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Mitigation of Suspendable Road Dust in a Subpolar, Oceanic Climate

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Abstract: Tire and road wear particles (TRWP) are a significant source of atmospheric particulate matter and microplastic loading to waterways. Road wear is exacerbated in cold climate by the widespread use of studded tires. The goal of this research was to assess the anthropogenic levers for suspendable road dust generation and climatic conditions governing the environmental fate of non-exhaust particles in a wet maritime winter climate. Sensitivity analyses were performed using the NORTRIP model for the Capital region of Reykjavík, Iceland (64.1° N). Precipitation frequency (secondarily atmospheric relative humidity) governed the partitioning between atmospheric and waterborne PM_{10} particles (55% and 45%, respectively). Precipitation intensity, however, increased proportionally most the drainage to waterways via stormwater collection systems, albeit it only represented 5% of the total mass of dust generated in winter. A drastic reduction in the use of studded tires, from 46% to 15% during peak season, would be required to alleviate the number of ambient air quality exceedances. In order to achieve multifaceted goals of a climate resilient, resource efficient city, the most important mitigation action is to reduce overall traffic volume. Reducing traffic speed may help speed environmental outcomes.

Keywords: particulate matter; microplastics; non-exhaust emissions; NORTRIP

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1. Introduction

Road infrastructure plays a significant role in sustainable cities. Besides enabling the transport of people and goods, roads must ideally be safe, economical, climate resilient, and non-compromising of the urban environment [1]. A key challenge to attaining these joint environmental, economic, and societal goals is the multifaceted pollution associated with the frictional contact between a moving vehicle and the road surface (Figure 1). Non-exhaust particles from tire-, road-, and break wear have been recognized as an important source of particulate matter pollution in the 2.5 to 10 µm diameter range [2–8]. More recently, tire and bitumen asphalt road wear particles have emerged as a major microplastics (MP) source to the environment [9–11], and the largest MP contributor to aquatic environments [12], accounting for 5–10% of all plastics in the oceans, with country estimates ranging from 0.9% in The Netherlands to 32% in Norway [13]. Over 30% of the coarse airborne tire and break wear particles (≤10 µm diameter, PM_{10}) is ultimately deposited in the world's oceans; a similar order of magnitude as direct and riverine transport [14]. The frictional contact between tire and road also generates noise pollution and pavement deterioration, which is influenced by climatic factors such as air temperature, solar radiation, and precipitation, each of which governs road wetness [15,16]. Fine particulate matter and traffic noise have been found as the first and second most important environmental causes of ill health in Western Europe [17]. A growing concern is that the smallest waterborne MP particles can accumulate in the cells and tissues of aquatic organisms and enter the food chain [18].

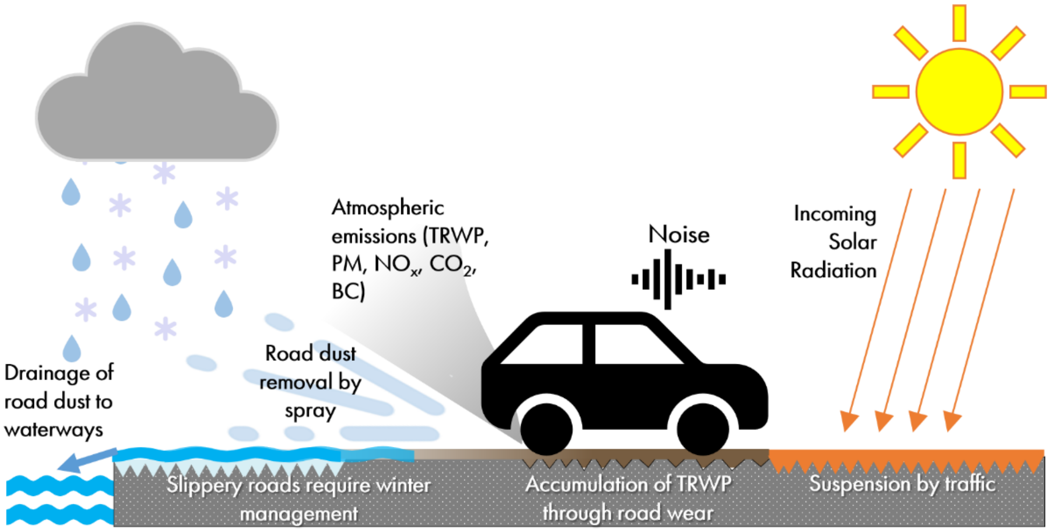


Figure 1. Road wear compromises the multifaceted goals of sustainable urban living, including safety, resource efficiency, amenities, and climate resilience.

Climatic conditions strongly influence the physical characteristics of pavements. Road safety and environmental problems are greatest near freezing air temperatures (±2 °C) [19], which exacerbate the use of studded tires and deicing agents for anti-skid protection [5,20–22]. Studded tires paired with high vehicle speed further increases road abrasion rates [8,20,23,24]. Indirect emissions from winter road maintenance activities such as the application of road sand (and to a lesser extent road salt) for traction control can be important [8,25]. While only 0.5% of road salt became suspended, salting was attributed to 1–10% of total PM_{10} emissions [21]. Through its control on both road dust generation and emissions, local meteorology can cause to up to a 60% variation in mean winter PM_{10} concentrations [21,24]. Surface wetness is an effective particle binder, contributing to the buildup of dust to be released episodically during dry periods [24,26]. To the authors' best knowledge, no study has systematically assessed the contribution of individual weather parameters on the fate of suspendable road dust.

Even if many cities have readily switched to newer, lower-polluting vehicles (e.g., Euro 5 and Euro 6) and made major investments in sustainable and shared mobility, their ambient air still often exceeds the European standard for PM_{10} [27]. Many of these cities have applied a host of short- and long-term mitigation measures to limit road dust emissions, such as speed reductions, studded tire bans, stronger bitumen asphalt, and the application of dust-binding and road cleaning chemical agents with some success [21,26]. As winter temperature, atmospheric humidity, and precipitation increase in many parts of the world due to climate warming, maritime winter conditions with frequent snow and frost cycles may become more prevalent in high-latitude regions [28]. The degree to which these wet, oscillating weather conditions affect the magnitude and fate of road dust is not fully understood.

