Chapter

Pathway toward Sustainable Winter Road Maintenance (Case Study)

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Abstract

Life Cycle Assessment (LCA) method was applied to evaluate the environmental impacts of winter road maintenance managed by an innovative road-weather information system and the impacts of vehicles passing the road during the snowstorm event. A case study refers to 10-hour lasting snowstorm event, considering a specific road section and application of a road-weather information management system to help winter road maintenance agency optimizing activities (salt gritting and/or plowing). Reliable information on the timing of the beginning of the snowstorm event affects (1) the activities of winter road maintenance, (2) the mobility of all vehicles passing the road, and (3) the fuel consumption of the vehicles. Since activities are optimized in case of preventive operation of winter road maintenance, less salt is needed overall. The road remains free of snow cover in case of preventive winter road maintenance operation, meaning that passenger cars and trucks pass the road at normal speed, without undesirable acceleration and braking caused by wheels slipping if snow accumulates on the road. Fuel consumption of vehicles passing salted and snow-free road remains unchanged, while fuel consumption increases in case of snow cover. Reduction of environmental burdens in case of such optimized winter road maintenance operation, is shown in this case study. The overall results of the comparative LCA analysis showed that the use of the road-weather information system in road traffic allows for as much as 25% reduction of environmental footprints. In the scenario where the winter service does not use information system the winter service also uses 40% more salt, which is also related with additional environmental impacts.

Keywords: LCA, environmental impacts, road, snow cover, preventive operation, traffic, fuel consumption, safety

1. Introduction

The transportation sector is one of the key contributors to greenhouse gas emissions that are potentially affecting global warming. A great majority of emissions caused by the transportation sector originate from passenger vehicles and trucks, due to exhaust fumes. The combustion of fossil fuels in engines is thus one of the most important contributors to atmospheric greenhouse gases. Traffic delays, radiative forcing, and rolling resistance are factors, which have a significant impact on the fuel consumption of vehicles and trucks. However, also the management of road infrastructure is directly related with environmental impacts, due to raw material consumption and energy needs during the construction and maintenance of the road, as well as during end-of-life activities [1–3].

European Green Deal introduced several proposals for reducing net greenhouse gas emissions by at least 55% by 2030, compared to the 1990 level. One of the proposals refers to providing efficient, safe, and environmentally sustainable transport [4]. Within this frame, winter road maintenance (WRM) plays an important role. The main activity of WRM agencies is reducing ice and snow from roadways, which is of crucial importance to provide safe driving conditions for traffic and smooth mobility. In countries with cold and humid winters, snowstorms may cause problems in the mobility of road traffic resulting in congestions and delays. In such conditions, fuel economy of vehicles is deteriorated, and consequently emissions increase. From this point of view, ensuring snow- and ice-free road is of great importance to achieve targets set by European Green Deal. However, winter road maintenance also yields a significant amount of greenhouse gases and other emissions, especially in cold regions, with a relatively high frequency of such activities [5]. Moreover, salt and other deicers, which are gritted on the road, pose a negative impact on groundwater and freshwater quality, and consequently also on biodiversity and human health [5, 6]. This represents a serious environmental problem taking into account that significant amounts of road salt and other chemicals are used to remove ice and snow accumulated on the road or to prevent icing and snow compaction on the roads [5]. WRM agencies are under pressure to improve not only the effectiveness and efficiency of their activities but also to optimize the activities from the aspect of sustainability. To improve environmental sustainability, special attention regarding the application of materials, strategies, and equipment is required [7]. Application of best practices from other studies can be a pathway toward achieving environmental sustainability in the field of winter road maintenance.

Several authors addressed the problem of environmental sustainability of winter road maintenance and the number of such studies is growing in recent years. Cui et al. [7] provided a framework for assessing sustainability in the field of winter road maintenance with salt as a road deicer. Adequate selection of deicers (road salt, agro-based, and complex chlorides/minerals-based products) is of crucial importance for successful implementation of winter road maintenance. Decision on selection of deicers has been typically taken based on their cost and effectiveness. However, the environmental impacts of salt or other chemicals used for deicing should also represent an important aspect when deciding about different deicing alternatives. Environmental impacts can be direct, due to release of chemicals into natural environment (soil, surface water), or indirect. The latter refers to the repair of damage (mostly related with corrosion) that deicers cause on vehicles and road infrastructure. Repair of such damage is associated with environmental impacts as well [7].

Environmental impacts related with winter road maintenance in Norway were evaluated in a study by Vignisdottir et al. [5]. They took into account the production and transportation of road salt (deicer) and vehicles for winter road maintenance and the operation of the winter road maintenance (use of the vehicles for plowing and salt spreading, associated with fuel and salt consumption). Data on quantities of road salt used for deicing and data on fuel consumption of WRM vehicles were gathered from public reports, so the results of LCA reflect realistic conditions. The study showed that emissions related to winter road maintenance in Norway contribute around 1% of the total emissions from road transportation in Norway. Such relatively high contribution can be explained by two facts. The first one is that Norway is the leading country in the use of electric and hybrid electric vehicles, which cause zero- and low emissions. The second fact is that most part of Norway has a cold and relatively humid climate. In such regions, winter road maintenance is extensive.

Vignisdottir et al. [8] provided a comprehensive review of 35 scientific papers dedicated to the evaluation of environmental impacts and effects of winter road maintenance. Based on this review, some research gaps were emphasized. In most of studies, only local environmental effects of deicers were addressed. While rare studies provide a holistic overview on environmental impacts related with winter road maintenance operation methods or material selection.

