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Understanding effects of bioethanol fuel use on urban air quality: An integrative approach

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Abstract

Results obtained through combining different approaches, and aiming at contributing to the understanding of effects of bioethanol fuelled vehicles on urban air quality, are evaluated. The study is based on the results obtained by measurements, modelling and cost assessment estimates in a case study in Oslo under winter conditions, when the worst air quality episodes are registered and acetaldehyde and formaldehyde have the longest lifetime. Detailed levels of formaldehyde emitted by an E95-bus under on-road driving conditions are reported for the first time, and indicate that exposure to these levels may involve a high chance of developing cancer. Emission and air dispersion modelling were applied to evaluate the potential impact on urban environment. The results show that a full implementation of bioethanol (E85-vehicles) may affect urban air quality, subsequently affecting human health. Acetaldehyde emissions were estimated to increase by 233% for a full implementation of bioethanol (E85-vehicles) compared to the baseline (petrol/diesel vehicles), whereas CO_2, NO_x and exhaust particle emissions from traffic were estimated to decrease by 19%, 50% and 90%, respectively. Output from measurements and the air dispersion model were the basis for an impact assessment and economic valuation of implementing bioethanol fuel in a larger scale. The acetaldehyde-related health risk associated with emissions from bioethanol fuelled vehicles was estimated as oral cavity/pharynx cancer, and the related cost was found to increase by 300% for a full implementation of bioethanol relative to the current situation. Our study only shows part of the picture, and a full evaluation bearing in mind all potential pollutants' increases and reductions would be needed.

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Keywords: bioethanol; pollution; aldehydes; urban air quality; economic valuation

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1. Introduction

Climate change is one of the largest challenges of modern society and consequently reducing CO_2 and other greenhouse gasses (GHG) emissions has become crucial. Urban traffic is responsible for around 40% of CO_2 road transport emissions, and different measures to reduce them are greatly discussed and some are already being implemented. The use of biofuels (e.g. bioethanol, biodiesel or biogas) is a widespread issue in strategies for a sustainable transport; biofuels are proposed as an alternative to fossil fuel, and potential solution to reduce GHGs emissions. At the same time, reduction of GHGs often leads to other co-benefits, such as improvement of urban air quality and therefore reduction of associated adverse health impacts are expected.

Our study focusses on the use and potential impact of bioethanol fuel, which became popular as vehicle fuel in countries such as Brazil, United States or Sweden around the 1980s. Since then, bioethanol production has increased worldwide, for instance from 17.3 billion liters in 2000 to over 46 billion liters in 2007, and over 125 billion liters are estimated to be produced by 2020 [1]. Bioethanol can be a first or second generation product depending on the feedstock used, which ranges from the fermentation of raw materials such as starch-containing (e.g. corn, wheat), sugar-containing (e.g. beet and cane) to cellulose-containing (e.g. wood) plants. When used as fuel for transportation, bioethanol is commonly blended with petrol in different proportions, from 90% petrol and 10% ethanol, referred to as E10, to 15% petrol and 85% ethanol (i.e. E85), in which case certain modifications need to be applied to the vehicle. Nowadays it is a general practice to add around 7-10% of bioethanol to common petrol.

The advantages and disadvantages associated with the production, use and combustion of bioethanol have been addressed by several studies, however many uncertainties are still not solved as it will be pointed out in this study. Among the advantages, reduction of GHG emissions and sustainability [2] and enhancement of the agriculture sector have been highlighted. On the other hand, relatively high emission of hazardous air pollutants [HAPs; 3-4], or the uncertainties of reductions of CO_2 emissions under a complete cycle assessment evaluation have been pointed out as main disadvantages [e.g. 5]. Alcohol-based fuels oxidize to aldehydes, hazardous pollutants and precursors of strong oxidants such as ozone and peroxyacetyl nitrate (PAN). Whereby the ethanol molecule (C_2H_5OH) oxidizes to acetaldehyde (CH_3CHO), thus, bioethanol fuelled vehicles may contribute to urban pollution through emissions of unburned ethanol, acetaldehyde and acetic acid (CH_3COOH) as oxidation products of the former one.

