Air quality impact of intelligent transportation system actions used in a decision support system for adaptive traffic management

Abstract: The presented traffic control system (CARBOTRAF) combines real-time monitoring of traffic and air pollution with simulation models for traffic, emission and local air quality predictions to deliver on-line recommendations for alternative adaptive traffic management. The aim of introducing a CARBOTRAF system is to reduce BC and CO_2 emissions and improve air quality by optimizing the traffic flows. A chain of models combines microscopic traffic simulations, emission models and air quality simulations for a range of traffic demand levels and intelligent transport system (ITS) actions. These ITS scenarios simulate combinations of traffic signal optimization plans and variable messaging systems. The real-time decision support system uses these simulations to select the best traffic management in terms of traffic and air quality. In this paper the modelled effects of ITS measures on air quality are analysed with a focus on BC for urban areas in two European cities, Graz and Glasgow.

Keywords: dispersion modelling, traffic pollutants, urban air quality, traffic management, ITS, decision-support-system, emission reduction, black carbon, Glasgow, Graz

Introduction

Traffic congestion with frequent “stop & go” situations causes substantial pollutant emissions. Black carbon (BC) is a good indicator of combustion-related air pollution and is chosen as an indicator for traffic related air quality, which has been shown to be strongly related to health effects (Janssen et al. 2012). The aim of the CARBOTRAF project is the development of a decision support system (DSS) for adaptive traffic management in real-time to reduce BC and CO_2 emissions caused by road transport in urban and inter-urban areas.

Prior to the CARBOTRAF project, the impact of isolated ITS measures on emissions has been studied. Literature shows that traffic signal control strategies can lead to significant reductions in pollutant emissions, depending on the details of the implementation (Stevanovic et al. 2009, Zhang et al. 2009). The potential impact of Variable Messaging Signs (VMS) on emissions had already been recognized in studies integrating traffic and emission modelling. These studies show the impact on pollutant emissions and the link between traffic congestion and vehicle emissions (Decoensel et al. 2012, Erke et al. 2007, Zhang et al. 2011, Zhang et al. 2013). CARBOTRAF adds to the traffic and emissions the impact on local air quality and integrates all information with an online decision support system.

The focus of this paper is to evaluate the impact of the ITS measures on the air quality in the urban areas, using the results from emission models as input. We will first present the impact on emissions and then discuss the local impact on BC for different meteorological conditions and traffic states.

CARBOTRAF methodology

A schematic overview of the CARBOTRAF decision support system is given in Figure 1. A modelling tool chain has been set up to build and evaluate the adaptive traffic control and management system. Data from microscopic traffic simulation models is stored in an offline database. This database records the impact of individual ITS measures on traffic, emissions and air quality for selected traffic and meteorological conditions. More specifically, prevailing traffic states and meteorological conditions are used to model emissions and BC concentrations for each measure in the ITS scenario catalogue. As a consequence, the offline database provides evidence on how to rank certain ITS measures for a given traffic state and meteo condition. Real-time data is collected from traffic sensors, smart-eye cameras, black carbon monitors, and meteorological stations in both pilot cities. The sensors provide traffic flow rates and densities, pollutant concentrations, as well as wind speed and direction. The real-time data is processed by an online decision support system (DSS) that analyses which ITS measures are likely going to meet the objectives of reducing congestion as well as improving environmental factors given these actual traffic levels. In order to accomplish this, the DSS incorporates statistical models of the offline data. Separate models are constructed to predict CO_2 and BC emissions, travel time along major corridors, and BC concentration levels for associated traffic state, meteorological condition, and the ITS measures. These models are scored in real-time and the resulting ranking and estimated effects are presented to the traffic operator. The novelty of the system is that the traffic operator can select the traffic management scheme based on anticipated effects on both traffic (travel time) and emissions and air quality.

