% and 30% of the total target OD flows, to follow the suggested route. This effect is implemented by using the path routeing function in S-Paramics.

At the corridor level major effects, as expected, took place on Byres Road and University Avenue where the simulation results show a reduction in travel delay by 3 to 9% for all compliance rates and boundary conditions (except 4). These improvements are only partially offset by worsened traffic conditions along the alternative route (Dumbarton_Kelvin Way) where delay increases up to 2% for all boundary conditions except 4. The results under boundary condition 4 differ from the other boundary conditions as they show a substantial worsening of traffic conditions at corridor and network levels. This is explained by the increased demand from the South in condition 4, causing significant delay on Kelvin Way (on average 480sec), which has already seen moderate congestion in the base case even without the VMS. As a result, VMS30 shows an increase in delay by 20% on the alternative route. To conclude, the VMS action brings significant reduction in delay under boundary conditions 1, 3 and 5 at the corridor level (up to 9%), and at the network level (up to 3%).

The VMS actions bring a relatively small improvement on black carbon emissions for boundary condition 1, 3 and 5 in the range of 0 to 2% (network level). However, we have identified a few cases in which traffic and emission results conflict. One example is shown in Figure 4. On the corridor GUI_Dumbarton/KelvinWay an increased congestion is seen while both NOx and BC have been reduced.

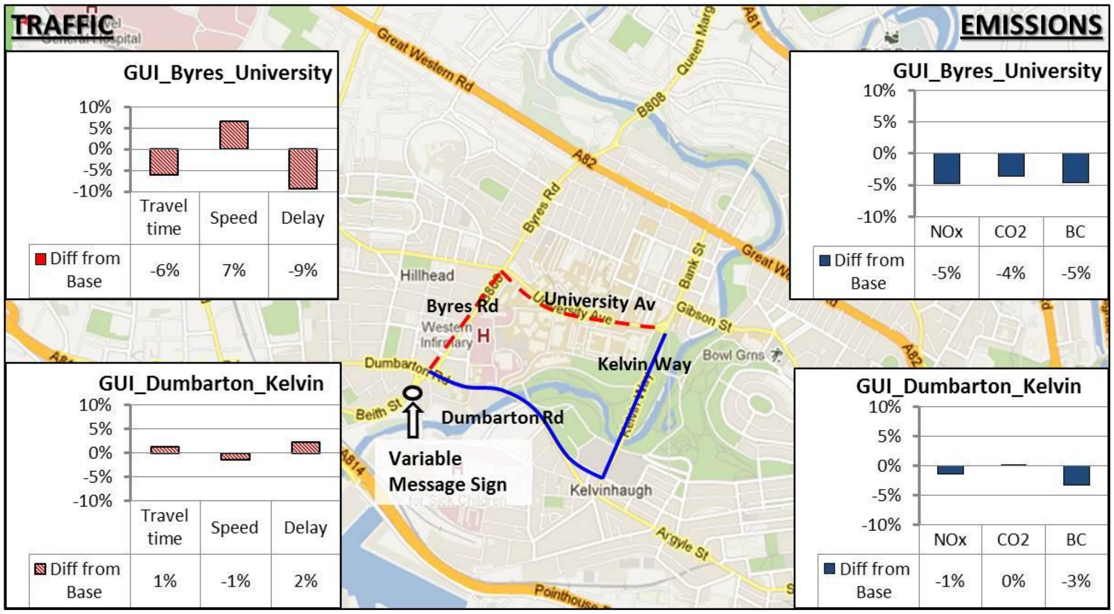

Figure 4: Impact of VMS30 on traffic and emissions under boundary condition 1.

Further investigation of the aforementioned conflicting results at a refined, link level within the corridor shows that the standard deviation of vehicle speeds is lower in the ITS case. This means that, although rerouting a few vehicles leads to a minor increase in delay on the alternative route, a smoothing effect takes place, which yields more homogeneous driving conditions among vehicles (i.e. less variation of speed). Such an effect contributes to a reduction in black carbon emission on the alternative route. Detailed link-specific data are reported in the table below.

