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Evaluation of Environmental Impacts of Adaptive Network Signal Controls based on Real Vehicle Trajectories

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Abstract

To improve livability in cities and to meet stringent regulations set by the European Union, municipalities are striving to reduce the amount of greenhouse gas (GHG) and particular matter (PM) emissions (39. Bundesimmissionsschutzverordnung (BImSchV)). Adaptive Network Signal Control (ANSC) strategies have been developed with the main goal of improving the flow of traffic in urban areas by reducing travel times and the number of stops on the strategic network. However, in addition to improving traffic flow, ANSC strategies could prove to be a useful means for reducing the GHG and PM emissions from traffic in urban areas. In order to test this hypothesis, real trajectory data from test sites in Germany was collected and is analyzed using the EnViVer model (based on VERSIT+) from TNO (Eijk et al., 2011), which takes into account the velocity-time profiles of individual vehicles and estimates the emitted CO_2, NO_x and PM_{10}. Trajectory data was separately collected within the framework of the two different German research initiatives TRAVOLUTION (Braun et al., 2009) and AMONES (Boltze et al., 2011). In TRAVOLUTION, a test site for the ANSC BALANCE (Friedrich, 1999) was installed in Ingolstadt. In Hamburg and Bremerhaven, the ANSC systems BALANCE and Motion (Busch and Kruse, 1993) were evaluated within the AMONES project. In both cases, trajectory data was gathered with and without the ANSC system. The study shows, that ANSC is able to achieve reductions in GHG and PM emissions on the strategic network in cities. Due to the change in driving behavior, which can be determined accurately from the data, a change in fuel consumption and thus a reduction of emissions can be observed. The paper examines the effects of different ANSC systems on the emission of different pollutants.

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Keywords: Adaptive Network Signal Control; GHG emissions; Vehicle trajectories

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1. Introduction

Adaptive Network Signal Control (ANSC) aim at influencing the traffic flow by coordinating the signal control of the strategic network in urban areas. The main goal is to optimize the traffic flow by harmonizing traffic. Motion and BALANCE are two German approaches of model-based ANSC systems, which optimize the signal plans dynamically by the use of different traffic models and which are widely used in Germany. Since more harmonized traffic with lower number of stops and less variation in speeds also leads to a more ecological way of driving in terms of fuel consumption and emissions, ANSC could also be used to optimize traffic with the ultimate goal of lowering emissions. The two research initiatives TRAVOLUTION and AMONES investigated on the question of optimizing traffic flow efficiency by analyzing the extended floating vehicle data (FVD) in three test sites with and without an ANSC applied.

In TRAVOLUTION, the BALANCE program run on the traffic control of the strategic network of Ingolstadt. The AMONES project was carried out in Hamburg, where also BALANCE was implemented and Bremerhaven, where Motion was tested. The data from the ANSC was in this case not only compared to fixed time control, but also to another method of traffic control, the local traffic actuated control.

Test vehicles were driving on the strategic networks of all three test sites during the periods with different control strategies and sent extended floating vehicle data (xFVD). The data can be used to evaluate the emissions of these vehicles, which can be calculated by the TNO software EnViVer (Eijk et al, 2011). The emissions taken into account here were PM_{10}, CO_2 and NO_x, the type of vehicles was assumed to be the same to make the study comparable. Additionally, based on data of the TRAVOLUTION project, selected vehicle trajectories were replicated on a dynamometer in order to measure real vehicle emissions.

This paper focuses especially on the effect of ANSC on fuel consumptions and therefore GHG and PM emission.

