Life Cycle assessment of Anti- and De-icing Operations in Norway

Hrefna Run Vignisdottir
Department of Civil and Transport Engineering, Norwegian University of Science and Technology
(email: hrefna.vignisdottir@ntnu.no)
Gaylord Kabongo Booto
Department of Civil and Transport Engineering, Norwegian University of Science and Technology
(email: gaylord.booto@ntnu.no)
Rolf André Bohne
Department of Civil and Transport Engineering, Norwegian University of Science and Technology
(email: rolf.bohne@ntnu.no)
Babak Ebrahimi
Department of Civil and Environmental Engineering, Chalmers University of Technology
(email: babake@chalmers.se)
Helge Brattebø
Department of Industrial Ecology, Norwegian University of Science and Technology
(email: helge.brattebo@ntnu.no)
Holger Wallbaum
Department of Civil and Environmental Engineering, Chalmers University of Technology
(email: holger.wallbaum@chalmers.se)

Abstract

During winter maintenance in Norway 2014-2015, 225 445 tonnes of chemicals were used and 1 610 000 km driven while removing snow and ice on national and state roads. Despite this significant amount of chemicals and distance, winter maintenance is often omitted from current environmental studies of roads and transportation. Current studies focus primarily on vehicles, fuel technology and construction activities. This focus has been based on the fact that these are the largest source of emissions from road transportation. However, as vehicle and fuel technology advances and have less impact per unit, other aspects of transportation, such as maintenance and operation of infrastructure become increasingly important and should be included in LCA studies of roads in cold climates. In this study, life cycle analysis (LCA) is used to estimate the environmental impacts of the production, transport and distribution of chemicals during winter maintenance in Norway. The study is based on reported quantities for winter maintenance during an average winter between 2010-2015. The functional unit is set as anti- and de-icing operations on national and state roads per km during winter an average winter from 2010 through 2014. The results show that environmental impacts from winter maintenance are significant, and thus we argue that winter maintenance should be included in LCA of roads in cold climates. Further investigations on current winter maintenance methods and future options are to be conducted in order to avoid solving one problem while creating another one (problem shifting) during policy development.

Keywords: Winter maintenance, highway, life cycle analysis, environmental impact, anti- and de-icing

1. Introduction

The transportation sector is estimated to be responsible for over a quarter of greenhouse gas (GHG) emissions in the world (Chapman 2007, European Commission 2015). Direct emissions from road transport are the single largest source of GHG emissions within the transportation sector, and therefore emphasis on vehicle technology and emission reduction in the use phase has been dominant (European Commission 2015). However, GHG emissions and the resulting global warming potential (GWP) is not the only impact transportation has. Other impact categories include ozone layer depletion (ODP), acid deposition and reduced air quality in urban areas, which affect human health (Colvile, Hutchinson et al. 2001).

As transport and transportation infrastructure are essential to our society, the construction of new and the handling of existing infrastructure has become a cornerstone of sustainable development (Reza, Sadiq et al. 2014, Santos, Ferreira et al. 2015). Sustainability in transport is only achieved if all aspects are optimized. Therefore, planning and designing new infrastructure as well as maintenance of existing ones are essential as roads are rarely dismantled but rather reconstructed (Stripple 2001). To be able to take into account all aspects of infrastructure life cycle analysis (LCA) is a tool often used. LCA accounts for emissions throughout the whole life cycle of a product or a service from production to the end-of-life. Additionally, LCA is useful to avoid problem shifting.

Several LCA studies have been directed at road infrastructure. These studies focus on various aspects of the transportation sector including fuel use, road construction materials, pavement options, lighting and vehicles (eg. Birgisdóttir, Pihl et al. 2006, Zhang, Keoleian et al. 2010, Huang and Parry 2014, Huang, Bohne et al. 2015). In addition, several reports have also been published especially the report by Stripple (2001) is of importance as a practical guide to LCA inventory analysis of road construction processes. Many of the processes mentioned in the report have been studied while other processes, like winter maintenance operations, have not been sufficiently explored. It is becoming increasingly important to include these operations in LCA studies on road and transport in colder climates as vehicle and fuel technology advances have led to less impact per unit.

The aim of this study is to estimate the environmental impact of anti- and de-icing operations in Norway. The results are presented in a way that allows for further use in other studies so that anti- and de-icing impact can be included in future LCA studies of roads in cold climates.

