Simulating Winter Maintenance Efforts: A Multi-Linear Regression Model

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Summary

Regarding the vital role of Winter Road Maintenance (WRM) in ensuring road safety and mobility and its huge costs and environmental impacts, decision-makers always need to balance its costs and benefits. Simulating winter maintenance services offers a potential new tool to find this balance. In this paper, we analyze Norway's WRM of state roads during the winter 2021-2022 and propose the first version of a GIS-based effort model as a computational core of a simulation tool. *Effort Model* predicts the frequency of maintenance operations at a given location.

Introduction

WRM is vital for road safety and mobility under adverse weather conditions, but it poses challenges in terms of high costs and environmental impacts [*1*]. Norway's WRM entails plowing 20 million km and using 240,000 tons of salt [*2*] costing €140 million annually [*3*]. It involves intricate decisions made on strategic, tactical, and operational levels [*4, 5*]. While the Norwegian Public Roads Administration (NPRA) sets long-term standards, private contractors manage tactical and operational levels. Despite this complexity, decision-makers must gauge effort amounts.

Winter Severity Indices (WSIs) [*6, 7*], Winter Service Management Systems (WSMS) [*8-10*], and optimization models [*5, 11-14*], that help decision-makers on strategic and/or operational levels, focus primarily on weather factors. A more comprehensive model, Swedish Winter Model, quantifies WRM based on weather and traffic conditions [*15*]. There is still a lack of a holistic approach supporting strategic/tactical decisions considering both non-weather and weather factors.

In response, NPRA has initiated the R&D project WinterSim, aiming to create a GIS-based simulation tool for quantifying WRM efforts in each given location. Covering the entire country, it predicts the number of operations (hence the term "effort") based on historical weather data, road geometry, level of service (LOS), and annual traffic volume (AADT). If successful, the model can assist in estimating budget costs and potentially reduce the tender-phase's uncertainties and consequent economic risk for the contractors. Fig.1 shows a conceptual model of *Effort Model*, the tool's computational core predicting operation (plowing, salting, etc.) frequency at given location based on various factors categorized into strategic, tactical, and operational groups.

Here, we present our results concerning model development, its validation, and its capabilities in simulating a standard-changing scenario.

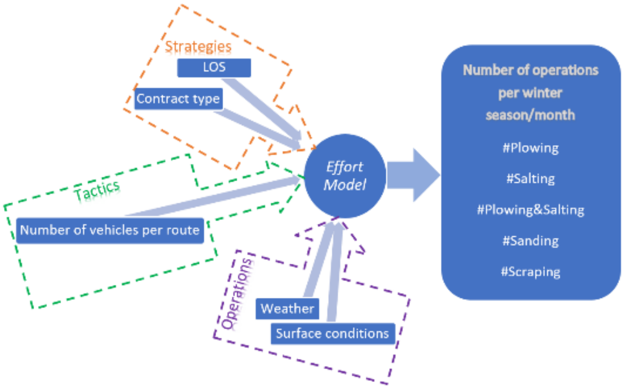

Fig. 1: Conceptual model of Effort Model

Key Terms

Norway has two WRM strategies; bare road to minimize snow/ice duration on the road, and winter road to maintain acceptable driving conditions with a presence of snow/ice [*16*]. Road segments are categorized into 5 classes DkA, DkB, DkC, DkD, and DkE. DkB is subdivided into DkB_high, DkB_medium, and DkB_low. DkA and DkB's are levels of service under the bare road strategy. This means salt is applied for anti-icing purposes, during snow weather (anti-compaction), and to regain bare pavement (de-icing). DkD and DkE belong to the winter strategy. Here the salt is not used during snowfalls, resulting in a compacted snow/ice layer that is maintained by plowing, scraping and, if needed, sand applications. The DkC comprises of a bare road strategy during mild periods, while it switches to a winter road strategy when temperatures colder than -3°C are forecasted [*16*]. The Cycle time (the time to perform an operation on a segment), the bare pavement regain time (the time for restoring approved driving conditions after a weather event), the minimum friction level, and specifications where and when to apply salt or sand are important differences between the classes [*16*].