Attaining joint environmental, economic, and societal benefits of a sustainable city requires a detailed knowledge of the interplay between the road surface, traffic, and meteorological conditions. The goal of this research was, therefore, to assess the anthropogenic levers of road dust generation and meteorological conditions governing the environmental fate of non-exhaust particles, as a foundation for mitigation policy-making. To compliment previous research undertaken in the northern parts of continental Europe and North America, this study focuses on the subpolar, oceanic climate of Reykjavík, the capital and largest city of Iceland. Reykjavik undergoes frequent freeze–thaw cycles and high amounts of winter precipitation. The study addresses the following questions: (1) Which meteorological driver most strongly governs the partitioning between atmospheric and water bound traffic related PM_{10} particles? (2) Which actions are required to achieve the goals of no exceedances to air quality standards of particulate matter? (3) Which air quality mitigation method(s) can achieve the broadest benefits of sustainable cities? To answer these questions, a numerical model was used to incorporate the complex interplay and feedback mechanisms amongst anthropogenic processes and the hydro- and atmospheres. Simulations were compared to other sites with different climatic conditions.

2. Materials and Methods

2.1. Site

The Icelandic Capital Region (ICR), which includes the City of Reykjavík and five surrounding municipalities, has a subpolar, oceanic climate characterized by frequent precipitation, freeze–thaw cycles, and a narrow annual temperature range [29]. Despite a relatively small population (~220,000 inhabitants in 2020), particulate matter exceeds the 24-h European Health Safety Standards (EHSS) of 50 $\mu g/m^3$ of PM_{10} from 7 to 30 times per year on average (Figure 2). Asphalt wear was attributed to approximately half of the measured PM_{10} in a series of source apportionment studies [30,31]. Tire wear, and to a much lesser extent road markings, was estimated to contribute to approximately 80% of microplastic generation in Iceland [32]. Given the range of episodic, but large, sources of PM_{10} causing exceedances of the EHSS, such as ash and dust storms, local resuspension, long-range transport, and fireworks [33–36], there is a dire need to reduce the exceedances associated with traffic.

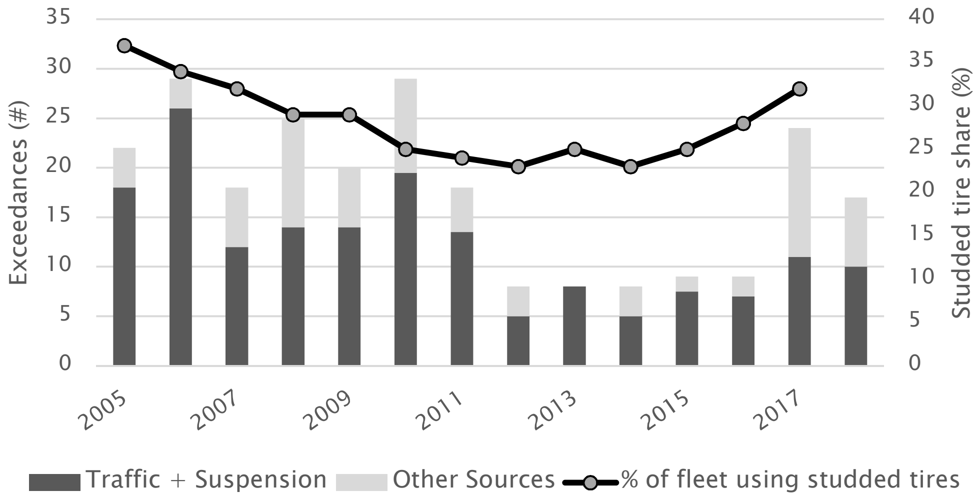


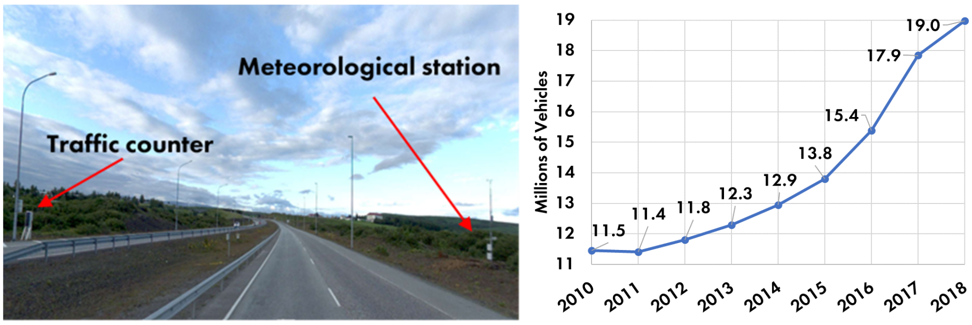
Figure 2. Annual exceedances of 24-h health safety limits and average share of Light Duty Vehicles on studded tires (data taken from in [37,38]).

2.2. Approach

The NORTRIP (Non-Exhaust Road Traffic Induced Particle) model is a comprehensive non-exhaust emissions model developed in collaboration between various Nordic governmental agencies and academics [39]. The model was selected because of its proven ability to (1) reproduce measured concentrations of particulate matter with satisfactory accuracy for sites in Fennoscandia [23,24,39,40], (2) assess the climatic and anthropogenic influences on the sources and sinks of non-exhaust particles, and (3) replicate the successes of mitigation strategies [21]. The model sensitivity to varying mitigation actions and different local meteorology, was tested. The results were interpreted in relation to previous studies.

2.3. Data

The Kauptún site is a four-lane urban traffic artery situated in an open lava field in the municipality of Garðabær (Figure 3a). The road experienced a steady increase in traffic volume in the aftermath of the 2007–2008 financial crisis (Figure 3b). The Kauptún site was equipped with traffic data counters and weight sensors to distinguish light- (LDV) or heavy-duty (HDV) vehicles, as well as a meteorological station recording wind, air temperature, road surface temperature, and conductivity. Moreover, information about road and winter management was available from the Icelandic Road & Coastal Administration [41]. Studded tire counts were conducted every five weeks based on a sample of 250 parked passenger vehicles in parking lots at two shopping centers, a university, and in the city center [38]. The chosen locations targeted vehicles owned by the local inhabitants. Rental vehicles, all of which were on studded tires in winter, may be underrepresented.