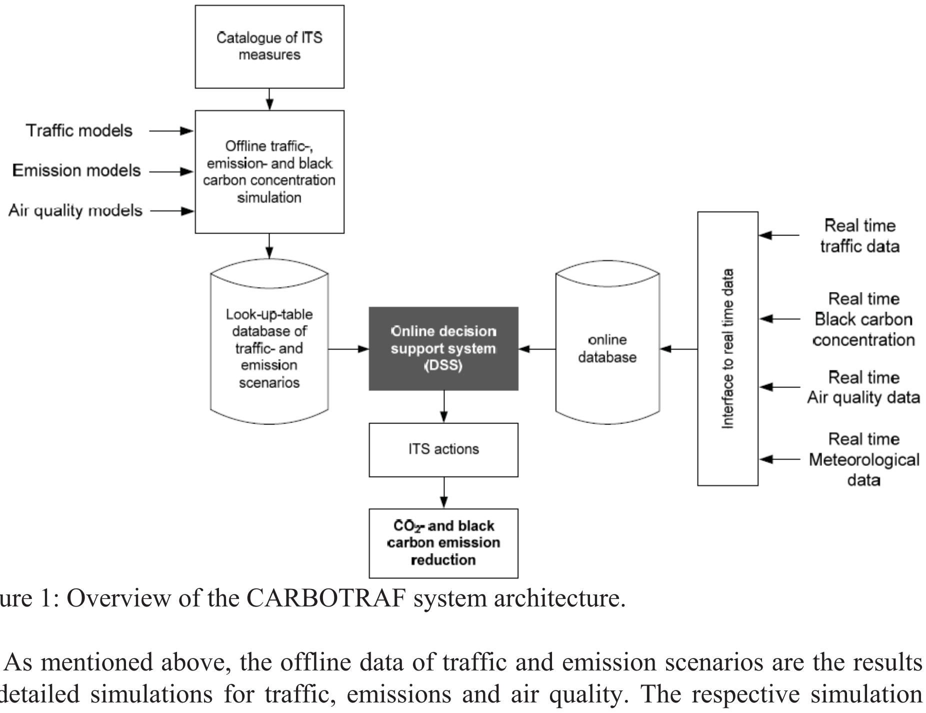

Figure 1: Overview of the CARBOTRAF system architecture.

As mentioned above, the offline data of traffic and emission scenarios are the results of detailed simulations for traffic, emissions and air quality. The respective simulation models are coupled in a modelling chain and include the following modules:

- Microscopic traffic models: S-Paramics (Glasgow) VISSIM (Graz) (PTV 2012)
- Emission model: AIRE (AIRE 2011) + COPERT 4 (COPERT 2011)
- Atmospheric dispersion model: IFDM + OSPM (Lefebvre et al. 2013b)

The microscopic traffic models require as input the network information, measured traffic flows and link speeds, signal plans, vehicle fleet composition and operational driver behaviour. For each ITS action, simulations are completed for a range of boundary conditions, representing variations in traffic conditions at the entry links of the simulated network. The microscopic simulations yield detailed vehicle trajectories including acceleration and speed. The output of these off-line traffic models is used as input for the emission calculation together with detailed information on the vehicle fleet composition. The emission model computes the BC and CO_2 emissions for every link of the entire network at every time step for each ITS scenario. The pollutant dispersion model uses the emissions and meteorological data to calculate the pollutant concentrations. Available information on building dimensions along the network is used to account for street canyon effects on the dispersion process.

Methodology dispersion modelling

The IFDM model (Immission Frequency Distribution Model), a bi-Gaussian plume model, has been selected for CARBOTRAF. A street canyon module based on the OSPM model (Berkowicz et al. 1997) is coupled to IFDM to simulate the dispersion in street canyons. In a series of studies the IFDM model has been validated for use in urban applications (Lefebvre et al. 2013a, Lefebvre et al 2013b, Lefebvre et al. 2011). The modelling approach is described in detail in Lefebvre et al. (2013b). However, in this study only the local contribution is modelled and no background contribution to the pollutant concentrations is taken into account. This simplified approach is used since the aim of the study is to compare different scenarios. IFDM is a receptor model that can be used for both regular and irregular grids; for this study an irregular road following grid was applied to account for the steep gradients along the roads. The street canyon module is run on a grid with a receptor point every 10 m along the roads in the street canyon. In a next step, calculated concentrations at receptor points can be interpolated resulting in concentration maps. The street canyon module is only applied for Graz, since no detailed building dimensions were available for Glasgow.

For both pilot cities, simulations are performed for each ITS scenario and traffic boundary condition for 252 meteo conditions. Each meteo condition is hereby a combination of 36 possible wind directions at 10° intervals and 7 different stability classes.