The goal of this study is to compare the environmental impacts of two scenarios related to the operation of winter road maintenance. Life Cycle Assessment (LCA) method was applied to conduct such a comparison. In baseline scenario, the agency responsible for WRM does not use a road-weather information system, meaning that it does not have accurate information about the exact timing of the beginning of the snowstorm event. Winter road maintenance operations start only when snow began accumulating on the road.

In alternative scenario, the WRM agency does use road-weather information system. In such a case, it obtains reliable information on timing of snowfall event and if snow or ice will accumulate on the road. Based on such detailed weather forecast, the WRM agency can take preventive measures, and if necessary, start gritting the road just before the snowfall event. In such conditions, the agency can optimize the consumption of road salt required for anti-icing and/or deicing. The purpose of this study is to benchmark the environmental impacts of baseline WRM operation scenario versus alternative scenario (preventive WRM operation scenario).

2. Materials and methods

Typical winter road maintenance activity is the mechanical removal of snow accompanied by deicing with chemicals or traction enhancement with abrasives. To conduct such activities, vehicles equipped with liquid and solid spreaders, and plows are required. Plowing and/or spreading of deicer are associated with the consumption of fuel (vehicles are typically run on diesel) and deicers, which are most commonly salt and sand [6, 9]. Other deicers can also be used, such as calcium chloride, magnesium chloride, agro-based products, acetates, formates, glycols, and succinates [9].

Special Road-Weather Information Systems (RWIS) have been designed for WRM agencies to help them evaluating road conditions in cold climates in a way, that they can optimize the timing of salting and plowing activities [10]. By using Road-Weather Information System, the WRM agency obtains reliable information about the timing of snowfall on a particular section of the road and about the bonding of the snow with the road surface. The system is based on physical, energy-balance model to predict road conditions such as dry, wet, snowy, icy, for every hour and for 12 hours in advance. The forecast is high-resolution in time (forecast per every hour) and space (forecast for every km of road section).

2.1 Scenarios

2.1.1 Baseline WRM operation scenario

WRM agency does not use Road-Weather Information System and for this reason, the activities related with road maintenance (gritting with salt and plowing) begin only when the snow is already bonding with the road surface. During a long-lasting snowstorm, the WRM vehicle must pass the road section several times. The vehicle conducts gritting and plowing simultaneously. Fuel consumption of the WRM vehicle is increased because the vehicle drives in demanding weather conditions (when the snow is already bonding with the road surface). Moreover, the use of a plow has a direct impact on the relatively higher fuel consumption of the WRM vehicle. Other vehicles (passenger cars, trucks) passing the road section during snowstorms must adapt their driving to the snow conditions on the road. Fuel consumption of vehicles driving on the road is higher, which means that associated emissions are also higher. In general, snow and ice coverage on a road surface increase the fuel consumption of vehicles. The wheels can slip on the road, wasting energy as they have reduced grip, while driving speeds are significantly lower than normal [11]. For the purpose of this study, it was assumed that the corresponding increase in fuel consumption is 10, 20, and 30% respectively. This assumption is supported by literature data [12–14].

2.1.2 Preventive WRM operation scenario

Taking into account information obtained by Road-Weather Information System, the WRM agency can perform a preventive operation and start gritting with salt just before the beginning of the snowfall and its bonding with the road surface. The effectiveness of preventive activity (e.g., gritting with salt or some other anti-icing agent) is strongly linked to precise timing of the activity. The WRM vehicle conducts the preventive gritting with an anti-icing agent (salt) still on a dry road, while subsequent gritting operations are conducted during snowfall, on a wet, but still snow and ice-free road (meaning that plowing is not needed). The number of subsequent operations depends on the duration of weather event (e.g., snowstorm). The first preventive and subsequent gritting operations result in snow melting, so there is no snow accumulation on the road surface. In such conditions, the WRM agency uses up to 40% less salt than in baseline WRM operation scenario. Other vehicles passing the road section during the snowstorm event may drive at normal speeds, adapted to conditions of the wet road surface. Vehicles do not consume more fuel than usual. If so, emissions related to exhaust gases do not increase compared to normal weather conditions.

2.2 Life cycle assessment

The environmental impacts in the two scenarios were assessed using the Life Cycle Assessment (LCA) method. LCA is a standardized (SIST EN ISO 14040:2006) and internationally recognized method for assessing the potential environmental impacts of the products or processes under study. The LCA method is often used to evaluate the environmental impacts of comparable technologies or processes. In this study, LCA was applied to compare the environmental performance of two scenarios related to the operation of winter road maintenance. The optimized operation was evaluated against the classical operation of the WRM vehicle during a particular snowstorm event. Holistic environmental benchmarking of two scenarios, which take into account also mobility of all road vehicles passing the road during the weather event, was the main goal of this LCA study.

The functional unit of the LCA is the operation of WRM vehicles due to a particular snowstorm event. The weather event lasted 10 hours and the snow cover reached a thickness of 25 cm. Alternatively, the functional unit can take into account also mobility of all road vehicles passing the road section during the weather event. The length of the road section is 10.4 km. The functional unit thus includes the use the WRM vehicle (fuel consumption and related emissions) which conducts gritting (consumption of road salt) and when necessary the simultaneous plowing (the latter in case the baseline WRM operation scenario, when snow is assumed to accumulate on the road surface), as well as road traffic passing the road section during the weather event (fuel consumption and related emissions). Mobility of passenger vehicles and trucks, or disturbance in their mobility, has a direct impact on emissions to the environment.