(**a**) (**b**)

Figure 3. Kauptún study site. (**a**) Overview. (**b**) Traffic volume trends (data taken from in [41]).

Precipitation and net short-wave radiation data were obtained from the Icelandic Meteorological Office in Reykjavik [42]. The hourly precipitation was partitioned between rain (total 425 mm; max 6.3 mm/hr) and snow (total 81 mm; max 2.9 mm/hr), using a temperature threshold based on relative humidity (*RH*),

$$TRH = 0.75 + 0.85\,(100\% - RH). \tag{1}$$

If the air temperature exceeded *TRH*, then precipitation was treated as rainfall; otherwise, it was treated as snowfall [43].

Air quality data from the fixed, urban traffic station at Grensás, Reykjavík, were used for comparison [37]. The data sites had similar topographical features. Grensás, however, had a higher traffic (38 million cars annually) than the study site Kauptún (19 million cars annually).

2.4. Baseline Model Setup

The simulation period was defined as 15 October 2017 to 1 May 2018 representing 15 days before and after the legal period for use of studded tires in Iceland. Comparing the key model inputs to previous NORTRIP model sites (Table 1), Kauptún tends to be more humid, windy, and wet, with lower solar radiation to warm up and dry the bitumen road surface, and more winter road management activities such as salting and snow ploughing. The atmospheric PM_{10} concentration was simulated using the Operational Street Pollution Model (OSPM). Although designed to calculate dispersion within street canyons [44], a characteristic that does not apply to the study site, it generated significantly more stable and realistic concentrations than the primary NORTRIP option of utilizing the closest available NO_x data to calculate concentrations. Most of the default NORTRIP settings were used in accordance with previous applications of the model. However, some parameters such as asphalt characteristics were altered to better represent the specific conditions of the investigated site.

Table 1. Key model input and output parameters for baseline simulations in three Nordic cities.

		Hornsgatan [a]	RV4 [a]	Kauptún
		Stockholm	**Oslo**	**Garðabær**
Simulation	Latitude Period (winter; nr. of days)	59.3° N 2006–2007; 243	59.9° N 2004; 121	64.1° N 2017–2018; 196
Traffic & Pavement	Annual average daily traffic ($\times 10^3$ vehicles)	29.1	42.6	51
	Heavy duty vehicles share (%)	3	4.9	9
	Mean/Max studded tires (% LDV)	47/75	26/27	23/46
	Mean speed (km/hr)	43	75	80
	Pavement type factor (h_{pave})	0.83	1.6	1.62
Meteorology	Mean short wave radiation (W/m^2)	66 [b]	57 [b]	37
	Mean air temperature (°C)	5.8	1.0	1.0
	Relative humidity (%)	75	76	82
	Total precipitation (mm)	197	178	507
	Precipitation frequency (%)	5.8	13	17
	Mean wind speed at 10 m (m/s)	4.0	2.5	6.0 [c]
Winter Management	Total salt (ton/km)	6.3	39	14
	Salting events (NaCl)	45	113	526 [d]
	Ploughing events	2	9	115 [d]
Model Outcomes	Wet roads frequency (%)	43	48	53
	Net mean/90th percentile PM_{10} ($\mu g/m^3$)	39/90	30/80	20/49

Notes: [a] Norman et al. (2016); [b] Global radiance, *I*, converted to incoming short-wave radiation using mean cloud cover, *n*, as $SW_{in} = I \times (1 - 0.75 \times n^{3.4})$; [c] Wind speed at 2 m (4.0 m/s) upscaled to 10 m elevation using the logarithmic law for neutral conditions $(10/2)^{0.25}$; [d] Multiple salting and ploughing events per day. Abbreviation: LDV = Light-Duty Vehicle.

Baseline simulations assumed a typical Icelandic asphalt, with local aggregate hardness as 7.9 Nordic ball mill (*NBM*). The maximum stone size (*MS*) was 16 mm, and the percentage of stone size greater than 4 mm was 65%. The pavement type factor (h_{pave}) was characterized using the Swedish Road Wear Model [45] as

$$h_{pave} = 2.49 + 0.144 \cdot NBM - 0.069 \cdot MS - 0.017 \cdot S_{>4\text{mm}}. \tag{2}$$

The resulting value was 1.62 g/km/veh corresponds to a higher wear rate than the reference in NORTRIP (4.68 vs. 2.88 g/km/veh, respectively). A more thorough description of the inputs and model setup is presented in the master's thesis by Brian C. Barr [46].

2.5. Sensitivity Analysis

A sensitivity analysis was conducted to understand which lever, either anthropogenic or meteorological, was most significant for PM generation and release of PM, to the atmosphere and waterways. Traffic-related parameters, such as studded tire share, traffic volume and speed, and the fraction of HDVs, were increased or decreased on percentage bases.

Incremental changes in meteorological conditions were simulated without changing road management practices. This approach gives an indication of lever strength but is not meant for forecasting purposes. Temperatures and relative humidity were raised or lowered by a uniform amount, and the amount of rain and snow values adjusted according to Equation (1). Precipitation frequency was reduced by eliminating the mildest precipitation (0.1–0.4 mm/hr) and increased by adding the minimum threshold precipitation (0.1 mm/hr) during dry periods with relative humidity exceeding different thresholds (>97, 98, and 99%). Precipitation intensity was investigated by proportionally increasing or reducing the amount of precipitation that occurred for each hourly data point. The interdependence of different meteorological variables, e.g., climate warming and relative humidity [29], and to which degree such parameters reinforce or balance each other was not a focus of this study.

Three non-realistic ("extreme") precipitation scenarios were applied to better understand the control of road wetness and precipitation phase. Furthermore, simulations were conducted with proportionally changing the amount of road salt applied and incorporating cleaning and wetting. No simulations were performed using sanding, because sanding is not applied at this site, and sanding is not yet fully developed in the NORTRIP model [24,40]. Last, the sensitivity of the model was tested by increasing the hardness of the aggregate (*NBM*).