Pilot Cities and ITS actions

The test site in the north of Graz (Austria), presented in Figure 2, comprises two main arterial roads linking the Mur valley in the north of the city with the inner city centre. ITS actions that are implemented are alternative route recommendations via VMS and adaptation of traffic signal plans. Five additional traffic sensors are installed on the test site. Two BC monitors are installed along the arterial roads (AQ6, AQ7) and one additional monitor at the AQ monitoring station in the centre of the test site (Graz North).

The following measures of adaptive traffic control have been simulated and can be implemented:

- Control of the traffic signal settings along the western and eastern arterial
- VMS suggests drivers to use the western or eastern arterial when approaching the test site from the north-west. Three levels of compliance, 5, 10, and 15% have been simulated.

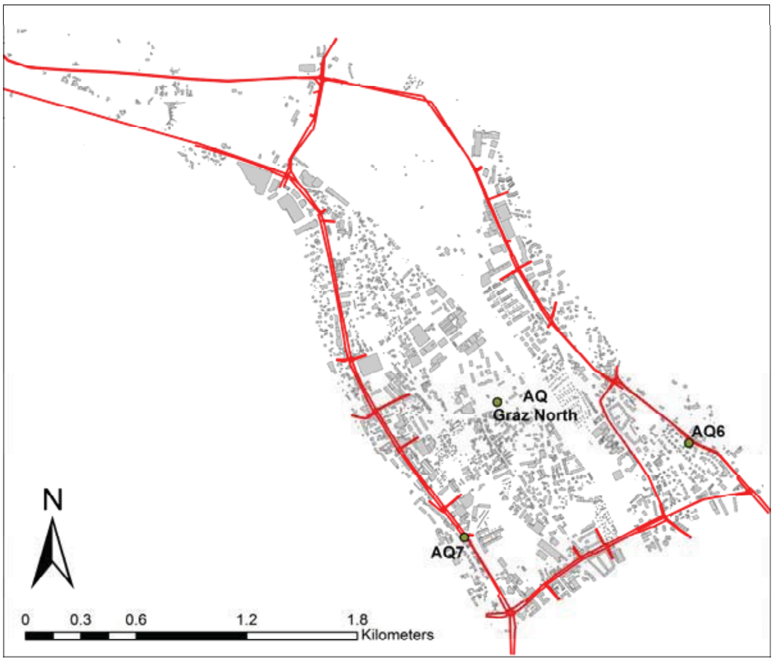

Figure 2: Overview of the test site in Graz, roads with simulated emissions highlighted in red, BC monitor locations indicated by green dots, buildings in grey. The VMS is located along the highway to the north-east.

The second test site is located in the West end of Glasgow (UK) around Byres Road, depicted in Figure 3. Local stakeholders expressed their preference for this area because it has congestion and pollution problems for many years. The ITS actions that are implemented are VMS and traffic signal plan optimization. VMS is used to reroute drivers away from congested area where BC and CO_2 emissions are expected to be high and air quality can be improved by decreasing the amount of traffic and the stop & go traffic. Three traffic sensors and two BC monitors are installed near the main roads in the test site. The following measures of adaptive traffic control have been simulated:

- Traffic Signal Control (TSC): a new traffic signal plan is proposed at the junction Byres Road /University Avenue which keeps the signal coordination with the adjacent junction at Church Street. The proposed plan reduces the green time from West and North at the benefit of the traffic approaching the junction from the South and the East.
- VMS: the VMS is located on Beith Street, upstream of Byres Road, focus of the project. The aim is to reroute drivers away from Byres Road. The main alternative route to the city centre is using the parallel road to the east, Kelvin

Way and Bank Street (route highlighted in Figure 3). Three levels of compliance rate have been simulated: 10, 20, and 30%.

- Combination of TSC and VMS: the two actions above are combined to further smooth traffic flow on Byres Road.