This study is based on results obtained through combining different approaches; measurements, modelling activities, impact assessment and cost evaluations. Moreover, detailed levels of formaldehyde emitted by an E95-bus under on-road driving conditions along with new emission estimates (NO_x, CO_2, exhaust particles) are reported for the first time. The discussion presented in this study addresses the role of bioethanol as a fuel for transportation based on previous and new results, and an extensive review of the available literature. Our study will 1) contribute to the understanding of effects of bioethanol fuelled vehicles on urban air quality; and 2) emphasize the need of new integrative approaches to evaluate the use of alternative fuels.

2. Results and Discussion

2.1. Measurements

In Oslo, the opportunity of an interesting case study arose to evaluate the effects of emissions from vehicles running on alternative fuels as all buses on a particular bus line were running with high bioethanol blend (i.e. E95). Strong smell of acetic acid was already noticed as a negative side effect, and possible implications of bioethanol combustion on urban air quality were assumed. A study based on different types of measurement techniques was then carried out and the first results showed that the use of E95 blend as fuel for buses could have adverse impact on urban air quality, especially due to acetaldehyde, a hazardous compound that was measured and modelled at high concentration [6]. Acetaldehyde and acetic acid were identified as of concern based on ambient and on-line measurements during driving conditions of the E95 bus. Acetaldehyde was 1) measured at mixing ratio levels above 150 ppm in the exhaust of the E95 bus, 2) measured at higher ambient concentrations at locations exposed to the E95 buses than those not exposed, and 3) estimated to be above the threshold limit value at close distance to the bus.

The results obtained from the measurements carried out under on-road driving conditions have been reanalyzed and other organic compounds have been additionally identified and are reported in this study. Apart from ethanol, acetaldehyde and acetic acids, the most abundant compounds, formaldehyde, methanol, acetone and butanone have also been identified in the exhaust of the E95 bus, in addition to propenal, propanal, and butanal, whose identification is less certain. All identified compounds are measured in average around 1 ppm with the exception of acetaldehyde (i.e. 40-50 ppm), acetic acid (i.e. 30 ppm) and formaldehyde (i.e. 10-15 ppm). Peak values for those compounds reach up to 200 ppm, 40 ppm and 15 ppm for acetaldehyde, acetic acid and formaldehyde, respectively.

Detailed levels of formaldehyde under on-road driving conditions are reported for the first time in this study (Fig. 1). Formaldehyde is known to cause several adverse health effects, such as eye, nose, throat and skin irritation, coughing and allergic reactions. Moreover, high levels of formaldehyde have been associated with cancer in humans and laboratory animals. Formaldehyde is normally present at low levels in outdoor air, commonly below 0.03 ppm, and higher levels are measured indoors as formaldehyde results from the outgassing of building materials. Due to the presence in indoor environment, several occupational exposure limits have been defined for formaldehyde [7]. The Occupational Safety and Health Administration (OSHA) defined a permissible exposure limit of 1 ppm as time weight average concentration over 8 hours, and a short-term exposure limit of about 2 ppm for any 15-minute sampling period. The National Institute for Occupational Safety (NIOSH) define otherwise 0.016 ppm and 0.1 ppm as exposure limit for 8-hour time average and ceiling concentration for 15 min exposure, respectively. The lowest concentration that has been associated with nose and throat irritation in humans after short-term exposure is around 0.08 ppm, although some individuals can sense the presence of formaldehyde at lower concentrations. To prevent significant sensory irritation in the general population, an air quality guideline value of 0.08 ppm ($\approx$ 0.1 mg m^{-3}) as a 30-minute average is recommended [8]. This value is over one order of magnitude lower than a presumed threshold for cytotoxic damage to the nasal mucosa (i.e. 0.8 ppm), this guideline value represents an exposure level at which there is a negligible risk of upper respiratory tract cancer in humans [8].

Formaldehyde measured from the exhaust pipe of the E95 bus reach levels around 11 and 15 ppm (Fig. 1). Levels of about 11 ppm where detected in the first half of the round trip, from the departure station (i.e. Helsfyr) to the final destination (i.e. Aker Brygge), whereas levels of around 15 ppm where measured in the opposite direction (i.e. from Aker Brygge to Helsfyr). This may indicate that formaldehyde emissions are especially high when the engine is warm. Formaldehyde levels were modelled in the dispersion plume and at close distance to the bus (detailed methodology published elsewhere; [6]), resulting in levels above 1 ppm (permissible exposure limit 8-hours) and 0.8 ppm (threshold for cytotoxic damage) at close distance to the bus (i.e. <5 meters; Fig. 1). This indicates that formaldehyde associated with emissions from bioethanol fuel vehicles may be a concern for human health.