2.6. Model Outputs

Air quality was primarily assessed based on three metrics: the average PM_{10} concentrations during simulation period as related to annual guidelines (40 and 20 μg/m^3 according to European Air Quality Directive and WHO guidelines, respectively [47,48]), the number of exceedances to the European Standard of 24 h PM_{10} of 50 μg/m^3, and the maximum daily PM_{10} concentrations.

Road surface conditions were primarily assessed by surface wetness, as the percentage of total time that roads were wet. The key metric used to gauge the need for winter management was the number of days when road ice was above the 0.1 mm threshold.

Road wear is mainly represented as a function of traffic (i.e., vehicle count, *LDV* vs. *HDV*, and speed), and road surface strength in the NORTRIP model [39]. Sand sources (road abrasion and crushing) were not relevant in this study. The generated road dust is either directly emitted to the atmosphere or retained on the road surface (wear retention), which is subsequently removed from the road surface via four sink mechanisms: (1) Atmospheric suspension due to the contact of tires with a dry road surface; (2) spray, because of tire contact with a wet road; (3) drainage into the stormwater collection system via street inlets; and (4) windblown material, negligible in all simulations and not discussed further. The sink terms are either presented as rates (g/m^2/hr) or as cumulative mass over the simulation period.

Cumulative dust generation, including both the instantaneous losses to atmosphere and wear retention, was estimated by summing up all sink terms during a simulation with continuous mild (0.1 mm/hr) rainfall as 2219 g/m^2.

Mass loading (g/m^2) represents the mass of road dust and sand that accumulates on the road surface.

3. Results

3.1. Baseline Simulation

The model was effective at representing the timing of observed PM_{10} episodes at the urban traffic air quality station in Reykjavík (Figure 4a), but tended to overpredict concentrations, particularly during the nearly sunless months of December and January. Concentrations of PM_{10} were overestimated by 22% on average during the simulation period, resulting in 20 modeled Health Safety Limit (HSL) exceedances, as opposed to 13 observed ones. The New Year's Eve exceedance was due to fireworks and as such, not represented in the model. Overall, the 0.57 correlation coefficient between modeled and observed particulate matter concentrations was comparable to other Scandinavian studies, and as such, is considered a satisfactory performance.

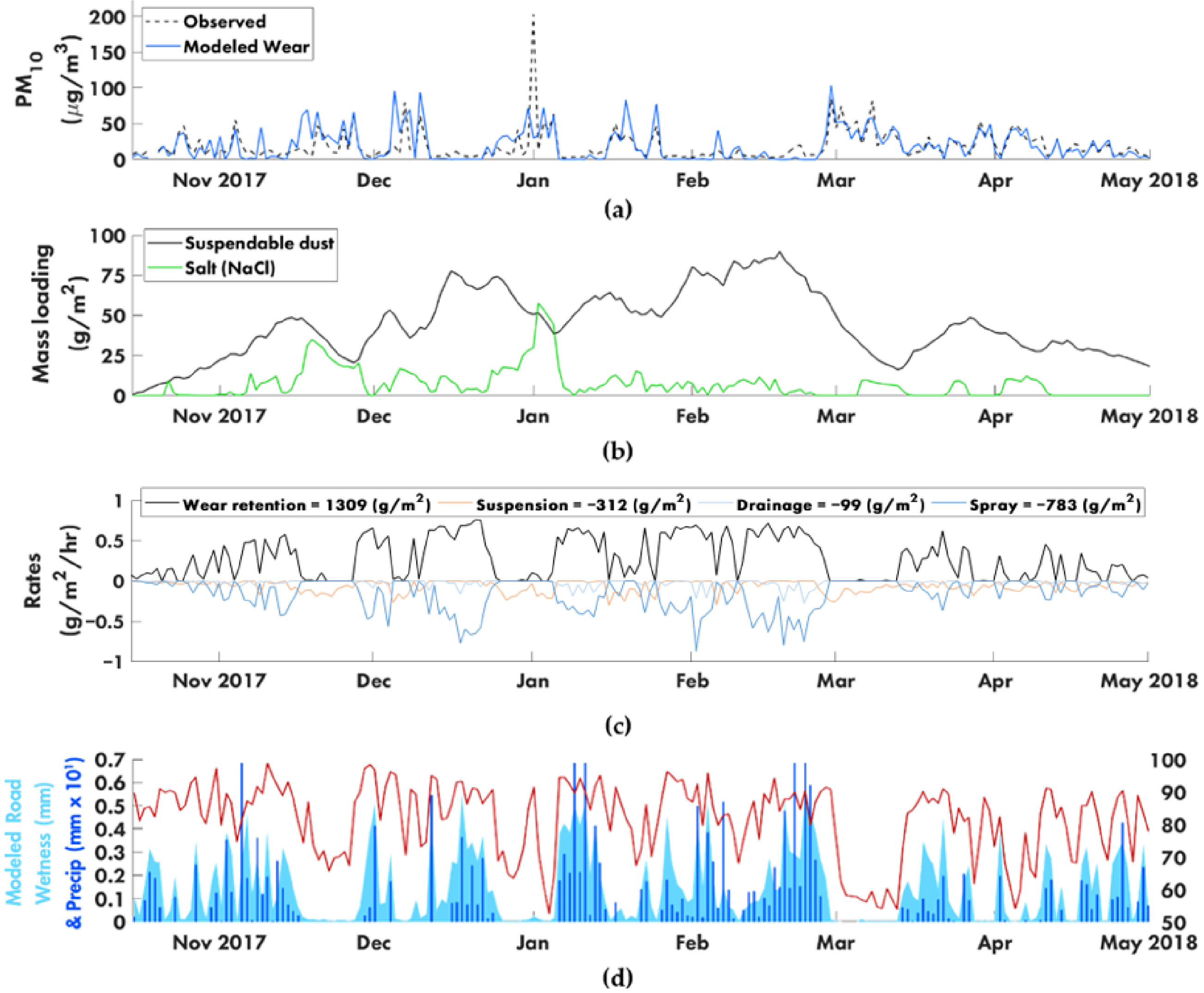


Figure 4. Daily baseline simulation outputs at Kauptún during winter 2017/2018. (**a**) Modeled and observed PM_{10} concentrations. (**b**) Amount of dust accumulated on the surface of the road that is available for resuspension. (**c**) Source and sink rates for accumulation of dust on the road surface. (**d**) Daily modeled road wetness (shade), precipitation (bars), and relative humidity (line).