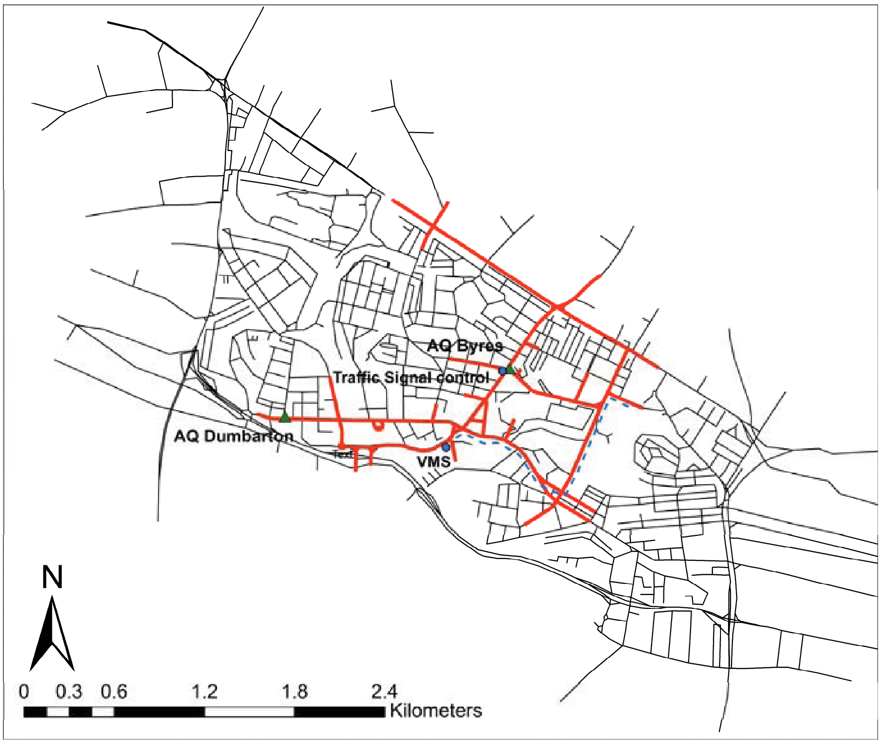

Figure 3: Overview of the test site in Glasgow, validated network highlighted in red, full network in black, BC monitors and ITS locations indicated by green triangles and blue dots, re-routing by VMS highlighted by dashed blue line.

Emissions

Table 2 and

Table **1** show the BC emissions (as percentage of total emissions of the base scenario) over the network for Graz and Glasgow respectively. In Graz, a base scenario and 12 ITS scenarios are calculated for three boundary conditions. For Glasgow emissions are calculated for 5 boundary conditions (BC1-BC5) and one base scenario and 9 ITS scenarios. The results show that the implementation of ITS actions can result in potential changes in total BC emissions of -5% to +2%. The change in emission at locations along the network can be much larger, up to 50% decrease for the central junction in Glasgow for a specific meteo condition.

Table 1: Total BC emissions for all ITS scenarios as percentage of the total mission of the base scenario for the respective boundary condition – Graz. The different boundary conditions BC1-3 reflect different traffic volumes at different time slots.

Traffic signal plan	VMS	Compliance	BC1 (6-7)	BC2 (6:30-7:30)	BC3 (7-8)
W2E2	no display	/	100%	100%	100%
W2E2	Go East	5	99%	101%	99%
W2E2	Go East	10	99%	98%	97%
W2E2	Go East	15	98%	98%	96%
W2E2	Go West	5	99%	100%	99%
W2E2	Go West	10	99%	100%	101%
W2E2	Go West	15	99%	101%	101%
W2E5	Go West	5	99%	99%	96%
W2E5	Go West	10	100%	99%	97%
W2E5	Go West	15	99%	100%	98%
W5E2	Go East	5	100%	100%	99%
W5E2	Go East	10	100%	99%	98%
W5E2	Go East	15	100%	98%	97%

Table 2: Total BC emissions for all ITS scenarios as percentage of the total emissions of the base scenario for the respective boundary condition – Glasgow. TS1-2-3 are different traffic signal plans, VMS10-20-30 are the VMS scenarios with respective compliance rates, the final three scenarios are combinations of both. BC1-5 are 5 different boundary conditions and the average over all boundary conditions**.**