2. Winter Maintenance Operations

The general goal of maintenance operations is to ensure mobility and traffic safety, limit environmental effects, provide good service and take care of the road infrastructure capital that exists (Statens Vegvesen 2014). One of the most important method for achieving this is friction control. Friction between the tire and the pavement is essential for control of the vehicle and effects acceleration, breaking distance and directional control. Friction control is achieved by either salting or sanding, where salting is used on roads with heavy traffic while sanding is more common on road with lower traffic (Norem 2009).

In the report *National Plan of Action for Road and Traffic Safety 2014-2017* (Statens Vegvesen 2015), where the goal of zero casualties is presented, it is shown that fatalities and severe injuries are most likely on national and state roads with total share of 37% and 45% respectively. Fatalities directly linked to weather and driving conditions were on average 16% of the total fatalities in the years 2005-2012. The category where the speed is well over the speed limits, or higher than road conditions allow for, has a share of 45% of the fatalities (Statens Vegvesen 2015). This could be directly related to road conditions. It is, however, known that drivers do not adjust their speed in proportion with reduction in road friction (Norrman, Eriksson et al. 2000). The report lists several measures to reduce incidents that include:

- Increased user awareness
- Control measures
- Motor vehicle measures
- Measures on roads.

Winter maintenance falls under the category *Measures on roads:* clearing of snow, increasing friction as well as training winter maintenance operators. Winter maintenance operations are often complicated and unpredictable and require vigilance. Of the more important tools that winter maintenance operators use are weather forecasts. However, the forecasts' quality and reliability varies, as does local situation and sudden changes in both temperature and precipitation. In a standard for operation and maintenance for roads, there are guidelines for activities that winter maintenance operators are to follow. These activities are, for example, to monitor the situation visually and through the weather forecast, use anti-icing when needed as well as de-icing and mechanical snow- and ice-removal (Statens Vegvesen 2014).

The term anti-icing is used for the action of applying chemicals to prevent wet pavements from freezing by lowering the freezing point of the water. De-icing is the act of using chemicals to remove snow and ice that have already bonded with the pavement. Additionally, chemicals are used for anti-compaction purpose where the chemicals weaken the bond between the snow crystals and prevent the snow from forming a hard crust and bonding to the pavement surface making snow removal easier (Wåhlin and Klein-Paste 2015).

In Norway, highway winter maintenance has evolved over the past decade from reactive operations towards more proactive actions. A study conducted in North America regarding operators experience shows that most winter maintenance operators felt that anti-icing and pre-wetting helped them to improve roadway safety as bare pavement was achieved more efficiently and made mechanical snow removal easier (Cui and Shi 2015). Even though salting is very helpful in winter maintenance, it is not always appropriate. In Figure 1 the temperatures and precipitation (in mm water equivalent per hour) where salting is advised, not advised or should be done with caution are presented.

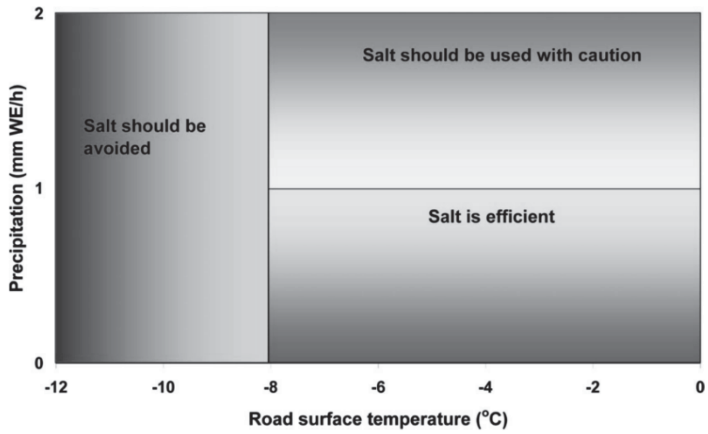

Figure 1: Weather situation and salting efficiency (Norem, 2009 p. 115)

The lower the temperature, the higher the concentration of salt must be in order to efficiently prevent ice formation and to reduce the risk of bonding between both snow crystals and snow crystals and the pavement surface. Therefore, the salt quantity is highly dependent on these weather situations shown in Figure 1 where the highest consumption is then when the weather is cold and with precipitation while salting is most efficient for temperature -8 to 0 degrees Celsius with fairly low or no precipitation (Norem 2009).