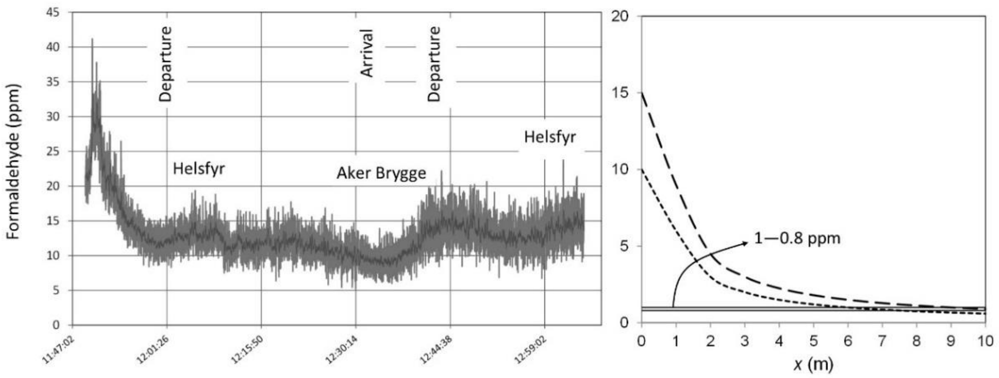

Fig. 1: Formaldehyde measured from the exhaust pipe of an E95 bus during on-road driving conditions (left) and estimated along the center line of the dispersion plume as a function of distance from the exhaust pipe (right).

2.2. Emissions

To our knowledge, very few studies modelled emissions and air pollutant concentrations from alternative fuels such as bioethanol at urban scale. Acetaldehyde and formaldehyde are precursors of ozone, hence ozone exposure associated with the use of ethanol has been modelled at regional scale in several studies, such as in the United

States. Results showed that ozone increases, especially during winter conditions, and so does the related mortality [9-11]. A study carried out in a county in Sweden estimated emissions considering two fuel scenarios, petrol versus E85 vehicles, and concluded that the change in emissions under the E85 scenario regarding petrol would be a decrease of about 6.5% for NO_x, 3.4% for $PM_{2.5}$, and 67% for benzene, whereas acetaldehyde emissions will increase by 770% [12]. In our study, emissions are estimated at urban scale, in particular for Oslo urban area under winter conditions when acetaldehyde lifetime reaches 15 days. Two scenarios are compared, a baseline scenario characterized by the current situation (i.e. petrol, diesel cars and one bus line running on E95) and a scenario characterized by a full implementation of bioethanol as fuel for transportation, so named E85-fleet. Acetaldehyde emissions were estimated to increase by 233% [13-14].

New estimations have been carried out for other compounds in order to contribute to a more complete evaluation of the use of bioethanol as fuel for transport, and the results are presented here. A full implementation of bioethanol as fuel for transportation would involve a decrease on CO_2, NO_x, and exhaust particles emissions of about 19%, 50% and 90%, respectively. These figures seem promising but there are several uncertainties. Nowadays, most European member states already have some percentage of biofuel (i.e. biodiesel or bioethanol) in diesel or petrol fuels. In Norway, for instance, standard 95 octane petrol contains up to 7% bioethanol and for diesel the share is up to 10% biodiesel blend. The addition of small amounts of bioethanol to petrol modified the emissions, and therefore modifications in the baseline are expected. The lack of knowledge concerning emissions and specifically emission factors constitute the main reason for the uncertainties. There is no consensus about the emission of some compounds, and inconsistencies have been observed for NO_x, CO, benzene and 1,3-butadiene [15]. Low ethanol blend (e.g. E10) has been reported to increase NO_x and CO emissions, and acetaldehyde and formaldehyde increases have been reported for both low and high ethanol blends. The evaluation of the potential impact of the use of bioethanol blend fuel in urban air quality is challenging due to the high number of uncertainties regarding emissions. However, there is some consensus, which involves certain concern from the use of bioethanol; it is on the fact that the use of bioethanol increases emissions of acetaldehyde and formaldehyde, known hazardous air pollutants, which in addition are precursors of ozone and peroxyacetylnitrate (PAN), strong oxidants. Our evaluation has been mainly focussed on winter conditions, when the worst air quality episodes in Oslo are registered and when acetaldehyde and formaldehyde have the longest lifetime (above 10 days).