	Base	TS1	TS2	VMS10	VMS20	VMS30	TS3	TS3-VMS10	TS3-VMS20	TS3-VMS30
BC1	100%	101%	95%	100%	99%	99%	99%	98%	97%	97%
BC2	100%	100%	97%	102%	100%	101%	99%	101%	100%	99%
BC3	100%	101%	99%	100%	100%	100%	100%	97%	99%	98%
BC4	100%	102%	99%	101%	101%	102%	101%	100%	99%	101%
BC5	100%	99%	99%	100%	101%	101%	101%	99%	100%	99%
Average	100%	101%	98%	101%	100%	101%	100%	99%	99%	99%

Air quality results

The results of the dispersion modelling yield the pollutant concentration for each meteo condition, traffic boundary condition and ITS scenario. For Graz and Glasgow we have in total 9828 and 12600 sets of results respectively. Each set of results lists the pollutant concentration at each receptor point of the grid used for the simulation. This set of results can be interpolated to a pollutant concentration map. A single meteo condition map has large gradients in concentrations as the effect of emissions is observed downwind of the source. To present more informative maps, the pollutant concentrations have been averaged over the 252 meteo conditions with equal weight, prior to interpolation. This yields maps which clearly show the regions where the higher pollutant concentrations are expected. Important to stress here, is that the pollutant maps only show concentrations resulting from local emissions and do not take into account background concentrations (not feasible for scenario calculations due to the absence of data). This is sufficient for this application, since we are especially interested in differences between scenarios.

To highlight the local impact of ITS measures, ITS scenarios are compared with the base scenario in concentration difference maps, again averaged over all meteo conditions.

An example of a BC concentration difference map is given in Figure 4. This map shows for Graz the impact of rerouting the traffic from the western arterial road to the eastern arterial for one specific traffic signal plan and compliance rate. This traffic measure causes decreases of up to 0.3 µg/m³ along the western road and increases of up to 0.1 µg/m³ along the eastern road. The exact influence of an ITS measure on the pollutant concentration depends on the location, the meteo condition and the combined effect of the ITS measure, including the traffic signal plan, and the compliance rate.

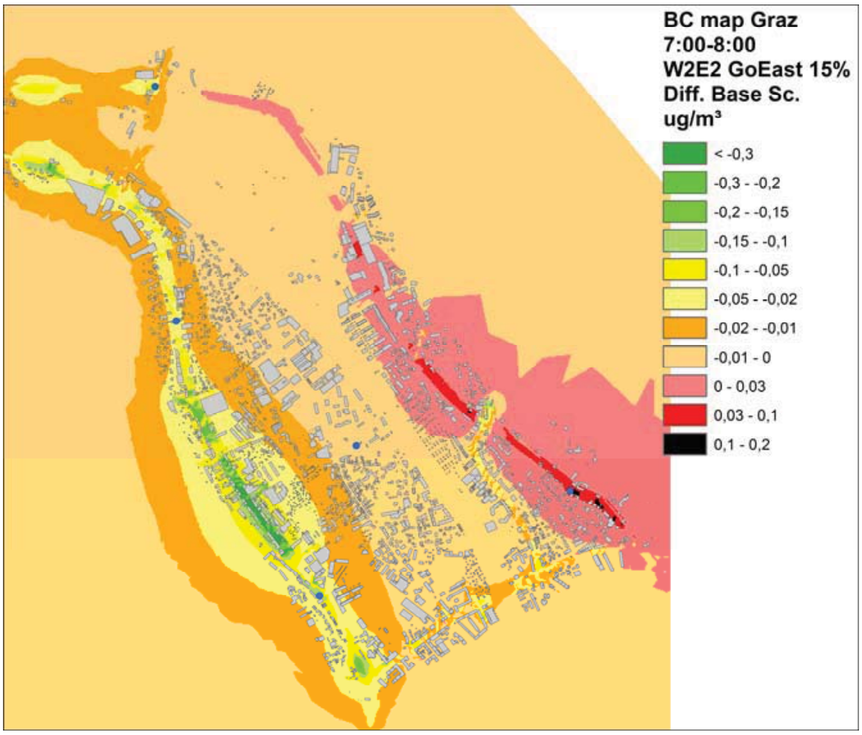

Figure 4: Example of a black carbon concentration difference map for Graz. Results of the ITS scenario and the base scenario have been averaged over all meteo conditions. Buildings in grey, units: µg/m³.