A progressive accumulation of road dust was predicted as increasing number of vehicles using studded tires were included in the model (Figure 4b). More dust was retained on the roads during wet periods (Figure 4c), but at the same time, the removal mechanisms of spray and drainage became more effective, reducing the amount of dust available to be suspended in air. Once the road dried (reducing road wetness, Figure 4d), the source and water-related sink terms became negligible while suspension, due to tire contact with the road, begins, elevating the particulate matter concentrations in the air (Figure 4a) and reducing the mass loading on the road (Figure 4b). Of particular note are the few dry periods promoting atmospheric releases in the months of November through February. As a result, considerable amounts of dust accumulated on the road to be released during a series of closely spaced spring dust episodes.

Predicted road wetness correlated well with measured precipitation and relatively humidity (Figure 4d). Specifically, the road dried quickly after precipitation ended, usually within a few hours. Additionally, dry roads corresponded well with times when relative humidity dropped below 70%. Albeit infrequent, wet roads were predicted on days with no precipitation, but elevated relative humidity. This suggests that precipitation and relative humidity can be used as indicators of road wetness, and by extension, can be used to anticipate periods of elevated dust suspension.

3.2. Sensitivity to Traffic and Pavement Parameters

The model predicts a near linear deterioration in air quality in response to increasing traffic-related parameters (Table 2). The fraction of light-duty vehicles on studded tires is identified as the single most influential traffic-related parameter to air quality: A 10% reduction in the usage of studded tires resulted in an ~25% decrease in average PM_{10} concentrations, and a 10 μg/m^3 drop in maximum daily PM_{10} concentration. According to the model, the studded tire usage of the light-duty vehicle fleet needs to go down to 15% in order to achieve zero exceedances of the health safety limit.

Table 2. Model sensitivity to traffic and pavement.

Category	Alteration from Baseline	Δ Max PM_{10} (μg/m^3)	Δ Avg. PM_{10} (μg/m^3)	Δ HSL Exceedances (Days)
Baseline	46% Max ST	104	21	20
Studded Tires	35% Max	−21	−4	−7
	25% Max	−39	−7	−16
	15% Max	−58	−10	−20
	0% (full ST ban)	−80	−16	−20
Traffic Volume	−10%	−7	−2	−3
	−20%	−15	−4	−6
Traffic Speed	−10%	−4	−2	−2
	−20%	−9	−4	−6
Composition	HDVs Excluded	0	−2	−2
Wear resistant DGP	h_{pave} = 0.93	−40	−8	−16
	h_{pave} = 1.3	−19	−4	−7
	h_{pave} = 1.5	−9	−2	−3

Abbreviations: HSL = Health Safety Limit; ST = Studded tires; HDV = Heavy-Duty Vehicle; DGP = Dense Grade Pavement.

The model suggests that shortening the legal time to use studded tires does not reduce the number of exceedances to HSL (not shown), albeit it can moderate the concentrations early in the season. Average and maximum particulate matter concentrations dropped 2 and 7 μg/m^3, respectively, for every 10% reduction in traffic volume, which can be traced back to the reduction in studded tires vehicles; a 10% reduction in traffic volume is tantamount to an approximately 4.6% reduction in studded tires. A 10% decrease in traffic speed had a similar effect as 10% reduction in traffic volume, except that daily maximum PM_{10} was not reduced as much (Table 2). Removing heavy-duty vehicles (HDVs) from this particular road segment, which represented 9% of the total traffic count, was predicted to slightly reduce the average PM_{10} concentrations and cause two fewer HSL exceedances. Last, resurfacing the road with a more wear-resistant dense graded pavement (DGP), similar to that at Hornsgatan in Stockholm (Table 1), would strongly reduce road dust generation and exceedances, more so than reducing traffic volume by 20%.

3.3. Sensitivity to Meteorology and Winter Management

The model sensitivity to local meteorology was first tested by changing each parameter while maintaining others fixed (Table 3). The range tested was chosen to represent conditions at the two reference sites (Table 1). The results highlight that rainfall frequency, more so than rainfall intensity, controls the air quality (mean concentrations and exceedances) via the frequency of wet or icy roads. Relative humidity (RH) exerts a secondary control on road wetness, which translates to increasing atmospheric particulate matter mean concentrations and exceedances as RH is lower, but has limited effect on road ice and hence the need for road salting. Air temperature, however, highly influences road ice formation, and by extension, winter management practices, and it should be noted that the response was nonlinear. Lowering mean air temperature to or below freezing point affected average PM_{10} concentrations (and exceedances to ambient air quality standards) more than warming from the freezing point.

Table 3. Model sensitivity to meteorological parameters and road management practices.

Category	Alteration from Baseline [1]	Δ Avg. PM_{10} (μg/m^3)	Δ HSL Exceedances (Days)	Δ% Wet Roads	Δ Road Ice > 0.1 mm (Days)
Baseline	507 mm; frequency 17.1%	20.5	20	53.3%	38
Precipitation Frequency	+7.7%; 544 mm total	−2.8	−4	5.7%	15
	+5.6%; 534 mm	−2.2	−3	4.2%	13
	+3.9%; 526 mm	−1.8	−3	3.9%	10
	−3.2%; 492 mm	0.5	0	−1.6%	0
	−6.3%; 463 mm	1.3	0	−3.8%	−2
	−8.2%; 436 mm	1.6	0	−4.5%	−4
	−9.8%; 406 mm	2.1	0	−6.5%	−11
Relative Humidity	−6%; mean: 77%	1.8	2	−4.8%	−1
	−4%; mean: 79%	1.2	2	−3.2%	−1
	−2%; mean: 81%	0.6	0	−1.6%	0
	+2%; mean: 84%; max: 100%	−1.0	−1	2.3%	0
Air Temperature	+5 °C; mean: 6 °C	0.5	0	−1.0%	−37
	+2 °C; mean: 3 °C	0.3	1	0.0%	−26
	+1 °C; mean: 2 °C	0.4	0	−1.0%	−13
	−1 °C; mean: 0 °C	−0.9	−1	2.0%	23
	−2 °C; mean: −1 °C	−1.6	−2	4.0%	40
Precipitation Intensity	×1.20; 608 mm total	−0.2	0	1.0%	2
	×0.80; 406 mm total	0.4	0	−1.0%	−1
"Extreme" Scenarios	No precip	6.1	7	−15%	−36
	No precip; No WM	7.1	3	−26%	−36
	Rain only ($T_{air} \geq 4$ °C); No WM	−2.3	−7	3.0%	−38
	Constant rain (0.1 mm/hr); 475 mm	−19.8	−20	47%	80
Salting	−50%	−0.8	1	1.0%	3
	50%	1.2	2	−1.0%	−3
Wetting	0.2 mm every four hours during long, dry periods	−4.2	−9	11%	16

Note: [1] Winter management (WM) practices same as in base line simulation, unless otherwise noted.