2. Former GHG and PM Evaluations of BALANCE and Motion

Hischmann and Fellendorf (2009) compare real and simulated driving cycles on a chassis dynamometer. The simulated driving cycles are derived from a VISSIM simulation. The desired acceleration function of the Wiedemann 74 model (Wiedemann, 1974) is therefore calibrated from recorded GPS-drives as they have a major impact on emissions. For CO_2 emissions a reduction of 7 % for the observed drives and a reduction of 4 % for the simulated drives is found. For PM_{10} the reduction of the observed cycles is 5 % and for the simulated cycles 7 %. For NO_x the observed cycles show an increase of 4 % whereas the simulated drives show a reduction of 11 %. The study indicates that also from calibrated models it is difficult to get clear quantitative results for GHG and PM_{10} emissions from simulated data. But a qualitative trend for a reduction can be seen. The results from using the VISSIM standard parameters will lead to unrealistic results.

Brilon et al. (2014) analyze the ANSC systems BALANCE (Friedrich, 1999) in the city of Remscheid and Motion (Busch and Kruse, 1993) in the city of Münster using the traffic flow simulation VISSIM. For the simulation only the Wiedemann 74 parameters and the desired speed distributions are calibrated. The desired acceleration functions and the desired deceleration functions are not changed. In both test sites major technical problems occurred which had a direct impact on traffic and emission results. Due to that that reason both systems are switched off meanwhile. The problems also had effects on the evaluation results. The reduction of travel times for Münster is only 0.7 %. Therefore, the fuel consumption only decreases by 0.4 %, the NO_x emissions by 0.7 % and the PM_{10} emissions by 0.9 %. In Remscheid even an increase in travel time by 7.2 % occurs. This also has a negative effect on the fuel consumption which increases by 2.6 %, the NO_x emissions, which increase by 2.75 % and the PM_{10} emissions which increase by 1.75 %. The study indicates that from negative traffic performance of ANSC systems also negative results on emissions can be expected.

Kohouthek (2010) tried to predict NO_x and PM_{10} emissions from weather and traffic data in a measurement period of four weeks within the AMONES project in Hamburg and Bremerhaven (Boltze et al., 2011). His outcome was, that the NO_x emissions highly correlate with the wind speed, the wind direction and the atmospheric pressure but that there is only a minor correlation with the traffic volumes. Within the traffic the main correlation refers to the number of acceleration maneuvers and the portion of heavy goods vehicles (HGV). For PM_{10} the correlation with the traffic is even less. The reduction potential from ANSC for GHG and PM emissions is estimated below 20 %. The study shows, that the influence of meteorology on emissions is very high. Therefore a reduction in emissions does not necessarily lead to a reduction in emissions.

3. Validation Approach

Testing the effects of traffic control strategies on the real emissions of vehicles is due to many uncertainties a challenging task and is therefore usually carried out using simulations. Since these do not describe all interdependencies and effects of a whole network completely though, results are only partly useful for the evaluation of emissions. Real tests are therefore needed to evaluate whether or not the driving behavior can be changed towards more ecological driving patterns and thus have a positive effect on the emissions. This study combines the knowledge of real driving patterns in different traffic situation by evaluating real vehicle trajectories and xFVD with different control strategies applied. With this information a good estimation of emissions can be made which evaluate the changes in emissions in a more realistic way.

Additionally using the real trajectories of vehicles from field operational tests leads to more realistic results than using vehicle trajectories determined from microscopic traffic simulations.

3.1. Traffic Signal Control

The baseline signal control for all three test sites is a rule based actuated local control, which is coordinated. The ANSC systems BALANCE (Friedrich, 1999) and Motion (Busch and Kruse, 1993) optimize the frame signal programs on a tactical level every 15 minutes. This is done by predicting the traffic demand for the next time period and optimizing the control using a traffic model and a performance indicator to evaluate possible solutions. The optimal solution is chosen and sets parameters to the local actuated rule based control.