2.3 System boundaries and assumptions

The system boundaries for the baseline WRM operation scenario where the WRM agency does not use Road-Weather Information System are shown in **Figure 1**. The WRM vehicle has to pass the road section four times during a snowstorm event. The length of the road section is 10.4 km; therefore the vehicle travels 41.6 km. The WRM vehicle conducts gritting and plowing simultaneously. The salt consumption is 40% higher than in the preventive WRM operation scenario, reaching 10 tons (**Table 1**). Because of the plowing, the fuel consumption of the WRM vehicle increases to around 50 L per 100 km (**Table 1**). Other vehicles passing the road section during snowstorm event must adapt their driving to the snow conditions on the road. We assumed fuel consumption to be 10 or even 20% higher in

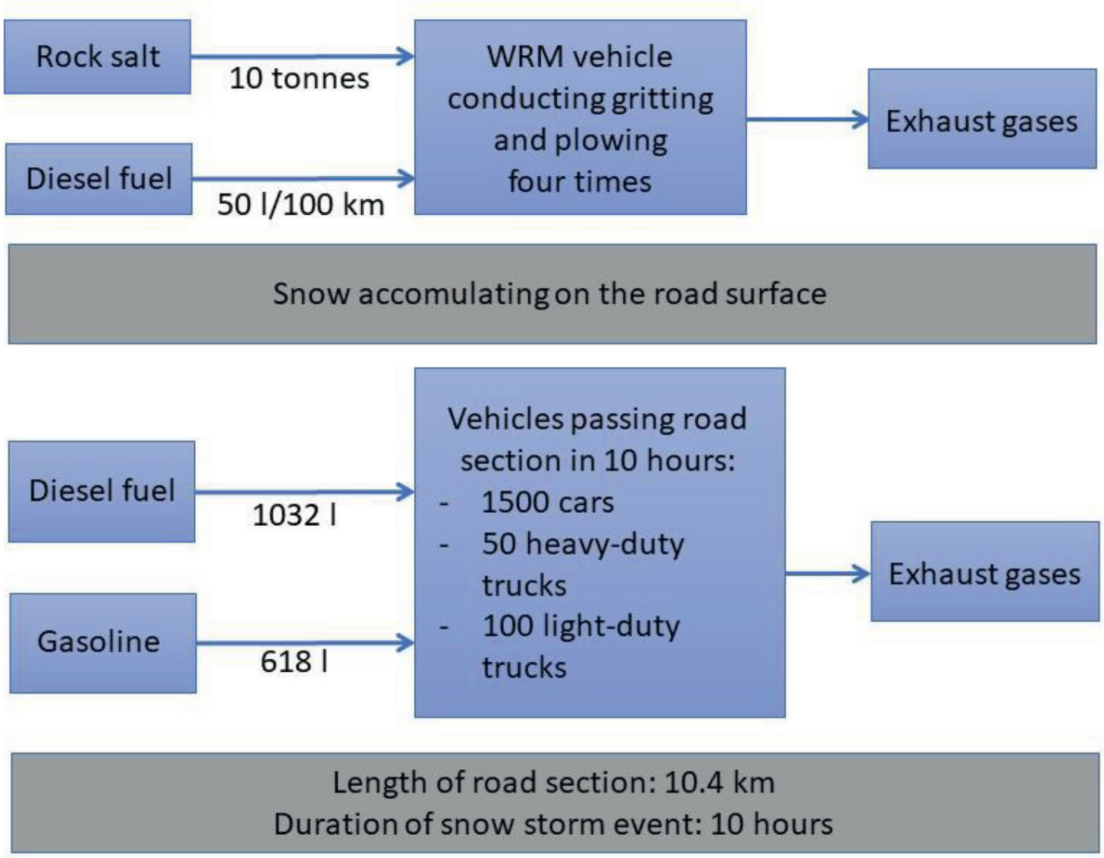

Figure 1.
System boundaries for the baseline WRM operation scenario.

case of driving on a road with snow bonding compared to driving on snow-free road (**Table 1**).

The system boundaries for the preventive WRM operation scenario, where the WRM agency uses Road-Weather Information System are shown in **Figure 2**. In this scenario, the WRM vehicle drives at normal speed (30 km/h), consuming around 40 L of diesel fuel per 100 km (**Table 2**). The WRM vehicle conducts a preventive gritting before the beginning of the snowfall and two more gritting operations during the snowfall event lasting for 10 hours. The 6 tons of road salt are required for such an operation, taking into account the length of the road section (10.4 km) and the fact that the WRM vehicle passes the road section three times. No plowing is required. All other vehicles passing the road section during a snowstorm event are assumed to be able to drive at normal speed. The fuel consumption of vehicles was accounted accordingly (see **Table 2**).