The "extreme" scenarios provide additional insights to the control of precipitation and road management on particulate matter pollution. In the absence of precipitation, the mean PM_{10} concentrations would be higher, and more exceedances of the air quality standards would occur, in accordance with wet removal processes being eliminated. Discontinuing winter salting and plowing results in fewer exceedances to air quality standards. If all the precipitation would fall as rainfall, so no winter management would be needed, the average PM_{10} concentration is lowered by 10 μg/m^3, and the number of exceedances reduced by one-third. Therefore, winter management is a secondary, yet significant, contributor to particulate matter pollution.

A more aggressive salting scenario increased road dust on the same order of magnitude as a moderate change in meteorological conditions (1 μg/m^3 mean PM_{10}). Salt has the potential to increase moisture, which itself has a mitigating effect on suspension (Denby et al., 2012). Road wetting on an as-needed basis (Table 3) almost reduces the exceedances to national health safety limits by half, in accordance with the strong dependence on precipitation frequency.

3.4. Fate of Road Dust

Of the 2219 g/m^2 of road dust generated over the 6.5-month simulation period, 41% was directly emitted to the atmosphere and 14% suspended during dry periods with traffic. The major wet removal process was spray, predicted to remove 35% of the generated dust off the road to the roadside curb. Direct drainage to waterways via the stormwater collection system constituted only 4.5%. Of the meteorological factors tested, rainfall frequency controlled most whether road dust was emitted to the atmosphere or became water bound (Figure 5). Most notably, more frequent rainfall, and to a lesser extent higher atmospheric humidity, shifted direct emissions to wet removal via spray (Figure 5a,b). In the unrealistic extreme condition of constant, mild rainfall, 89% of the generated dust would leave the road surface via spray. The response to air temperature was much less pronounced and nonlinear around freezing point, where atmospheric emissions were predicted to be at minimum (Figure 5c). Increasing rainfall intensity shifted only slightly the removal from the atmosphere to wet removal (Figure 5d). Of all the meteorological parameters tested though, rainfall intensity exerted one of the strongest controls on drainage to waterways. For example, a 10% increase in rainfall intensity resulted in a 6 g/m^2 increase equally to spray and drainage. At the end of the simulation period, all scenarios tested suggested that around 110 g/m^2 of the generated road dust was still present on the road to be removed at a later time (noted as mass loading; Figure 5).

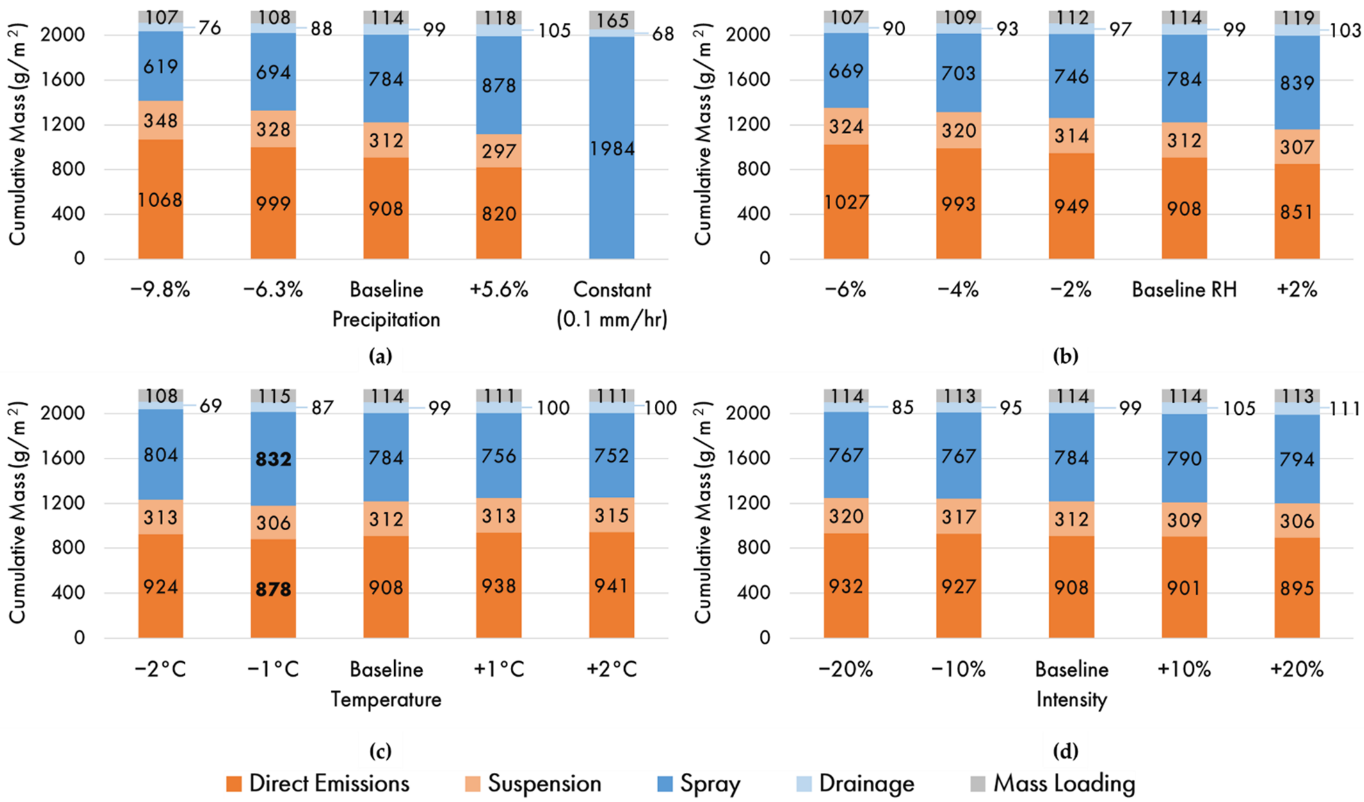


Figure 5. Sensitivity of wet (blue) and dry (orange) removal processes to individual meteorological parameters: (**a**) Precipitation frequency; (**b**) Relative humidity; (**c**) Air temperature and precipitation phase; (**d**) Precipitation intensity.