3.2. Emission Estimation using EnViVer

The emissions production associated with the collected trajectory data was estimated using the emission calculation tool EnViVer. This tool is based on the statistical Versit+ model and can be used to estimate emissions of CO_2, PM_{10} and NO_x from the output from microscopic traffic simulation tools (such as VISSIM). In order to create a dataset in a format suitable for input into EnViVer, the CAN-Bus data from the probe vehicles was transformed to conform to the .fzp output format from VISSIM. As a basis for the emission estimations, the traffic composition “Light Duty City 2010”, which reflects the typical composition of vehicles in European cities in the year 2010 was selected for the Versit+ model. Each of the trajectories was analyzed using EnViVer in order to estimate the average emissions of carbon dioxide, particular matter and nitrogen oxides for each route and direction, before and after Motion and BALANCE were introduced. An example of the output from EnViVer is given in Fig. 1.

Vehicle trips count:		**1**		
Vehicle samples count:		**568**		
Vehicle types count:		**1**		
Era:		**2010**		
Vehicle:	**Car 100**	**Light_Duty_City_2010**		
		ALL Euro Light Urban		

Emission totals per Versit3 vehicle class:

Distance_km	Duration_sec	CO_2g_Total	NO_xg_Total	PM_{10}g_Total
2.14	283.50	423.20	0.97	0.10

Emission per km per Versit3 vehicle class:

Distance_km	Duration_sec	CO_2_g_km	NO_x_g_km	PM_{10}_g_km
2.14	283.5	197.66	0.45	0.05

Fig. 1. Example of EnViVer Output Data.

3.3. Statistical Analysis of Emission Data

In order to discern whether the introduction of the BALANCE and Motion systems at the test sites lead to a statistically significant reduction in emissions, the output from EnViVer was analyzed using the statistical analysis program SPSS. The emissions per kilometer value for each of the trajectories were taken into consideration rather than the total amount of emissions during the trip to account for any differences in trip length. The number of trajectories analyzed in each group at each of the test sites (one group before and one after implementation of the ANSC system) ranged from 268 to 549.

For each of the test sites and for each of the three studied pollutants, a two tailed T-test that assumed independent samples was preformed to determine if the means of the before and after groups of trajectories were significantly different. As the emissions do strongly depend on the driver’s behavior the variance of emissions are higher than the one for travel times or number of stops. Therefore the reduction in emissions of CO_2 and NO_x is not significant for Bremerhaven. The reduction in PM_{10} emissions are only significant on a confidence interval of 80 %. In Hamburg all reductions in emissions are significant on a confidence interval of 80 %. As the reduction of emissions is not significant or only on a low interval of confidence, it was not possible to explore the effect of the ANSC systems at a more detailed level (e.g. per direction).

4. Test Sites

xFVD was collected by probe vehicles in three different German cities with ANSC systems. For the ANSC BALANCE a field operational test (FOT) was carried out in the city of Ingolstadt between 2006 and 2008 within the TRAVOLUTION project and Hamburg in 2008 within the AMONES project. Additionally Bremerhaven was the test AMONES site for the ANSC Motion FVD in 2009.

4.1. Ingolstadt (BALANCE, 2006 and 2008)

For the research project TRAVOLUTION (Braun et al., 2009) three routes in the inner city of Ingolstadt (see Fig. 2) were chosen to collect xFVD from prove vehicles driving in the West (green route, 2.1 km long), in the East (red route, 4.4 km long) and in the North (black route, 4.0 km long) of the city center. The test drives were carried on two weekdays in June 2006 between 06:00 and 19:00. Additionally the test was repeated in June 2008 with an activated BALANCE system controlling each traffic signal (indicated by the red dots) along the three routes. All together more than 500 single vehicles trajectories data were recorded on these routes including detailed CAN-bus data sets for further emission calculations.