The data on the number of vehicles passing the particular road section considered in this study are from the year 2020. Data were obtained from the two traffic counting points located along the road section. It was assumed that the daily traffic in the

Equipment, material/energy requirements	Data inventory	Process description	Amount
Winter road maintenance vehicle	GLO: Truck, Euro 5, 12–14 t gross weight /9.3 t payload capacity	1 vehicle conducting salt gritting and snow plowing—passing the road Section 4 times	Diesel fuel consumption 50 L/100 km
Road salt	EU-28: Sodium chloride (rock salt)	Road salt gritting	10.000 kg
Heavy-duty trucks	GLO: Truck, Euro 5, 28–32 t gross weight / 22 t payload capacity	50 trucks passing the road section	Diesel fuel consumption 41 L/100 km or 44.7 L/100 km
Light-duty trucks	GLO: Truck, Euro 5, 7.5 t–12 t gross weight / 5 t payload capacity	100 trucks passing the road section	Diesel fuel consumption 25.5 L/100 km or 27.8 L/100 km
Diesel passenger cars	GLO: Car, diesel, Euro 5, engine size 1.4-2 l	600 diesel passenger cars passing the road section	Diesel fuel consumption 5.5 L/100 km or 6 L/100 km
Petrol passenger cars	GLO: Car, petrol, Euro 5, engine size 1.4-2 l	900 petrol passenger cars passing the road section	Gasoline consumption 6.6 L/100 km or 7.2 L/100 km
Diesel fuel	EU-28: Diesel mix at filling station	Diesel fuel for trucks and passenger cars passing the road section	1032 L
Gasoline (petrol)	EU-28: Gasoline mix (regular) at filling station	Petrol fuel for passenger cars passing the road section	618 L

Table 1.
Input data for baseline WRM operation scenario without application of road-weather information system. Winter road maintenance operation and road traffic mobility during snowstorm events are adapted to conditions with snow accumulating on the road surface.

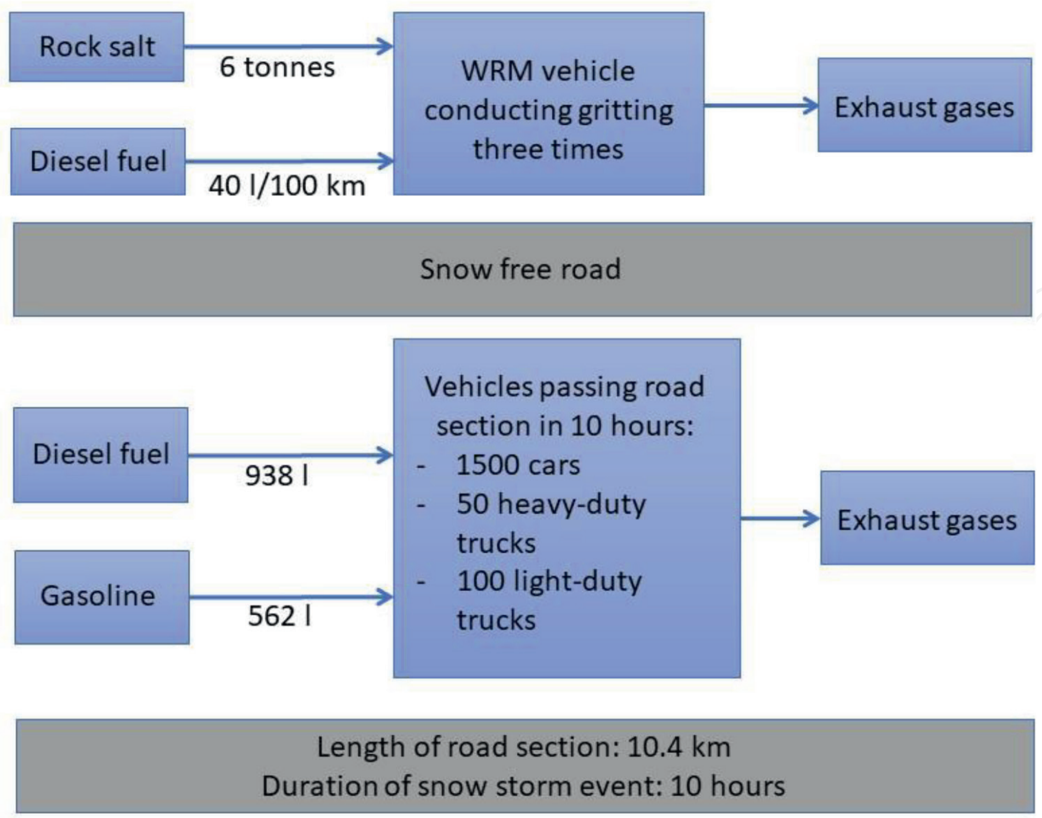

Figure 2.
System boundaries for the preventive WRM operation scenario.

studied section is the average number from the two counting points. Based on these data, it was assumed that during a 10-hour weather event, the road section is passed by 1500 passenger cars, 100 light-duty trucks, and 50 heavy-duty trucks. For passenger cars, we assumed that 40% of them are diesel cars and 60% are petrol cars, which is realistic information for Slovenian conditions, to which the case study refers.

2.4 Life cycle inventory analysis

GaBi professional software (version 10.6) was used to conduct a comparative LCA analysis. Data related with the use stage of vehicles, data for the production of fuels required for vehicles and data for deicer were gathered from the Professional database, which is integrated into GaBi software. Inventory data applied in two scenarios are indicated in **Table 1** (baseline WRM operation scenario without application of Road-Weather Information System) and **Table 2** (preventive WRM operation scenario with the application of Road-Weather Information System).