Table 1: Link analysis for conflicting results with VMS30 under boundary condition 1

link	length	delay base	delay ITS	delay diff %	black carbon diff %	speed av diff %	speed σ base	speed σ VMS30
225:222z	57.62	2.80	2.88	3%	-2%	-1%	0.75	0.6
375z:376z	87.24	16.39	16.81	3%	-3%	-2%	1	0.44
374z:377	71.98	26.64	28.99	9%	-4%	-6%	2.1	1.37
377:372	58.84	60.13	61.77	3%	-8%	-2%	0.24	0.15

5.3 Combined TSC-VMS

This section provides an overview of the results in the combined TSC-VMS scenario in which both the optimised traffic signal plan at the Byres/University junction described in the TSC case, and the VMS with three compliance rates (10/20/30%) are simulated at the same time.

At the network-wide level the combination of TSC and VMS brings traffic improvement for all boundary conditions and compliance rates with a reduction in delay in the range 3-6%. Additionally, the combined strategy brings substantial traffic improvement for the corridor Byres Road/University Avenue for all boundary conditions and compliance rates, in particular:

- An increase in speed by 19-24%
- A reduction in delay by 21-29%.

However, these benefits are partially offset by localised increase in delay:

- Up to 8% along the alternative VMS route (highlighted in blue in Figure 2) under boundary conditions 1, 2 and 4;
- Up to 36% at the junction Byres Road / University Avenue (highlighted in broken red line in Figure 2) under boundary conditions 2 and 4, mainly due to the reduced green time in TSC on the West arm of the junction.

The combined strategy also leads to a substantial reduction in black carbon emissions on Byres Road and University Avenue, namely between 2 to 11% across all different boundary conditions. However, increased emissions are observed on the GUI Dumbarton/Kelvin corridor. Overall the improvement outweighs the worsening, and as a result the combined ITS action leads to a change in black carbon emission ranging from -3% to 1% at the network level.

The figure below shows the traffic and emission KPIs for the combined ITS action under boundary condition 4 for the two GUI corridors.

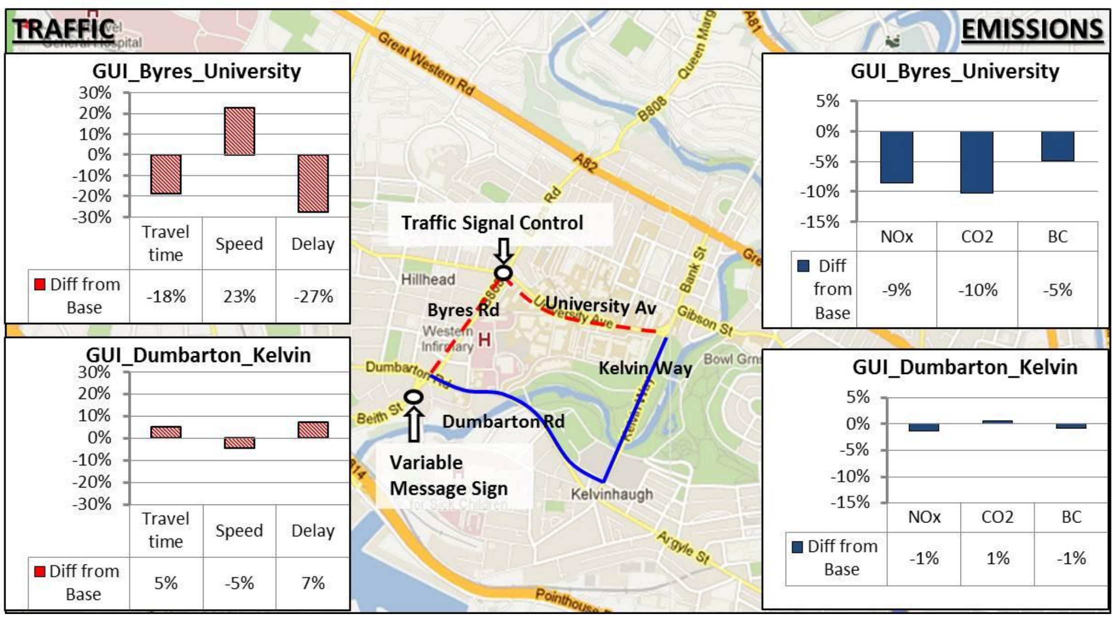

Figure 5: Impact of TSC_VMS30 on traffic and emissions under boundary condition 4.

While the results along GUI_Byres_University corridor show that traffic and emission KPIs improved simultaneously, the results on the GUI_Dumbarton_Kelvin corridor appear to conflict. That is, traffic became more congested while black carbon emissions reduced. In order to explain this, our analysis, again, has been brought to the link level. The following table shows a breakdown of the BC emission and delay on different links along the GUI_Dumbarton_Kelvin corridor. The ordering of the links is consistent with the direction of the flow and the horizontal line in the middle of the table indicates the end of Dumbarton/Argyle and start of Kelvin Way.