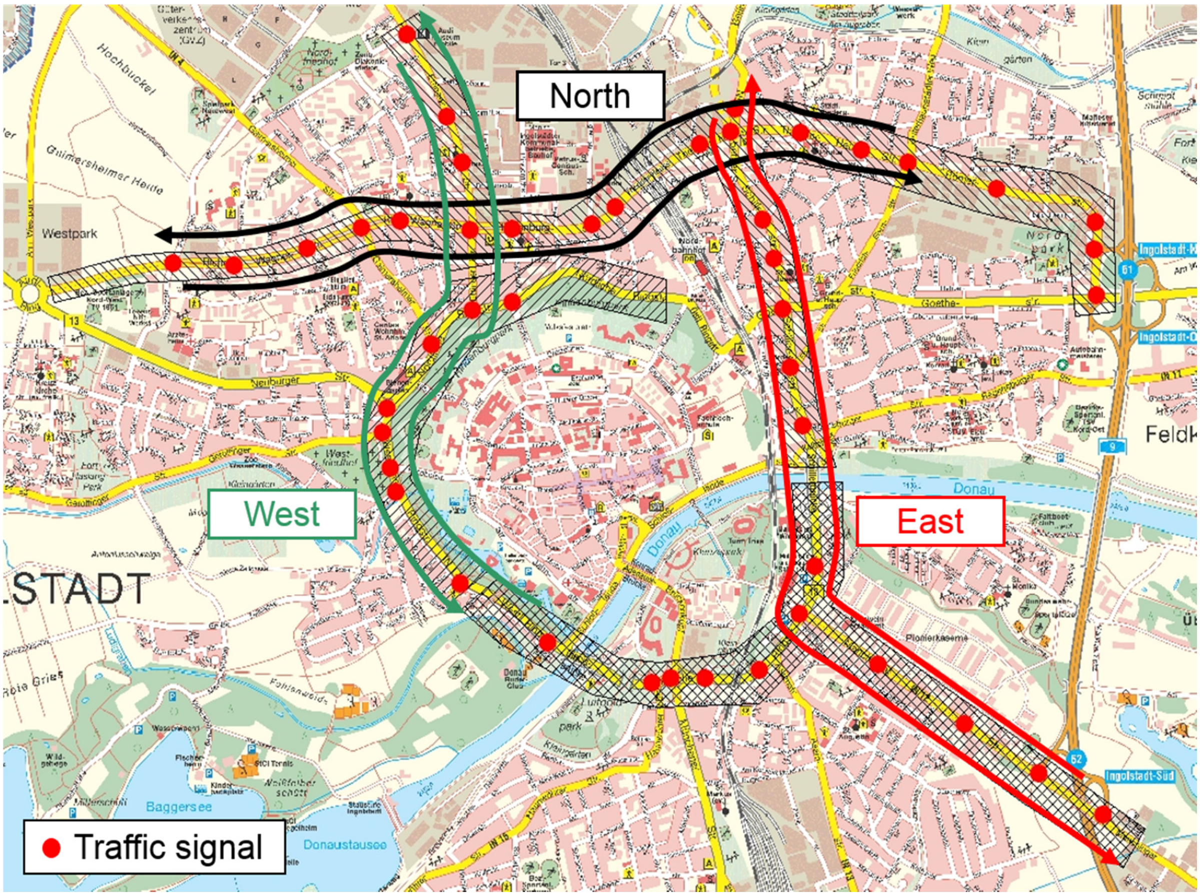

Fig. 2. TRAVOLUTION test site in Ingolstadt showing the three different routes (Braun et al., 2009).

4.2. Bremerhaven (Motion, 2006)

The test site in Bremerhaven Mitte includes the Columbusstraße in North-South direction and the Lloydstraße in East-West direction (see Fig. 3). Along this road segment, with a length of 1.6 km and mostly two lanes in each direction, the probe vehicles are passing by nine traffic signals controlled by the ANSC Motion. A 10 weekdays FOT was carried out in February 2009 between 06:30 and 18:30 in the test area. The traffic volumes on these roads are relatively low and range between 6,000 and 10,000 vehicles per day.