Other factors affect the amount of salt on the road are dependent on three physical processes: the initial loss, the dissolution of salt and the loss of salt (Lysbakken and Norem 2011). The initial loss of salt occurs when it is spread to the roads by wind or turbulence from the winter service vehicle (WSV) itself or because of the speed of the vehicle and spreader. The initial loss can be reduced by pre-wetting or by spreading brine. Other factors such as road surface conditions and texture as well as wind also affect the initial loss of salt. Dissolution of salt in water or brine on the road surface is mainly affected by the solubility of the chemical used and the dissolution rate. The process of salt loss includes several process where the salt leaves the road surface. These processes include salt lost by traffic as either blow-off (dry) or spray off (brine) and finally the runoff (Klein-Paste 2008). It is important that winter maintenance operators are aware of these physical processes.

3. Method

LCA is often used in assessing environmental effects from products and services in order to avoid problem shifting. LCA is therefore a very suitable tool in assessing environmental impacts of winter maintenance operations. An LCA study is conducted in four phases. First, goal and scope are defined; this includes defining the functional unit and system boundaries. Then inventory analysis is conducted where all physical products that go in and out of the system are accounted for. Environmental load of these flows are then calculated to form an impact assessment and finally the results are interpreted (International Standards Organization 2006). During each of these phases, the previous and next phase should be reconsidered in order to make any necessary changes that are revealed during the investigation. The LCA software SimaPro was used for this study, with the ecoinvent database (Weidema, Bauer et al. 2013) and calculations made with CML baseline impact assessment method.

It is very important that the inventory is carefully executed and accurately reflects use of any equipment, materials and energy. Poor inventory will only lead to high inaccuracy and maybe even wrong environmental impact results at a later stage.

3.1 Goal and Scope

The goal of this study is to map and analyse the activity of anti- and de-icing operations in Norway. The system boundaries are limited to winter maintenance operations; specifically anti-icing, de-icing and anti-compaction for increased friction and making ploughing easier. Within the system boundaries are material production and transportation as well as storage but also equipment and energy use. However, the chemicals effect on the environment after distribution is left outside the system boundaries due to lack of data.

By mapping the activities, a detailed inventory can be made to realize resource intensity. The study covers average winter maintenance operations in Norway for winters 2009/2010 through 2014/2015, from now on referred to as winter 2010 through 2015, on national and state roads. Mechanical snow removal is however outside the scope of this study.

The results are intended to be available for use by other LCA practitioners as well as winter maintenance personnel. Therefore, the results will be set up systematically, making it possible to contribute to other LCA studies that have results per kilometre to give an indication of the environmental impacts of winter maintenance.

3.2 Functional Unit

The functional unit is the very corner stone of any LCA but finding a suitable functional unit within the transportation sector can be difficult. This difficulty stems from large variations in design, location, material use, geographical profile, transportation distances and traffic load. In this study, the functional unit is the *anti- and de-icing operations on national and state roads per km during winter an average winter from 2010 through 2014*.

4. Life Cycle Inventory

The inventory for winter maintenance is quite complex and different from a more common product based inventories. It is different in the way that there is no standard recipe for achieving safe roads during the winter season. Therefore, it is necessary to base the calculation on an average. Whether it is most suitable to have an average based on the previous winter or if the last five should be used, is debatable. In this study the average of the last 5 winters was chosen as they are believed to be well documented and give good representation of an average winter in Norway. These averages will then have to be presented per kilometre for all different types of equipment, materials and transportation distances. There are few things that are constant, or could be assumed constant, between seasons. Locations of the distribution storage for example, where the ships dock and the salt is unloaded and stored, can be assumed to be fairly constant as the biggest importers have the same or similar locations (Aslaksen 2015, Heggedal 2015). In the following section, necessary equipment and materials needed for winter maintenance are listed along with important background information.

4.1 Equipment

Equipment in winter maintenance mainly refers to the winter service vehicles (WSVs) such as trucks and their extra equipment. Extra equipment includes tanks, salt/sand spreaders and the different types of blades and ploughs. However, it also includes information about storage facilities for the salt and sand regarding type of storage, the location and possible energy use. In Norway, the most commonly used WSV is a truck or a tractor with mounted a spreader, plough, grader or loader. For highways, trucks with a mounted plough or a grader and salt spreader are the most common. These vehicles mentioned are used during and right after a weather event. Additionally, other WSV might be needed soon after a weather event to clear areas of snow for example to improve visibility or to remove compact snow and ice from the road. (Sivertsen 2015). The WSVs are owned and run by the contractors that are awarded contracts for approximately 5 years at a time. The quantity of vehicles in use during winter season is therefore difficult to determine.