2.5 Impact assessment

ReCiPe 2016 version 1.1 Life Cycle Assessment Impact method was used to evaluate the environmental impacts of two scenarios. The ReCiPe method was developed in 2008 to harmonize the results of two other methods, CML 2001 (midpoint-oriented) and Eco-indicator 99 (endpoint-oriented). ReCiPe is one of the most commonly used methods for the calculation of environmental impacts [15]. The main principles of the ReCiPe 2016 method are based on the ISO 14040 and 14044 standards. The characterization factors are continuously updated according

Equipment, material/ energy requirements	Data inventory	Process description	Amount
Winter road maintenance vehicle	GLO: Truck, Euro 5, 12—14 t gross weight/9.3 t payload capacity	1 vehicle conducting salt gritting—passing the road Section 3 times	Diesel fuel consumption 40 L/100 km
Road salt	EU-28: Sodium chloride (rock salt)	Road salt gritting	6000 kg
Heavy-duty trucks	GLO: Truck, Euro 5, 28–32 t gross weight/22 t payload capacity	50 trucks passing the road section	Diesel fuel consumption 37.3 L/100 km
Light-duty trucks	GLO: Truck, Euro 5, 7.5–12 t gross weight / 5 t payload capacity	100 trucks passing the road section	Diesel fuel consumption 23.2 L/100 km
Diesel passenger cars	GLO: Car, diesel, Euro 5, engine size 1.4-2 l	600 diesel passenger cars passing the road section	Diesel fuel consumption 5 L/100 km
Petrol passenger cars	GLO: Car, petrol, Euro 5, engine size 1.4-2 l	900 petrol passenger cars passing the road section	Gasoline consumption 6 L/100 km
Diesel fuel	EU-28: Diesel mix at filling station	Diesel fuel for trucks and passenger cars passing the road section	938 L
Gasoline (petrol)	EU-28: Gasoline mix (regular) at filling station	Petrol fuel for passenger cars passing the road section	562 L

Table 2.
Input data for preventive WRM operation scenario: Winter road maintenance operation and road traffic mobility in case of application of road-weather information system take place on road, which is snow- and ice-free.

to new knowledge [16, 17]. The ReCiPe 2016 method allows the calculation of impact categories according to three-time perspectives (Individualist, Hierarchist, and Egalitarian). The Hierarchist perspective, which considers the most acceptable time period, is used in this study. The LCA results at the midpoint levels are presented by 19 impact categories (**Table 3**).

3. Results and discussion

First, only environmental impacts associated with the operation of WRM vehicles in two alternative scenarios were evaluated. The results show that the production of road salt (rock salt respectively) required for gritting the road yields significantly higher environmental impacts than the operation of the WRM vehicle itself. Production of road salt contributes 90% or more to the total parameter value of all impacts categories, the only exception is the impact on ozone layer depletion potential, where salt contributes around 70% of the total parameter value. Operation of the WRM vehicle is associated with diesel fuel requirements and exhaust gas emissions due to fuel combustion. These kinds of environmental impacts are thus relatively minor compared to impacts associated with salt gritting. Those are even

Impact category	Abbreviation	Unit
Climate change, default, excl. Biogenic carbon	GWP_default	kg CO_2 eq.
Climate change, incl. Biogenic carbon	GWP_incl. biog. C	kg CO_2 eq.
Fine Particulate Matter Formation	PM 2.5	kg PM2.5 eq
Fossil depletion	ADP_f	kg oil eq.
Freshwater Consumption	FWC	m^3
Freshwater ecotoxicity	FWAETP	kg 1,4 DB eq.
Freshwater Eutrophication	FWEP	kg P eq.
Human toxicity, cancer	HTP_cancer	kg 1,4-DB eq.
Human toxicity, non-cancer	HTP_non_cancer	kg 1,4-DB eq.
Ionizing Radiation	IR	kBq Co-60 eq. to air
Land use	LU	Annual crop eq.·y
Marine ecotoxicity	MWAETP	kg 1,4-DB eq.
Marine Eutrophication	MWEP	kg N eq.
Metal depletion	MD	Kg Cu eq.
Photochemical Ozone Formation, Ecosystems	POCP_ecosystem	kg NOx eq.
Photochemical Ozone Formation, Human Health	POCP_human_health	kg NOx eq.
Stratospheric Ozone Depletion	ODP	kg CFC-11 eq.
Terrestrial Acidification	AP	kg SO_2 eq.
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq.

Table 3.
ReCiPe 2016 midpoint impact categories.

underestimated in this LCA study, as impacts of salt flushed into water or terrestrial ecosystems are not possible to evaluate by means of LCA. The fate of road salt released in the environment is poorly understood and because of this reason, no characterization factors for leaching of salt into the natural environment have been introduced in LCA [5, 7, 9].

A comparison of two scenarios shows that the use of the Road-Weather Information System can significantly contribute to a reduction of environmental impacts related to the operation of winter road maintenance. This is a direct consequence of optimization in the consumption of salt for gritting the road. In this specific case study, the WRM agency reported that they saved 40% of road salt due to preventive winter road maintenance operations. Environmental impacts were reduced between 43% (in case of photochemical ozone creation potential—POCP) and 36% (in case of ozone layer depletion potential—ODP) compared to the baseline WRM operation scenario. In most of the impact categories, the impacts were reduced by 39% (including in the case of global warming potential—GWP, abiotic depletion of fossil fuels—ADP-f, and human toxicity potential—HTP). Optimization of the operation of winter road maintenance in terms of less operational activities of the vehicle (e.g., less fuel consumption due to a lower number of travels along road section and conducting only gritting, no plowing) yields relatively minor contribution to environmental improvement of preventive WRM operation scenario compared to baseline WRM operation scenario (**Figure 3**).