Fig. 3. AMONES test site in Bremerhaven showing the evaluated route (Boltze et al., 2011) (Source: OpenStreetMap)

4.3. Hamburg (BALANCE, 2008)

The third test site in Hamburg is located in the district of Barmbek and consisting of the three links Steilshooper Straße, Bramfelder Straße and Habichtstraße (together approximately 6 km) is shown in Fig 4. The main traffic concentrates on Bramfelder Straße and Habichtstraße with two lanes in each direction. The test site is part of the Hamburg adaptive network control system (HANS) with a total of 41 single traffic signals, whereof 13 are directly located on the three streets of the test site. The data collection was carried out in June and October 2008 on normal weekdays from 06:30 to 18:30 with a running BALANCE ANSC. Due to the higher traffic demands between 16,000 and 24,000 vehicles per day in the relevant entrances of the test area disruptions in the traffic flow occurred in the morning and evening peak hours.

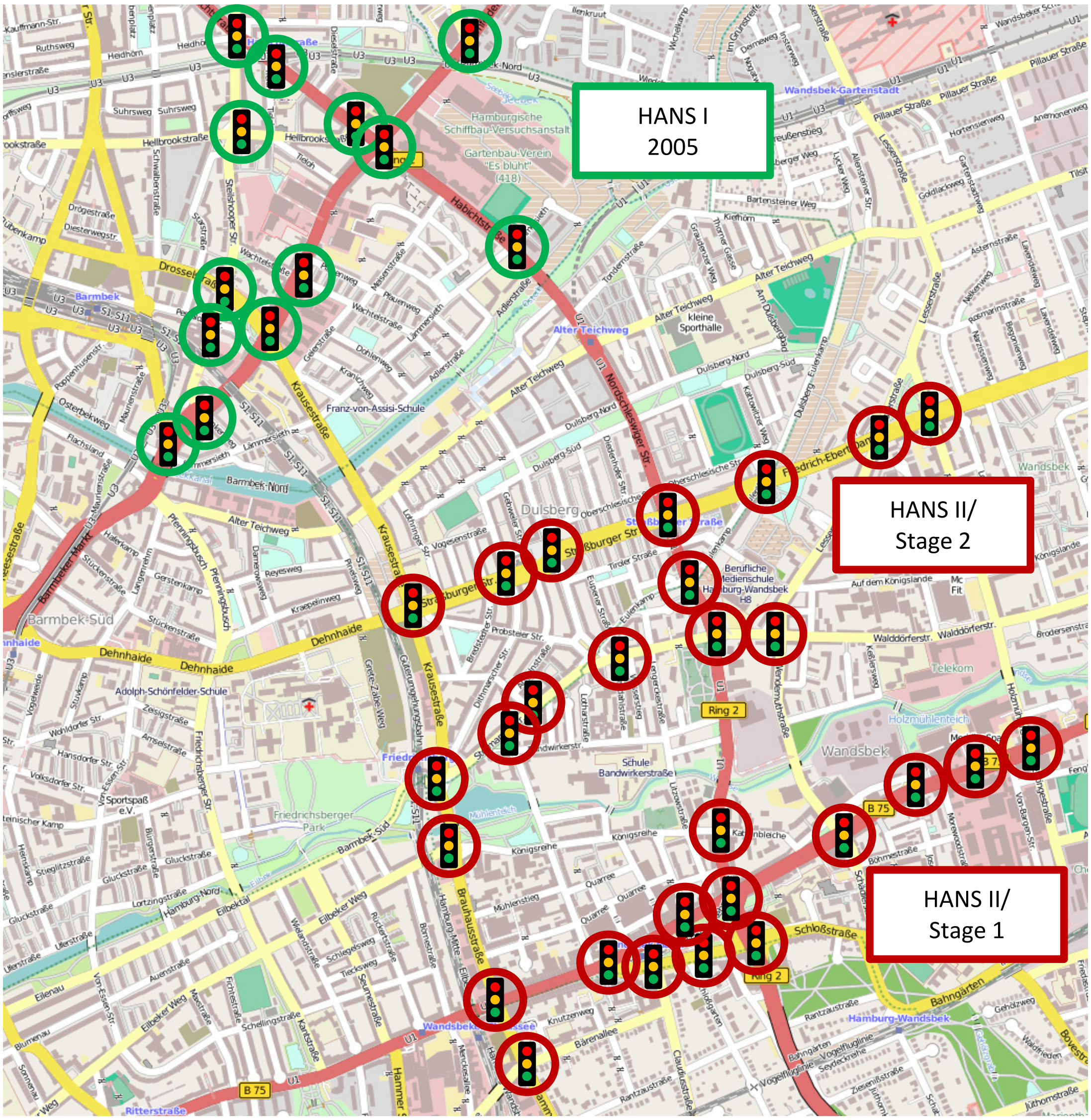

Fig. 4. AMONES test site in Hamburg showing the three evaluated roads (green circles) (Boltze et al., 2011) (Source: OpenStreetMap)

5. Results

In all three test sites, the studies show, that the ANSC – additionally to reducing the individual vehicles travel times and number of stops – has a positive effect on the emissions. After applying the ANSC, in all cases the average emissions were reduced on the strategic network. The following chapter gives an overview of the results. Both, the traffic relevant indicators travel time and number of stops and the environmental indicators fuel consumption and emissions are compared. The emissions evaluated by EnViVer are NO_x, PM_{10}, and CO_2.