Storage facilities are located at or near the shipping docks near the largest cities. These places are assumed to have storage facilities, which are warehouses with a roof and four walls. As they are assumed to have no heating and are used for a long time, they are insignificant in terms of emissions. The storage is therefore omitted from the inventory analysis.

4.2 Materials

Winter maintenance materials includes the chemicals used for anti- and de-icing. According to major importers of road salt and the largest contractors for winter maintenance operations on national and county roads, the largest share of salt is used in the south, west and mid-Norway to around the area of Trondheim. Information about the storage locations are obtained from Mesta (Heggedal 2015) and GC Rieber (Aslaksen 2015). Table 1 presents major storage facilities as well as quantity of salt in each location and percentage of the total imported salt.

Table 1: Location of salt storage facilities, quantities and share of total imported salt

Quantities / *Location*	*Salt [tonnes]*	*Percentage*
Oslo	*65 282*	*32%*
Arendal	*53 408*	*26%*
Stavanger	*52 511*	*26%*
Ålesund	*11 192*	*5.5%*
Trondheim	*11 192*	*5.5%*
Harstad	*4 602*	*2.3%*
Hammerfest	*4 602*	*2.3%*

The quantities of salt that are estimated to be at these locations are based on documentation from Norwegian Public Roads Administration (NPRA) and supported by information from importers and contractors. Reported quantities of salt used in Norway seem to be stable the last years and variations can be explained by changes in weather. However, when looking farther at years prior to the years included in the study, we can see that the use of salt has increased drastically. This increase is due to salt now being used on a larger portion of the road network (Sivertsen, Lysbakken et al. 2011). As mentioned previously, anti- and de-icing operations are beneficial within a range of approximately 0 to -10 degrees Celsius. This reflects well in the information from both importers, contractors and NPRA where salt quantities are lower per kilometre in the northern and in inland regions.

Note, that the impact assessment method used does not account for the salt itself during production. Which means that the production phase accounts for materials and energy used during production as well as equipment but not any effects of salt on the local environment at the excavation site. Additionally, there are no available LCA information about the effects salt has on the environment after distribution. Therefore, effects of salt after distribution are not included in the results. However, there are few things that should be mentioned.

The focus of available environmental impact studies are on the effect of salting on the ground, surface water, soil contamination and stress on vegetation (Fitch, Smith et al. 2013). Environmental impacts of salt are localized and are dependent on various aspects such as road location and weather where precipitation, temperature and wind are of importance. The salt mainly goes directly into roadside lakes, with run-off water to nearby lakes and streams or to roadside vegetation and soil (Ramakrishna and Viraraghavan 2005). During winter, road salt is released into nature in pulses, which can lead to a rapid change of salt in the surface water. This rapid change can have deteriorating effects on the water quality. It has been shown that chloride levels in roadside stream increase dramatically and is carried downstream. With a continued build-up of chloride in lakes, it can have serious effect on the use of the water in the future. Additionally, a large proportion of the salt can leach into the groundwater where drinking water supplies can be effected by the chloride concentration. Salt contaminated run-off water may impact surface water in several ways. It can alter both physical and ecological characteristics of lakes with insufficient mixing of denser deeper layers and fresher upper layers. Seasonal mixing is essential for oxygen transfer in the lake that is necessary for continued animal and plant life in lakes. Toxic metals in sediments can also be release as a result of high salt concentration in water bodies. Release of toxic metals such as mercury can lead to lake stratification which again effects animal and plant life (Ramakrishna and Viraraghavan 2005)

The effects of salt on soil are not as serious as the effects on water. However, it has the potential to increase overland flow, surface runoff and erosion while decreasing soil permeability and aeration. The impact of salt can therefore be assumed to potentially increase emissions that contribute to categories like fresh and marine water aquatic ecotoxicity and terrestrial ecotoxicity.

4.3 Transportation

Transportation of salt is an important factor as the distance are significant. Transportation starts at salt excavation point where it is transported to the harbour. From the harbour, the salt is transported on freight ships to Norway, specifically to the locations introduced in Table 1. To estimate the freight transportation distance an online tool was used (McGraw Hill Financial 2015) and the results can be viewed in Table 2.