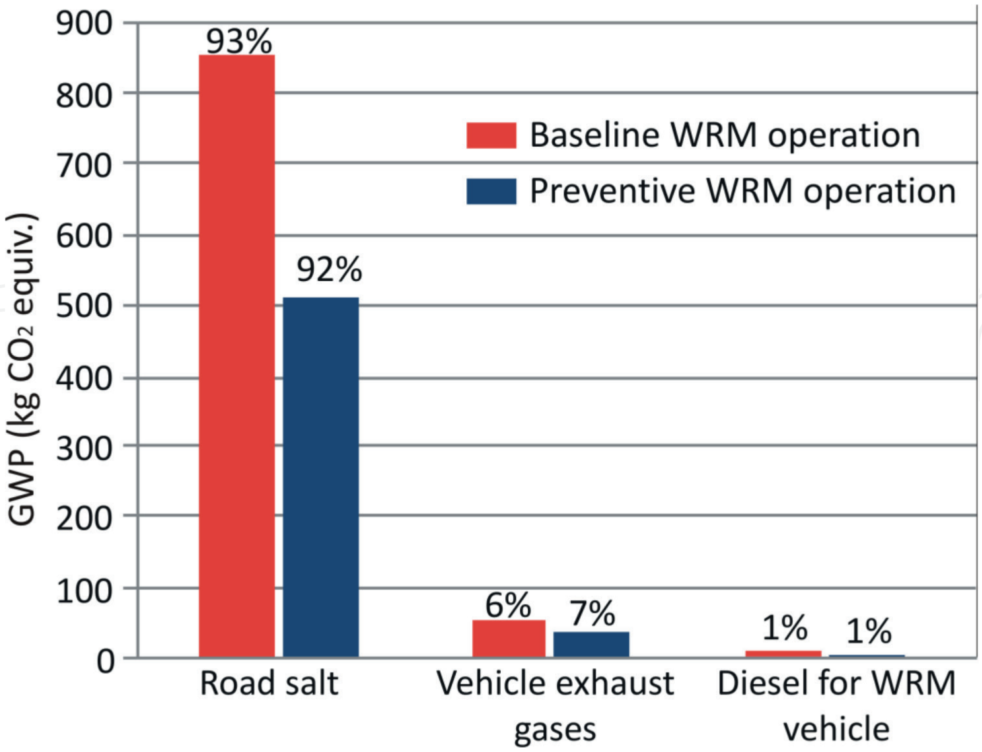

Figure 3.
Global warming potential associated with the operation of WRM vehicle (salt gritting, fuel consumption, and related exhaust gases) in two benchmarked scenarios.

In addition, two scenarios were compared by means of LCA holistically, accounting also environmental impacts caused by road traffic (passenger cars and trucks) passing the road section during a weather event. In such a case, the LCA results are greatly influenced by density of road traffic. Denser the traffic is, the higher is its contribution to the environmental impact of the studied system. It was assumed that road traffic in demanding winter conditions (due to snow accumulation on the road) consumes 10% of fuel more than in normal driving conditions (snow-free road). In case of baseline scenario, the traffic contributes around 80–90% of the total parameter values, depending on the impact category (the contribution is 84% in case of global warming potential—**Figure 4**). The rest of the influence is mostly affected by road salt, while the contribution of WRM vehicles is reasonably minor as already discussed. In a scenario with preventive WRM operation, environmental loads are reduced typically by 14% (GWP for example) compared to the baseline scenario. However, the impact on ionizing radiation is reduced even by 31%, due to less salt (anti-icing agent) consumption (**Figure 5**). Mining of rock salt is associated with electricity requirements. Taking into account that an important share of European electricity derives from nuclear power plants, such electricity yields a relatively high ionizing radiation footprint. This footprint is accounted also to resources (e.g., rock salt) for which exploitation requires electrical power. Moreover, an important share of electricity derives from thermal power plants. For this reason, mining of rock salt yields also relatively high impacts on fine particulate matter formation (PM 2.5), photochemical ozone formation (POCP), and acidification potential (AP). Because of less consumption of salt in preventive WRM operation scenarios, impacts on these three impact categories are also quite significantly reduced (PM 2.5 for 19%, POCP for 18%, and AP for 17%) (**Figure 5**).