The main goal of dynamic green waves is the improvement of traffic flow, by reducing the vehicles travel times and the number of stops. For the Ingolstadt test site, those indicators show positive results for all routes on the strategic network. The travel times decrease by up to 14.6 % and the number of stops was reduced by up to 31.6 %. The results for each route can be seen in the following Table 1.

Table 1. Comparison of travel time and number of stops in Ingolstadt by the use of BALANCE. (Own production)

Route	Base Travel Times [s]	BALANCE Travel Times [s]	Base Stops	BALANCE Stops	Improvement Travel Times [s]	Improvement Stops
North-East	382	373	3.2	2.8	2.2 %	11.8 %
North-West	449	405	4.2	3.3	9.8 %	22.8 %
West-North	582	556	5.6	4.9	4.5 %	12.8 %
West-South	452	401	5.4	4.3	11.3 %	21.2 %
East-North	506	432	4.7	3.2	14.6 %	31.6 %
East-South	488	481	4.2	3.8	1.4 %	10.1 %

In Bremerhaven and Hamburg distances driven had a very high variance, which is why a comparison of number of stops and travel times are not meaningful. What can be compared though, is the speed driven on the strategic network by the observed vehicles with the different control strategies applied. As can be seen in Fig. 5 below, the differences in Hamburg are rather low, whereas in Bremerhaven, an increase of 6.8 % in speed can be reached with the Motion control applied compared to fixed time control.

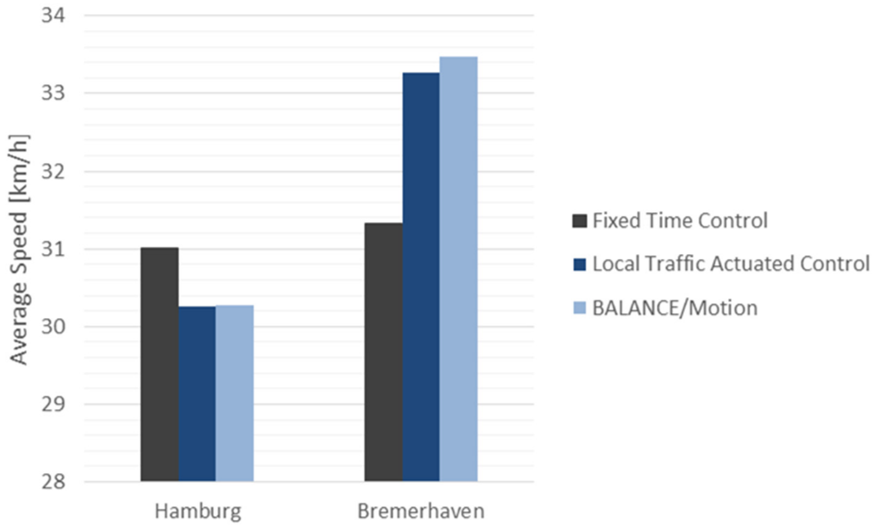

Fig. 5. Comparison of average speeds with different types of signal control strategies applied. (Own production)