Table 2: Shipping distances to the different storage facilities

Origin / Destination	*Spain*	*Tunisia*	*Germany*
Oslo	*4812*	*5274*	*963*
Arendal	*4513*	*5076*	*680*
Stavanger	*4410*	*5052*	*789*
Ålesund	*4621*	*5441*	*1248*
Trondheim	*5252*	*5712*	*1698*
Harstad	*5941*	*6276*	*2385*
Hammerfest	*6536*	*6628*	*2982*

It can be assumed that around 35% of the salt comes from Germany in the form of salt stone, while the remaining 65% come from Spain (25%) and Tunisia (40%) and are from salt lakes. To be able to calculate the environmental impact of the transport, it is important to find the average distance a kilogram of salt travels. Here the distance travelled with a freighter is 3620 km on average for each ton of salt.

The large centralized storage facilities are natural pick-up points for operators. The operators often collect salt on 30-tonne trailers (with a hanger) and either take the salt straight to distribution or drive to de-centralized storage for later use. Additionally, some of the salt is transported on smaller boats to local operators' storage facilities. The transportation distance from the central storage to a de-centralized storage is not taken into account, since commonly distributed directly.

4.4 Distribution

To be able to estimate the distribution distance, the salt quantity, which lies between 15-40 gr/m^2 (Statens Vegvesen 2015), was assumed 20 gr/m^2. The distribution distance can then be roughly calculated from the reported salt quantities used in each region. The result from these calculations are shown in Table 3. The table shows the distribution distance in kilometres for each region for year 2010-2015.

Table 3: Calculated kilometres driven during distribution of salt in each region

Region \ Year	2010	2011	2012	2013	2014	2015	Average
East	*426 668*	*501 768*	*433 676*	*477 357*	*470 163*	*488 178*	*466 302*
South	*391 471*	*335 939*	*320 923*	*380 691*	*434 672*	*425 230*	*381 488*
Vest	*340 356*	*501 045*	*394 496*	*387 557*	*205 079*	*421 931*	*375 077*
Mid	*150 203*	*207 287*	*165 165*	*140 706*	*116 555*	*179 360*	*159 879*
North	*56 125*	*54 197*	*59 319*	*70 142*	*59 091*	*95 620*	*65 749*
Total	***1 364 823***	***1 600 236***	***1 373 578***	***1 456 463***	***1 285 560***	***1 610 318***	***1 448 495***

The average distribution distance is then used to calculate the emissions per kilometre. When mechanical snow removal is conducted, which is not included in this paper, salt is most often also distributed at the same time. However, the distance calculated here is assumed to be attributed only to salting. This is done instead of reducing the distance by attributing some of it to mechanical snow removal and then adding extra distance to account for distance driven during observation.

5. Results

The results are presented for 11 impact categories. The impact categories and the origin of the emissions are shown in Table 4, where it is clear that distribution of salt in Norway is the major contributor to all impact categories, with more than 99% share of total emissions.

Table 4: Impact results per kilometre road in Norway during one average winter

Impact category \ Life cycle stage	Production	Freight transport	Distribution	Total emissions
Abiotic depletion [kg Sb eq.]	*0%*	*0%*	*100%*	*2.42*
Abiotic depletion [MJ]	*0%*	*0.02%*	*99.98 %*	1.4×10^{7}
Global warming [kg CO2 eq.]	*0%*	*0.02%*	*99.98 %*	8.8×10^{5}
Ozone layer depletion (ODP) [kg CFC-11 eq.	*0%*	*0.01%*	*99.99 %*	*0.16*
Human toxicity [kg 1,4-DB eq]	*0%*	*0.01%*	*99.99 %*	4.0×10^{5}
Fresh water aquatic ecotox. [kg 1,4-DB eq]	*0%*	*0.01%*	*99.99 %*	1.1×10^{5}
Marine aquatic ecotoxicity [kg 1,4-DB eq]	*0%*	*0.02%*	*99.98 %*	2.7×10^{8}
Terrestrial ecotoxicity [kg 1,4-DB eq]	*0%*	*0.01%*	*99.98 %*	1.4×10^{3}
Photochemical oxidation [kg C2H4 eq.]	*0%*	*0.07%*	*99.93 %*	1.5×10^{2}
Acidification [kg SO2 eq.]	*0%*	*0.11%*	*99.89 %*	3.0×10^{3}
Eutrophication [kg PO4--- eq.]	*0%*	*0.05%*	*99.95 %*	7.1×10^{2}

The only impact category that is slightly different from the others is acidification where freight transport contributes more than to the other impact categories. However, the main source of emissions is, like in distribution, the direct emissions of burning fuel during transport.