The concentration maps give a clear overview of the spatial variability of the ITS effects averaged over all meteo conditions. In Figure 5 and Figure 6, an overview is given of ITS impact for individual meteo conditions for a single location in each pilot area. Box plots show statistics of simulated effects that can be expected, with maximal effects up to 2.0 µg/m³ or 50% reduction in the local contribution to the BC concentration. The combination of an operational VMS with matching traffic signal plans leads to the best results for Graz. For the Glasgow case, individual traffic signal control scenarios, VMS scenarios and combinations have been studied. Combining a traffic signal plan with the VMS proves more powerful compared to individual measures. The first two traffic signal plans (TS1 and TS2) show a larger reduction compared to the third (TS3). No combination scenarios have been studied for the first two. During discussions with the local traffic control operators, it became clear that the first two scenarios will not be implemented in Glasgow due to physical constraints at the junction.

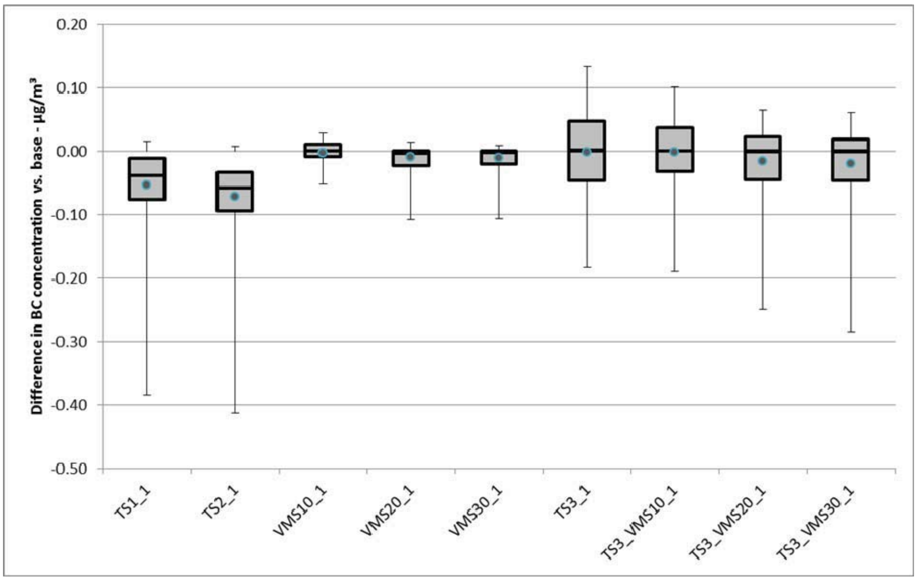

Figure 5: Boxplot of the BC concentration difference respective to the base scenario. Location Byres Road/ University Avenue (AQ Byres in Figure 3), Glasgow. Boundary Condition 1, units: µg/m³.

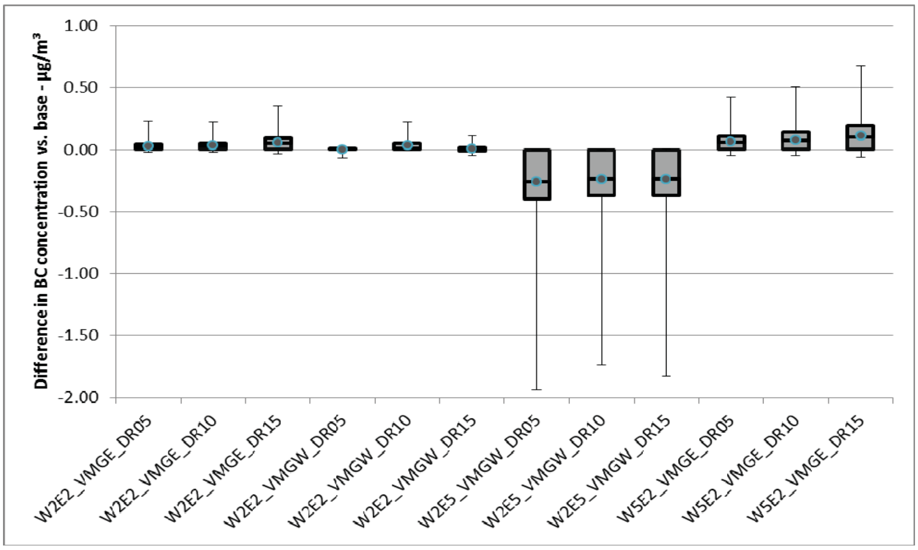

Figure 6: Boxplot of the difference in BC concentration *vs*. the base scenario, per ITS scenario, for BC monitor location eastern arterial (AQ6 in Figure 2), Graz. Boundary condition 7:00 – 8:00, units µg/m³.