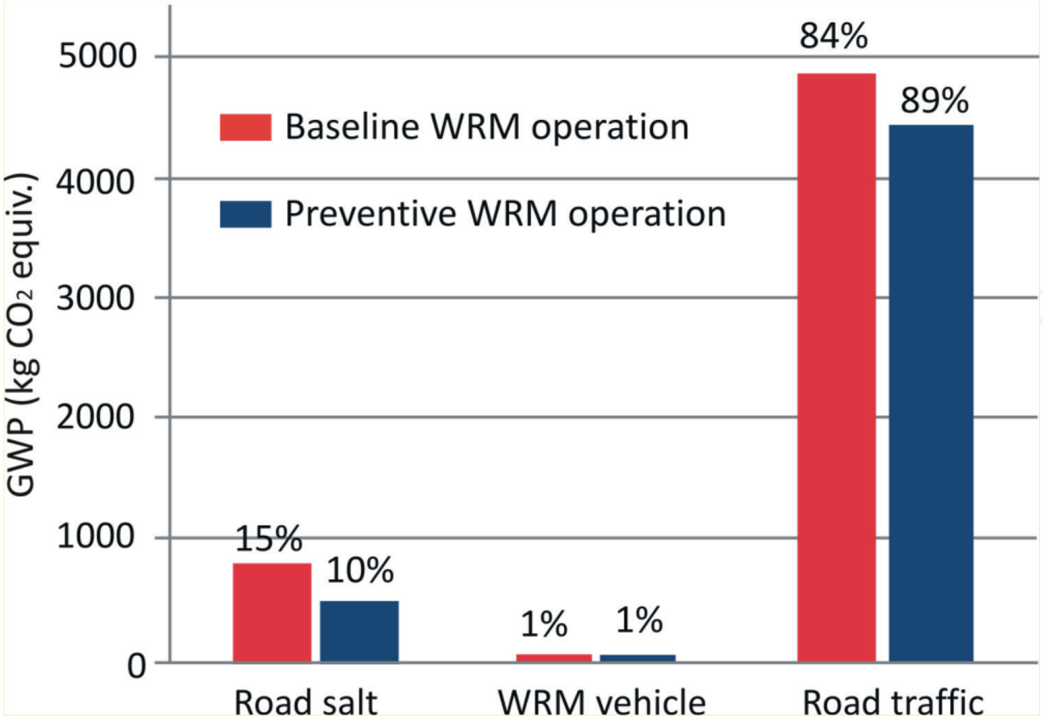

Figure 4.
Global warming potential of baseline WRM operation scenario versus preventive WRM operation scenario. Contributions of road salt, WRM vehicle (fuel consumption and associated exhaust emissions), and road traffic (fuel consumption and associated exhaust emissions) to GWP are shown in absolute and relative values.

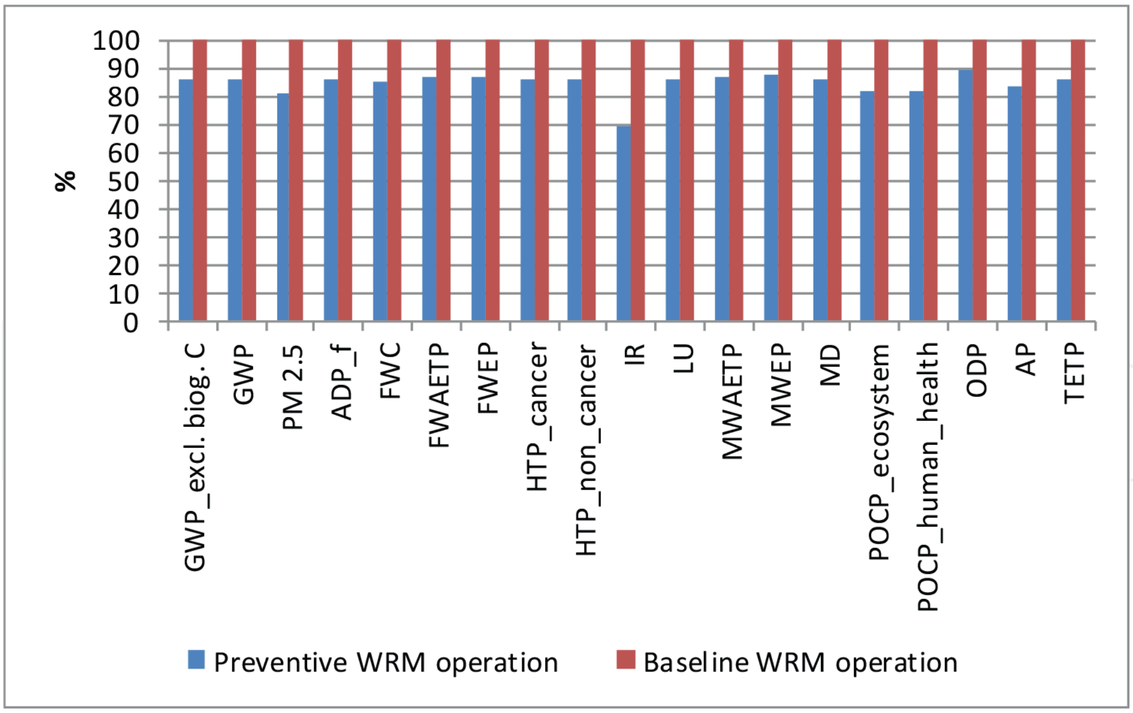

Figure 5.
Relative comparison of two scenarios. Baseline WRM operation scenario is set as a reference.

3.1 Uncertainty analysis

Uncertainty refers to data on fuel consumption of passenger cars and trucks passing the road section during a snowstorm event. Literature data indicate that increases in fuel consumption in different levels of slush vary between 10 and 30% [12–14]. Indeed, the practical experiences of the authors of this study showed that fuel consumption of passenger cars driving on roads with 10 cm snow cover increases by nearly 30%. In general, it was assumed that passenger cars and trucks consume 10% more fuel when driving on a road with snow cover, compared to driving on snow-free roads. If we assume that the traffic driving on the road with snow cover consumes 20% of fuel more than in normal driving conditions (preventive WRM operation scenario), then such a baseline scenario shows even greater environmental impacts. In such a case, differences between the two scenarios are typically 20% (GWP for example) or even more for some impact categories (up to 33% in case of impact on ionizing radiation). If we assume that the road traffic in the baseline WRM operation scenario consumes even 30% of fuel more than in preventive WRM operation scenario, the differences between the two scenarios are typically 25% (in terms of GWP, abiotic depletion of fossil fuels, human toxicity, ecotoxicity indicators etc.) and maximally 34% (in terms of ionizing radiation—IR) (**Figure 6**).