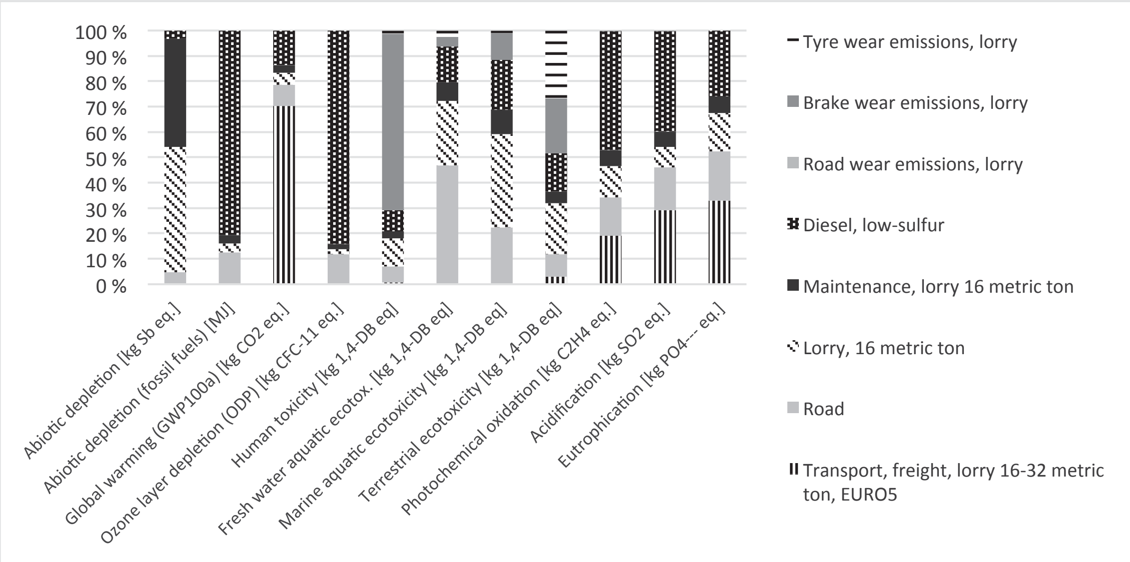

Figure 2: Emission source for the different impact categories.

Looking more closely at salt distribution shown in Figure 2, they are divided into 8 activities that contribute to the different impact categories. Towards global warming, the main contributor is the direct emission of burning fuel under transport while the production and maintenance of the truck are almost exclusively the source of abiotic depletion. The production of diesel is responsible for over 84% of the impact towards ozone layer depletion but also the largest contributor towards photochemical oxidation. Surprisingly, break wear emissions from the truck is responsible for approximately 70% of the emissions towards human toxicity.

For comparison, a Euro 5 personal vehicle would have to be driven over 2.7 million kilometres to reach the same emissions levels for global warming as is estimated emitted by salting operations in Norway.

6. Discussion

As expected, the results show that the highest impact from salting operations is from distribution in Norway. Because environmental effects of winter maintenance are highly linked to driving distances of the WSVs and material use it is important to reduce loss of salt as much as possible by optimizing speed of the vehicle and the spreader. Training and awareness of the winter maintenance staff can also contribute to less loss of salt and better winter road service. The quantities and the driving distance are however also very dependent on temperature and precipitation during the specific winter.

Furthermore, other efforts to reduce impact from winter maintenance are to focus on vehicle and fuel technology. Fuel efficiency combined with optimization of anti- and de-icing methods could potentially reduce emissions substantially. However, it should also be kept in mind that winter maintenance operators report that especially using anti-icing is beneficial as it makes mechanical snow removal easier and results sooner in clear and safe roads. Making mechanical snow removal easier can in itself be a method of reducing emissions during winter maintenance.

7. Conclusions

Life cycle analysis (LCA) was used to estimate the environmental impacts of the chemicals used during winter maintenance and their distribution. Results on the functional unit of *anti- and de-icing operations on national and state roads per km during winter an average winter from 2010 through 2014* show that environmental impacts from winter maintenances are significant. Therefore, we argue that winter maintenance should be included in LCA of roads in colder climates. The results are presented per kilometre so it can be used in other studies to roughly include the impact of anti- and de-icing.

Further investigations should be conducted on fate of salt after salting. In addition, mechanical snow removal and future options in winter maintenance will be investigated further within the current project. By doing so, enough information should be available for decision makers to avoid problem shifting.

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