The effect of implementing an ITS measure depends on the meteo condition. Figure 7 shows how the impact of the ITS measures in Graz changes with the wind direction for the BC monitor location along the eastern arterial. As can be expected, traffic scenarios avoiding congestion on the eastern arterial through suggesting drivers to use the western arterial, score best. As the location for which this analysis is made, is south-west of the main road, effects prove largest for north-easterly winds dispersing traffic pollution to this receptor point. Winds from the south-west blow the traffic pollution away from the analysed location, leaving only minimal impact of the changing traffic flows. Other locations will of course show different wind direction dependency.

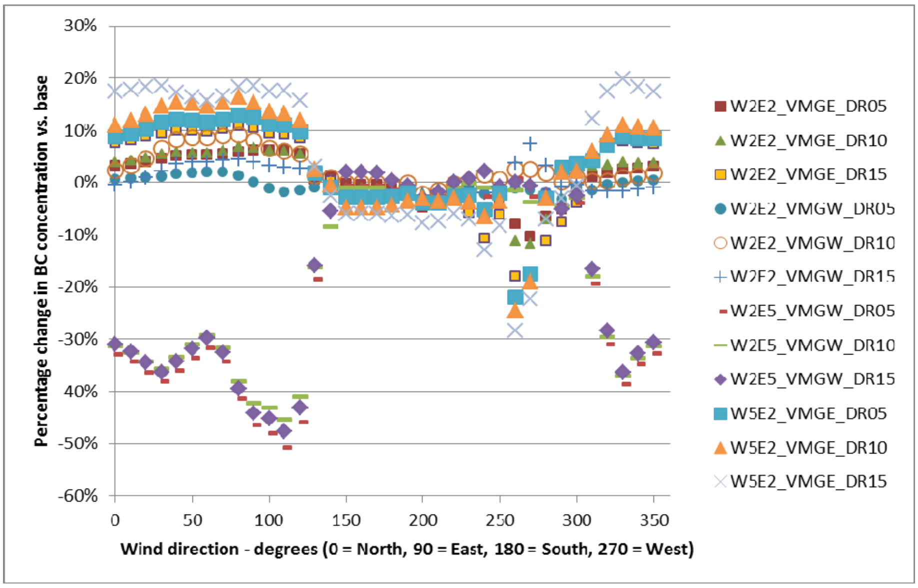

Figure 7: Percentage change in BC concentration for each ITS measures *vs*. base scenario at BC monitor location along the eastern arterial (AQ6 in Figure 2) for individual meteo conditions in Graz (Boundary condition 7:00 – 8:00).

Conclusions

Simulation results show the importance of taking into account current meteo conditions and traffic boundary conditions to evaluate the impact ITS actions on local AQ. In addition, the CARBOTRAF system will use this information to support traffic management in order to select ITS action for optimal traffic flow and reduced emissions and resulting improved AQ. The potential impact of the CARBOTRAF on air quality in both pilot cities is analysed using the simulation results. Implementation of ITS measures leads to potential changes in total BC emissions over the whole network with -5% to +2%. The effect on the BC concentration is illustrated for target locations. Averaged over all wind directions and stability classes the ITS measures lead to changes in the range of -0.3 to +0.1 µg/m³ BC. Maximal influence on the BC concentrations for individual meteo conditions range from -0.2 µg/m³ to almost -2.0 µg/m³. The effects of ITS measures on BC concentrations have large spatial and temporal variations. Overall, the best performing ITS measures have the potential to significantly improve the air quality at crucial locations. Averaged over the full test site effects remain fairly limited.

The CARBOTRAF system is operational in Graz from November 2014 until the end of February 2015. Data from the earlier reference period without DSS will be compared to the test period using real time data to evaluate the effect of the system on both traffic and air quality.

Author

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