By reducing the number of stops and making traffic flow more homogeneously, also the fuel consumption can be reduced. This hypothesis was tested by replicating a number of representative trajectories from the ones collected in Ingolstadt on a dynamometer. The test shows that the fuel consumption reduces by an average of 14.8 % depending on the type of vehicle.

The reduction of fuel consumption leads to a reduction of emissions. The three types of emissions which are evaluated in this study are the ones that can be calculated by the emissions estimation tool EnViVer. Carbon dioxide CO_2 is one of the so-called Green House Gases which are in public discussion due to the global warming effect they have. CO_2 from unnatural sources such as industry and transportation shall therefore be kept low.

The estimations with EnViVer show positive results for the estimated mean CO_2 emissions of all three test sites. In Hamburg, the mean CO_2 emissions reduced by 2.3 % after changing from local traffic actuated control to BALANCE even higher reductions are achieved comparing to fixed time control, where the average CO_2 emissions were 8.5 % higher than with the BALANCE control.

NO_x gases are different types of nitrogen oxides which also take effects on the ozone layer and thus also belong to the class of Green House Gases. The results of the study show, that the implementation of different control strategies has a high potential for the reduction of these types of gases. Already a change from fixed time control to local traffic actuated control in Hamburg brings a reduction of 10 % of NO_x emissions. With the BALANCE control strategy active, improvements are even greater.

The third type of emissions estimated by EnViVer, is PM_{10}, a particulate matter with a size of 10µm. The emissions of particulate matter are restricted by the European Union and under frequent observation in different cities. Transportation is one of the main producers of these harmful particles. Also here, a high potential can be seen when different control strategies are applied.

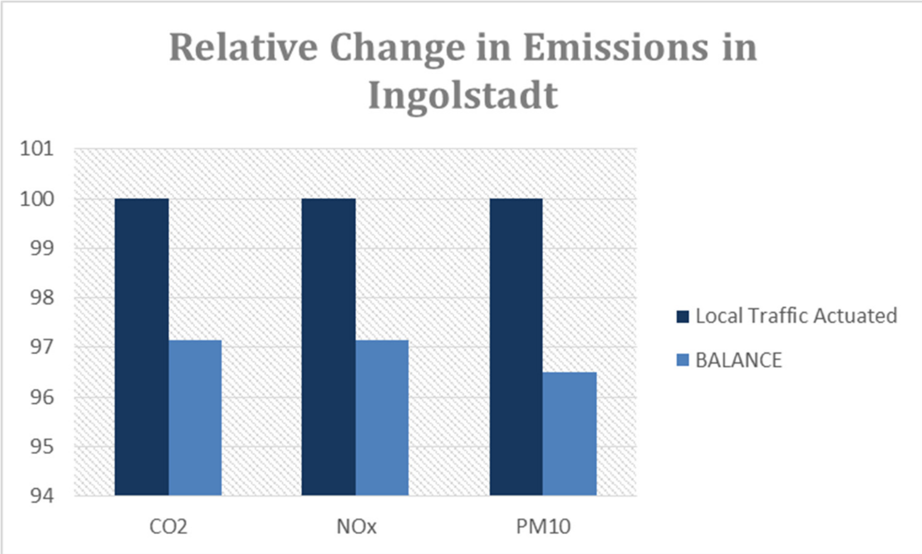

Fig. 6. Relative change in emissions with different control strategies on the strategic network of Ingolstadt, estimated with EnViVer.