Methodology

This study covers Norway's entire state roads. Three datasets were used: WRM production data from 57 contracts in the winter 21-22; road data including AADT, maintenance class, road width, and height; weather data as WRM triggers [*6*]. The varying topography makes measured weather parameters and road conditions unreliable once the distance from the station increases [*6*]. *Effort Model* addresses this using grid data for weather variables [*17*], rather than data measured at road weather stations. This data is used to identify four types of weather events that are known to correlate to the need for winter maintenance. Table1 summarizes these events and describes the indicators that are used. The air temperature is denoted as T. Statistics field provides a seasonal summary of each weather indicator for the whole network. The criteria were set through an optimization process to have minimal overlapped events and more correlation with effort amount [*18, 19*].

Table1: Weather parameters and related criteria, winter 21-22

Weather event	Weather indicator	Criteria	Statistics		
			min	mean	max
Fresh snow	daily fallen snow (cm)	daily snow >= 1 cm	0	309	1383
	snow days	daily snow >= 1 cm	0	37	105
	daily snow duration (h)	hourly precipitation >= 0.5 mm	0	255	1182
	daily snow depth (cm)	daily snow depth >= 0 cm	0	4657	42,770
Drifting snow	daily drift snow (cm)	daily drifting snow >= 0.1 cm	0	32	625
	drift snow days		0	29	156
Freezing rain	freezing rain days	daily rain >= 0.2 mm, Tmin<=3°c, fresh snow = 0, drifting snow = 0	0	20	66
Cold days	cold days of the season	daily Tmin < 0°c, rain = 0, fresh, snow = 0, drifting snow = 0	0	31	83

To analyze extensive production data, we created a dense network of 1500 random points which we denote “sample points”. These sample points were placed with an average intervals of 5 km, covering the whole state road network. The production data was obtained from the vehicles’ datalogging system and included variables like date, location, operation type, and spreader settings. Through a GIS process we obtained operation-statistics at each sample point. Fig. 2 shows the spatial distribution of sample points. DkA and DkB situated in southern part. DkD is mostly in the north. DkC covers a broad area. The share of each class is 9%, 27%, 22%, and 42% respectively. There was not sufficient data available on DkE roads.

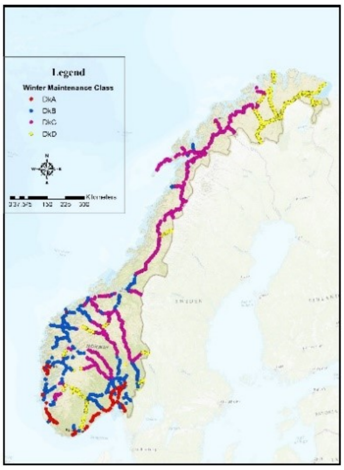

Fig. 2: Distribution of sample points categorized based on maintenance classes.

Each sample point was enriched with road data, weather data, and seasonal frequency of winter maintenance operations, and then input into a generalized linear regression analysis in GIS. In contrary to WSIs, we considered non-weather explanators including tactical variable (number of vehicles per route (NV)) and strategic variables (cycle time, regain time, AADT). The regression conducted separately for each operation type.

Results and Discussions

Data Analysis of Winter 2021-2022

The statistical analysis reveals that plowing, plowing-salting, salting, sanding and plowing-sanding constitute 59%, 18%, 16%, 4%, and 3% of total operations. in this phase, we focused on 3 former operations. Fig. 3 shows seasonal average of operations per maintenance classes. While plowing rises from DkA to DkD, salting declines. Combined Plowing & salting operation remains consistent in DkA and DkB but drops sharply in DkC and DkD. DkA and DkB follow a bare road strategy relying on salting, whereas DkD employs a winter road strategy focusing on plowing. DkC adjusts strategies based on weather severity, leading to higher salting and plowing-salting than DkD, and higher plowing than DkA and DkB.