4. Discussion

4.1. Wet Maritime Climate

This study expands the current knowledge of non-exhaust particulate pollution by considering the wet, humid, windy, and sunless maritime climate in the Icelandic Capital Region compared to other studied capitals in Northern Europe (Table 1). NORTRIP model sensitivity analyses highlight these climatic attributes (frequent rain, high humidity) as efficient dust retention and wet removal processes, which are primarily spray and secondarily drainage (Table 3, Figure 5). Therefore, maritime, wet, and cold conditions promote microplastics loading to aquatic and terrestrial environments, estimated as representing 45% of the total mass of PM_{10} particles generated. The positive effect of this efficient wet removal of dust is the moderate average winter PM_{10} concentration that almost adheres to the WHO guidelines of 20 $\mu g/m^3$, and 50% to 100% lower when compared to Oslo and Stockholm (Table 1), despite the greater traffic volume. Unfortunate artifacts of prolonged wet roads (53% of time) are closely spaced, intense particulate matter episodes, both midwinter and in springtime (Figure 4a). The potential effect of frequent freeze thaw cycles on road dust generation was not resolved in this study, as it was beyond the capability of the NORTRIP model. Previous research suggests a faster pavement deterioration in wet areas with frequent freeze–thaw cycles [16,49].

4.2. Mitigation Strategies for Atmospheric PM_{10}

The model identified the primary lever for road dust generation and abatement as reducing the number of light-duty vehicles on studded tires (Table 2). Traffic volume and asphalt type were secondary levers, followed by vehicle speed. Only a drastic reduction of studded tires usage in winter achieved the goals of adhering to ambient air quality standards. Yet, the share of light duty vehicles on studded tires has steadily increased since 2014 (Figure 2), partially as the public campaign "*Off with the studded tires*" (Icelandic: "*Burt með nagladekkin*") was relaxed. In addition, episodic road ice conditions forming in October just before the studded tires legal interval (Nov. 15) prompt car owners to choose studded tires, despite that Reykjavík Municipality winter management services are frequent enough that studded tires are not needed within the city perimeter. Moreover, traffic volume has been drastically increasing over the past years (Figure 3b), both because of personal car ownership and tourism. Considering these historical trends in studded tire use and traffic volume, it is unlikely that focusing solely on the optimal levers will result in a timely improvement in air quality. Therefore, it is important to evaluate combined mitigation strategies; both short-term when episodes are expected, and long-term.

Short-term response to foreseeable PM episodes: The strong correlation between modeled road wetness, precipitation, and relative humidity (Figure 4d) suggests that the risk of PM_{10} episodes can be predicted based on periods of prolonged road dryness and high dust load. This allows authorities to implement preemptive, short-term mitigating actions to stifle the suspension of dust. One mitigation action that has been employed in cities facing severe pollution episodes, locally called "gray days", is to ban cars with an even or odd license plate from driving in the city. This aggressive, active, short-term measure alone, however, would not alleviate the problem with exceedances. However, coupling 50% reduction in traffic volume with a 10 km/h speed limit reduction brings the number of traffic related HSL exceedances to two (Table 4). An alternative, less intrusive approach is to wet the road system on gray days as a dust binding measure. This, combined with slight traffic and speed reductions, is predicted to lower the PM_{10} concentrations during episodes to one-third. While a significant reduction, it still does not achieve the Icelandic government's goal of zero traffic-related PM_{10} exceedances by 2029. It is important to keep in mind that short-term mitigation strategies are focused on reducing the suspension of PM_{10}, not the generation. The short timeframe of these measure does not influence the long-term dust generation, and as such, the loading of road dust to terrestrial and aquatic environments.

Table 4. Selected combined short and long-term mitigation strategies.

Mitigation Scenario	Targets				Air Quality Outcomes	
	Traffic Volume Reduction	**Speed Reduction**	**Max. Studded Tire Usage**	**Road Re-Surfacing**	**Avg PM_{10} Reduction**	**Total HSL Exceedances**
Short-Term—Aggressive	50%	15 km/h	Unchanged	No	44%	2
Short-Term—Moderate	10%	10 km/h	Unchanged	No	33%	5
Long-Term—Aggressive	15%	None	20%	No	50%	0
Long-Term—Moderate I	10%	10 km/h	25%	No	41%	2
Long-Term—Moderate II	10%	None	25%	Yes	63%	0

Long-term mitigation actions: The sensitivity analysis suggests that the long-term strategy needs to be focused on reducing the use of studded tires as much as possible; coupling this with a decrease in traffic volume would further decrease the overall number of studded tires. Historically, the lowest seasonal average percentage of studded tires was 23% in both 2012 and 2014 (Figure 2). From this perspective, an aggressive scenario is to half the number of studded tires (20% maximum) in 9 years. Yet, this provision does not suffice to achieve the goal of zero PM_{10} exceedances, so a 15% reduction in traffic volume must be implemented as well (Table 4). A less aggressive approach would be to reduce studded tire use to 25%, and traffic speed permanently by 10 km/h; this would lower the average PM_{10} concentrations by 41%. Finally, road resurfacing would offer significant long-term dust reduction, but its effectiveness increases substantially when coupled with reductions in studded tire usage. Road resurfacing with a similar asphalt strength as used at Hornsgatan resulted in a 40% reduction in emissions in the model; this reduction increases to 63% when coupled with aggressive studded tire reduction.