However, totally opposed findings can also be found in the literature regarding the fuel consumption of vehicles traveling on the road with snow cover. Taking into account the study of Nordin and Arvidsson [18], the fuel consumption of vehicles does not increase in conditions with 1 cm of snow cover on a road. Argumentation is that demanding driving conditions related with slippery roads or reduced visibility forces drivers to reduce the speed. Lower speed of vehicles due to the presence of small amounts of snow can result even in lower fuel consumption compared to vehicles on a cleared road driving with the usual speed [18]. But this is certainly not the case when snow cover on road reaches a few centimeters [12–14].

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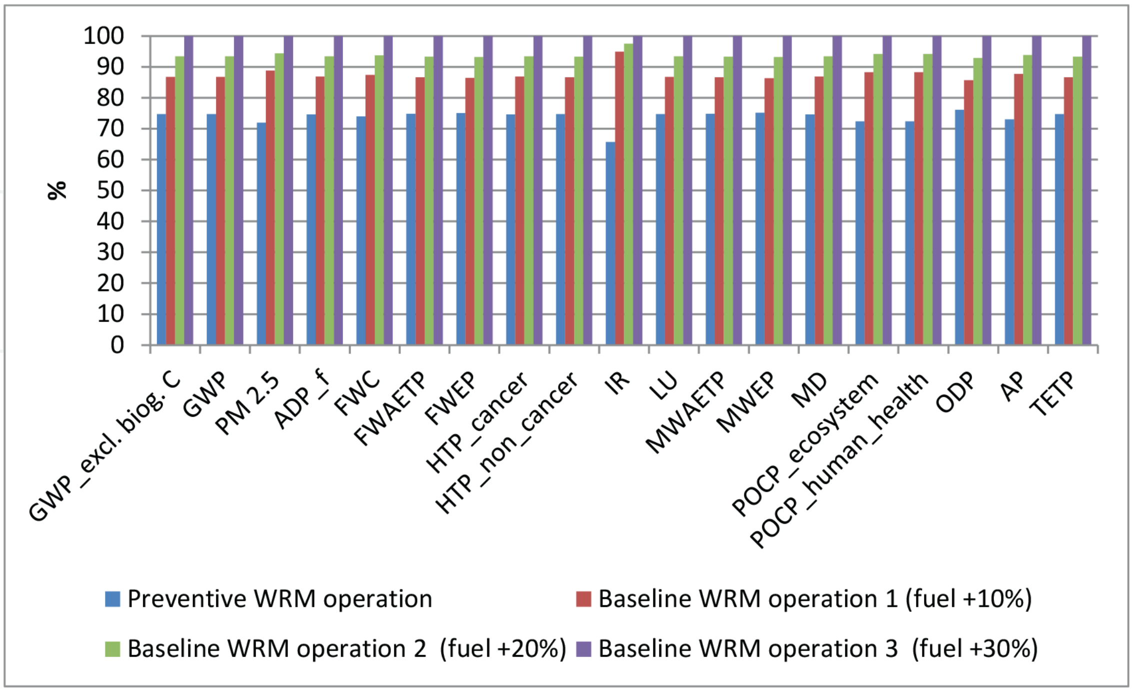

Figure 6.
Relative comparison of baseline WRM operation scenario versus preventive WRM operation scenario. In case of baseline WRM operation scenario, three assumptions were taken into account regarding the fuel consumption of cars and trucks passing the road covered with snow: 10, 20, or 30% increase in fuel consumption due to the presence of snow on the road. The assumption with the highest fuel consumption was set as a reference.

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4. Conclusions

The importance of optimizing winter road maintenance operations for achieving goals of environmental sustainability in the transportation sector is presented in a practical case study. Environmental impacts can be significantly reduced if the agency responsible for winter road maintenance optimizes the timing of operations and in this way uses less salt for road gritting. Moreover, the precise timing of winter road maintenance operations is of crucial importance for enabling smooth and undisturbed mobility of road traffic passing the road during a snowstorm event. Fuel consumption of road traffic and related exhaust emissions increase in case of disturbances and congestion due to snow accumulation on the road.

Currently, vehicles operating on fossil fuels still dominate road traffic in most countries. Ensuring smooth, undisturbed mobility of road traffic during snowstorm events is of great importance from an environmental point of view. For this reason, optimized in-time operation of winter road maintenance in case of snowstorm events can significantly contribute to a reduction of environmental pollution and achieving goals proposed in the European Green Deal for reducing net greenhouse gas emissions. However, it can be assumed that electric vehicles will dominate road traffic in the next decades. But heavy-duty trucks run on diesel fuel will likely be used for a longer period of time. Electric vehicles do not cause exhaust emissions on the road, however, there are indirect emissions taking place at power plants etc. These emissions depend on the share of electricity derived from renewable or non-renewable resources used for charging electric vehicles. Anyway, driving conditions (road with snow cover, snow-free road) may not have a significant impact on indirect emissions caused by road traffic with electric vehicles. But, the importance of providing safe driving conditions, due to optimized in-time operation of winter road maintenance will remain. Optimized road salt consumption will still be of great importance to reduce environmental impacts such as global warming potential, abiotic depletion of mineral resources, human toxicity, and eco-toxicity-related impacts.

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