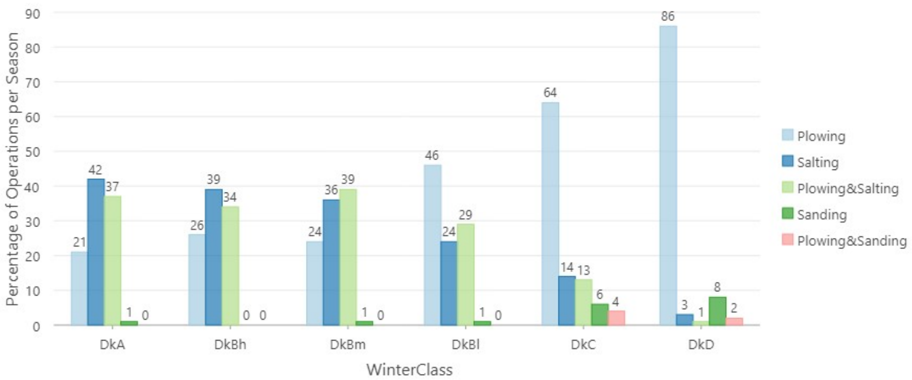

Fig. 3: Operations statistics vs maintenance classes, winter 21-22

Multi-Linear Regression Model

We developed three multi-linear regression models for salting ($N_{Salting}$), plowing ($N_{Plowing}$), and combined ($N_{Plowing\text{-}Salting}$) operations with adjusted-R^2 of 66%, 70% and 66% respectively. Each model predicts seasonal number of an operation type. Two main explanatory variables have been considered; 1- weather variables that mentioned in Table

1; 2- non-weather variables that include cycle time, regain time, number of maintenance vehicles per route, elevation above mean see level, and average annual traffic.

The first draft of *Effort Model* predicts number of total efforts through Eqs. (4). R^2 is 0.66. The models do not predict material rates, but only frequency of operations.

$$N_{TotalOperations} = N_{Salting} + N_{Plowing} + N_{Plowing\text{-}Salting} \quad (4)$$

As expected, the effective variables for explaining variation of different types of operations are not the same. For example, drifting snow is not a proper explanator for salting, and number of maintenance vehicles per route is an effective variable for combined operation.

Model Validation

To validate the model, we predicted 232 test points (20% of the sample points) were not included in the model. The correlation between predicted and actual values for salting, plowing, and plowing-salting operations was 65%, 71%, and 63%, respectively, and an overall accuracy rate of 65%

Model Application

To illustrate possible applications in strategic decisions, we simulated what happens when a stretch on the E39 highway was hypothetically downgraded from DkA to DkB. The model forecasted a 15% decrease in total number of operations, means a potential saving in efforts and costs. Although it cannot precisely predict road deterioration, the result aligns with the Swedish Winter Model's results, where shifting to unsalted roads reduced costs [*15*]. Fig.5 shows this scenario mapping predicted operations for DkA and DkB at each point.

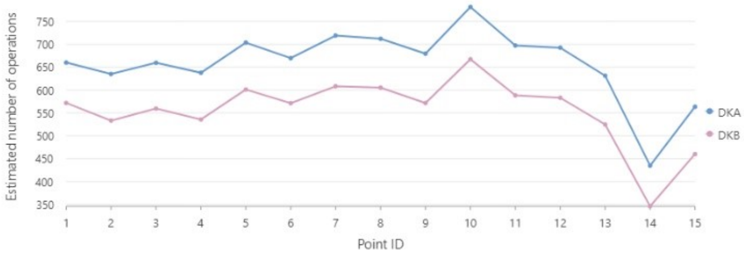

Fig. 5: Model estimations in the case of changing maintenance class

Conclusion

In this study, we analyzed Norway's 2021-2022 WRM and developed a multi-linear regression model for predicting seasonal salting, plowing, and plowing-salting operations. It uses cycle time, number of vehicles per route, average traffic volume, and height as non-weather variables that cover strategic and tactical decisions. Fresh snow, drifting snow, freezing rain, and cold days used as factors of operational level. The overall model accuracy is 66%.

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