Table 2: Link analysis for conflicting results for TSC_VMS30 under boundary condition 4

link	BC base average	BC ITS average	BC diff (ITS-Base)	delay base av.	delay ITS av.	delay diff (ITS-Base)	ratio diff BC/delay
335:205	952.12	945.72	-6.40	5.19	4.81	-0.37	17.11
205:206	705.19	674.22	-30.97	2.69	2.02	-0.67	46.55
206:336	325.13	313.43	-11.70	1.18	0.61	-0.56	20.80
336:224	1334.53	1261.65	-72.87	9.14	9.03	-0.11	685.84
224:347	957.68	922.87	-34.82	1.04	0.70	-0.34	103.47
347:225	1864.28	1735.38	-128.90	5.52	4.78	-0.74	174.62
225:222z	1098.46	1043.48	-54.98	2.86	2.57	-0.30	186.32
222z:375z	601.69	562.63	-39.06	3.83	3.43	-0.40	98.50
375z:376z	1673.04	1635.30	-37.74	16.71	16.52	-0.19	194.82
376z:374z	245.55	226.74	-18.81	-0.08	-0.67	-0.58	32.26
374z:377	736.10	676.09	-60.01	26.40	25.05	-1.36	44.22
377:372	933.20	893.94	-39.26	61.02	63.54	2.53	-15.55
372:362z	456.37	520.58	64.22	7.61	8.79	1.18	54.58
362z:221z	83.98	103.42	19.44	1.75	2.09	0.34	57.23
221z:227	471.04	570.22	99.19	8.49	15.52	7.03	14.11
227:220	1117.28	1324.07	206.79	42.68	56.39	13.71	15.08
220:364	94.81	107.83	13.01	6.58	6.82	0.24	53.65
364:365	80.31	89.40	9.09	8.09	8.13	0.05	200.04
365:357z	63.55	72.82	9.27	7.66	7.45	-0.21	-44.51
357z:361	89.95	94.50	4.55	11.09	8.50	-2.59	-1.76

The first part of this corridor is Dumbarton/Argyle where both delay and black carbon decrease. In the second part of the corridor (Kelvin Way), however, both delay and black carbon increase on the majority of the links. We note that the increased delay in the second half of the corridor dominates the reduction in the first half, leading to an overall increase in the delay. The reversed case is seen for the black carbon: the reduction in the first half of the corridor dominates the increase in the second half, and thus black carbon emission decreases on the corridor level overall. The conflicting result at the corridor level is actually caused by the very different behaviours of its two parts. Further insights can be drawn by looking at the last column in the table above, which shows the ratio of the change in the BC emission and the change in the delay. This column is particularly relevant because it shows that the first half manages to achieve a significant reduction in BC with a relatively minor reduction in delay. In analogy to an economic term, the “marginal saving” of BC emission is very high with respect to a unit reduction in delay. On the other hand, the second half brings an increase in BC emissions that is less significant compared to the increase in delay. In other words, the “marginal cost” to environment is relatively low with respect to a unit increase in delay.

Conclusions and next step

This paper assesses the effectiveness of combined ITS actions on traffic and emission KPIs. The combined traffic signal control and VMS action proves to be more effective than the individual actions in the simulated scenarios. However the results show various trade-off situations with regards to:

- Spatial reference of KPIs;
- Traffic and emission KPIs.

The impact of the ITS actions varies depending on the spatial reference of the indicators: at network and corridor levels the combined ITS action TSC-VMS10 seems to bring the highest benefits in terms of traffic across all spatial KPIs. However, at junction level all the VMS scenarios always bring improvement to traffic, while the combined action increases the delay due to the increased red time to certain arms of the junction.

With regards to the traffic and emission trade-off, most of the scenarios analysed in this study show that emission KPIs improve where traffic improves and vice versa as expected. However there are also scenarios where the results are conflicting, for example TSC_VMS30. Higher demand in this scenario from the South presents an increased delay along with reduced black carbon emissions. This can be explained by the lower speed variability and thus reduced acceleration and deceleration phases, the phases responsible for the majority of black carbon emissions.

The next steps of this research will involve the implementation of Pareto optimization methods in order to accommodate trade-off situations and support traffic operators when choosing the ITS action that best meets their objectives and priorities.

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