2.3. Cost and Impact

Our study results showed that a full implementation of bioethanol as fuel for transportation might reduce CO_2, NO_x and exhaust particle emissions substantially. Important conclusions from our study however, showed that such an action might also have negative impacts on urban air quality through increased acetaldehyde, formaldehyde and acetic acid emissions. To guide towards effective and viable approaches for protecting local and global atmosphere imposing least burden of human welfare changes, the authors investigate in order to facilitate a comparison on the economic value of local damaging compounds such as acetaldehyde, to the expected social benefits of emission reductions of the CO_2, NO_x and exhaust particles. The results of these counterbalanced effects will contribute to the discussion on efficient resource allocation with regard to local, regional or global environmental policy, with emphasis on climate policies.

A literature review to investigate current estimates on the social cost of CO_2 emissions (often referred to as the social cost of carbon) has been carried out. The social cost of CO_2 is usually an estimate on the discounted value of the damages associated with climate change impacts marginal to one metric ton of CO_2 emitted to the atmosphere. The estimate depends both on the CO_2 residence time in the atmosphere and the likely impacts of climate change. Uncertainties in these estimates are therefore linked to the science of climate change and the assumptions made on climate sensitivity. Other parameters include the choice of impact valuation techniques, discount rate, treatment of equity, and the handling of potential catastrophic impacts. Because of the high number of important uncertain parameters, social costs studies typically show large disparity among their results. The complexity of estimating CO_2 induced costs requires the understanding of natural, social and economic sciences. Integrated assessment models (IAMs) are therefore often being used for estimating social cost of carbon (i.e. models on population, economics, use of technology, and emissions), but even though they are meant for providing comprehensive estimates, they fail to include all important impacts. The IPCC Second Assessment Report proposed a marginal impacts estimate range of 1-34 US$(1990)/t$CO_2$ [16]. More recently, a mean of 24 US$(1995)/t$CO_2$ (standard deviation = 66) was identified in a meta-analysis [17]. The US Government Interagency Working Group on Social Cost of Carbon (2010) presented social economic estimates based on average values of three separate IAMs (i.e. FUND, PAGE2002 and DICE) as 35, 21 and 5 US$/t$CO_2$, at discount rates of 2.5%, 3% and 5%, respectively.

Acetaldehyde in ambient air is a potential cause of several impacts on human health. Due to risks of oral and nose cavity, and laryngeal cancer attributed to the prior lifetime exposure of acetaldehyde, we identified significant costs to occur from undesired pollution effects under both the baseline scenario and the alternative scenario characterized by full implementation of bioethanol as fuel for transportation in Oslo. Most of these estimated costs result from valuation of dis-welfare and loss of productivity, while medical treatment costs only account for a small amount. The total costs were estimated to increase by 300% for a full implementation of bioethanol compared to the baseline situation. Initial and preliminary cost estimates indicate that the economic costs of acetaldehyde in ambient air are expected to be relatively small compared to the global benefits of reducing CO_2. Additional cost evaluation that would need to be addressed are those related to the consequences of 1) reducing emissions of regulated compounds (e.g. NO_2); 2) increasing emissions of carcinogenic compounds (e.g. formaldehyde), 3) increasing emissions of corrosive compounds, especially concerning material degradation (i.e. acetic acid) among others.

3. Conclusions

Our study showed that climate change mitigation measures in traffic address both climate change and air pollution, being particularly true for reducing regulated air pollutants leading to reduced impacts on human health and the environment. However, increased emissions of organic compounds such as acetaldehyde and formaldehyde could offset some of these benefits. The study also showed that there is an increased understanding of the scientific linkages between air pollution and climate change, which can be utilized in environmental policy development. In this way, natural and socio-economic sciences are intersecting to support more integrated and effective policy. Several uncertainties concerning emissions exist, making the evaluation of the sustainability of bioethanol as fuel a challenging task that needs additional research, especially in the design of new integrative approaches.

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