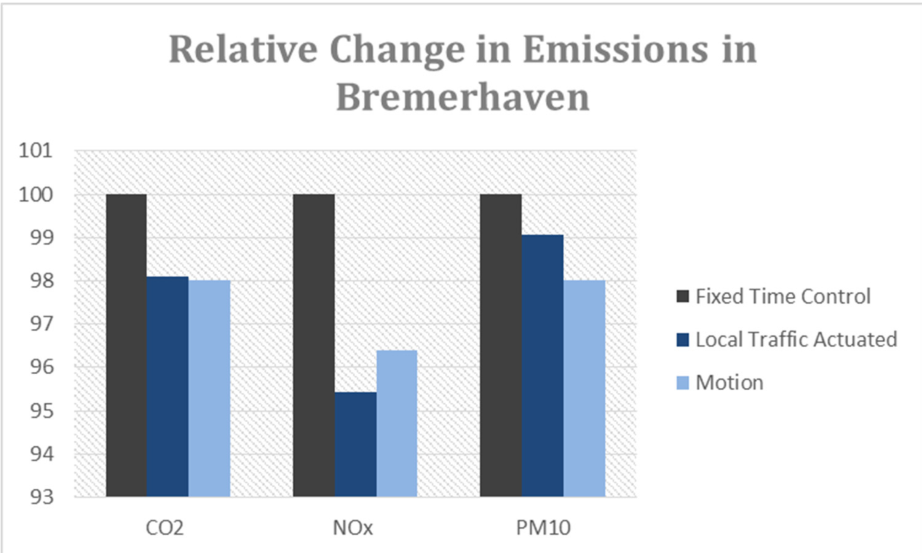

Fig. 7. Relative change in emissions with different control strategies applied on the strategic network of test site Bremerhaven.

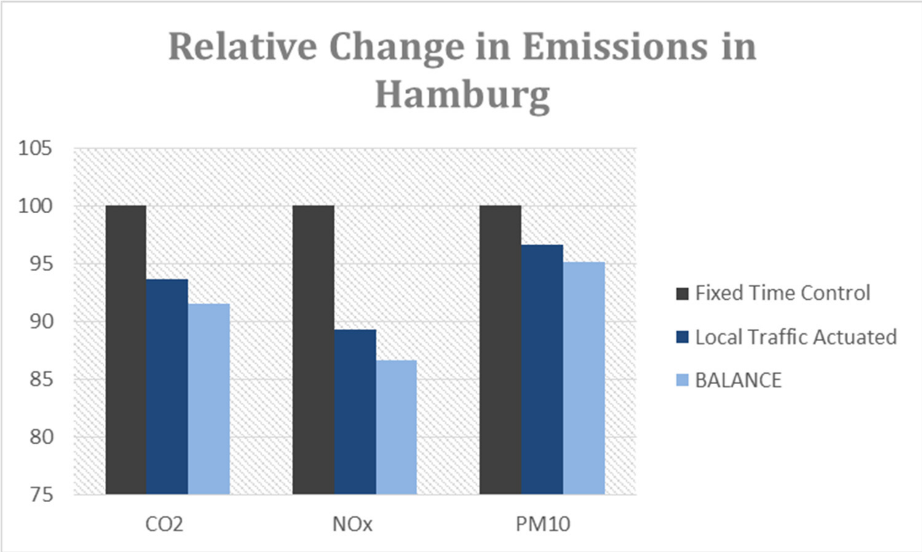

Fig. 8. Relative change in emissions with different control strategies applied on the strategic network of test site Hamburg.

6. Conclusions

As shown in the results of the two research initiatives AMONES and TRAVOLUTION, intelligent traffic control strategies may not only improve the performance of traffic in urban areas, but may also lead to reduced emissions and thus lower environmental harm of individual traffic. Even though the test results are statistically not significant due to a low sample size, the results clearly show the potential of ANSC towards a more sustainable system of individual motorized transport in metropolitan regions.

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