4.3. Mitigation Strategies for Sustainable Cities

As discussed in the previous section, a combination of different mitigation actions can help achieve the overall goal of zero road dust related particulate matter exceedances. However, in a broader context, it is important to recognize that some actions may provide auxiliary environmental benefits, such as greenhouse gas and noise abatement, while other may be more costly and take a long time to implement. Therefore, it is valuable to extend the criteria of beneficial outcomes to incorporate more multifaceted goals of a sustainable city. We will consider the anthropogenic levers tested in the NORTRIP model together with two new levers for comparison, the electrification of the car fleet and dust binding with agents such calcium magnesium acetate (CMA), which has effectively reduced peaks in PM_{10} concentrations [5]. Each lever was given a score based on its positive or negative contribution to goals of sustainability as stated in literature.

By considering more amenities than road dust generation, traffic reduction provided the most intense and diverse environmental benefits (Table 5). Moreover, fewer cars on the street drastically reduces collision rates and as such, this lever is ranked highest on safety. However, reducing personal cars requires a public transport alternative which may require substantial investment and may take a long time to implement [27]. Reducing studded tires is an effective noise and road dust abatement technique in cold climates. This measure, however, lacks climate resilience because of exhaust gas emissions and may raise winter safety concerns. Lowering speed limits contributes positively, albeit moderately, on all the diverse aspects of a sustainable city. Lower vehicle velocity generates less exhaust gases and noise [50] as well as road dust, but it should be kept in mind that more road dust is removed as drainage to local waterways due to lower suspension between tire and road surface. Its competitive advantage over the other traffic levers is, arguably, its ease and speed of implementation. Vehicle electrification provides only a reduction of harmful exhaust pollutants such as greenhouse gases [51], black carbon, and nitrogen oxides. While highly important, it cannot be the backbone of a strategy for sustainable cities because of concerns that electrical vehicles emit more road dust because of their greater weight compared to internal combustion vehicles [52], and of the natural resources depleted in converting the car fleet and time of implementation [53].

Table 5. Evaluation of multifaceted benefits of anthropogenic levers in a subpolar, oceanic climate.

		Environmental Benefits				Social Benefits	Logistics of Implementation	
Domain	**Anthropogenic Lever**	**Non-Exhaust**	**Exhaust (e.g., GHG)**	**Noise**	**Resource Efficiency [1]**	**Safety**	**Cost**	**Time**
Traffic	Reduce traffic volume	+	+	+	++	++	−−	12 years [2]
	Reduce studded tires	++	/	++	+	−	+	2+ years [2]
	Reduce speed	+	+	+	+	+	++	Days
	Increase electrical cars	−	++	/	−	/	/	12 years [2]
Pavement	Wear-resistant DGP	+	/	/	+	/	−−	6+ year [2]
	Open-graded OGP	−	/	+	−	+/	−	2 years [2]
Road Management	Dust binding	(+)	/	/	−	/	−	Hours
	Road wetting	(+)	/	/	−	−	−	Hours

Notes: Scale: ++ = Highly positive effect; + = Positive effect; / = Neutral/Unknown/Varies; − = Negative effect; −− = Highly negative effect; [1] Construction and rehabilitation needs for road infrastructure (pavements, bridges, parking lots). [2] Based on longevity of studded tires; personal vehicles; pavement. Abbreviations: GHG = Green House Gases; DGP/OGP = Dense/Open Graded Pavement.

The last four levers pertain to changing the properties of the road surface. The first lever is to increase the aggregate hardness (lower NBM) or the percentage of stones > 4 mm (Equation (2)) in dense pavement asphalt (DGP), as tested in the sensitivity analysis (Table 2). While this reduces road dust generation, and improves resource efficiency through less pavement wear, it is not expected to create additional benefits such as improved safety or reduced noise levels. Moreover, road resurfacing is only done at 6+ year intervals, and a stronger aggregate may not be found locally, as is the case in Iceland. An importation of stronger aggregates would thus increase greenhouse gas emissions from shipping. For comparison purposes, open-graded (OGP), permeable friction course pavements offer a host of safety and environmental benefits, including improved wet weather skid resistance, reduced splash and spray, reduced light reflection, reduced tire and pavement noise, improved pavement smoothness, reduced contribution to urban heat island effect, and reduced pollutant loadings in stormwater runoff [19]. However, they perform worse than DGP in winter, as they freeze faster and longer, need more deicing agents, their pores can store and retain snow and dust, and their aggregate structure makes them particularly susceptible to degradation, especially by studded tires [19,26,54]. Last, the short-term road management actions of dust binding provide no auxiliary benefits other than reducing particulate matter episodes. The amount of road dust generated will be the same, and it will ultimately be released to the atmosphere (at lower concentration) or hydrosphere. To conclude, our assessment suggests that increasing aggregate hardness is a good secondary option in a cold climate, after the traffic levers are applied, especially if such materials can be supplied locally.

5. Conclusions

With climate change, many regions of the world are experiencing warmer winter temperatures and more precipitation in the form of rainfall or rain on snow. Winter climates may transition from subpolar continental, characterized by little precipitation (that nearly always falls as snow) and low relative humidity, to subpolar oceanic with frequent, light, year-round precipitation, and a narrow temperature band. This study highlights that such changes, specifically more frequent rainfall, higher relative humidity, and higher precipitation intensity in winter, may on one hand reduce winter average PM_{10} concentrations; on the other hand, a maritime winter climate may promote air pollution episodes and more loading of microplastics to terrestrial and aquatic systems. Moreover, the indirect effect of frequent precipitation and fluctuating air temperature around the freezing point is ice formation, which calls for more winter management that generates more dust. The Icelandic experience is that it also prompts the usage of studded tires, even though local authorities regularly remind the population that the majority of the trips are conducted within the urban area where slippery conditions can be managed with plowing and salting. Short-term mitigation on grey days can alleviate air pollution episodes, but not the pollutant loading to waterways and concern of microplastics pollution entering the food chain. The strongest mitigation levers are to reduce the studded tire share and traffic volume, both of which take years to reverse unless strong measures are employed. Pairing restrictions of studded tires use with traffic speed reductions may both help with source reduction, and eliminate the competitive advantage of the personal vehicle being the fastest mean of transport. Last, electrification of the car fleet is no silver bullet in achieving a sustainable road system, as they contribute to road wear.

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