

Weather-Tuned Network Perimeter Control

A Network Fundamental Diagram Feedback Controller Approach

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Abstract: Inclement weather has been shown to increase congestion, justifying the need for weather-responsive traffic control. From one side, all existing weather-responsive controllers currently operate on freeways or limited road segments. From the other side, existing controllers operating on networks do not take into consideration the weather effect on the network fundamental diagram (NFD). This paper describes the development of a macroscopic weather-tuned perimeter controller. First, an NFD-based proportional-integral perimeter controller (PC) is implemented in INTEGRATION, tuned using clear weather data and then tested for clear and inclement weather conditions. In order to respond to weather changes, new sets of control parameters were tuned for each weather and given to the controller. This weather-tuned perimeter controller (WTPC) is compared to the regular PC. Simulation results show that the WTPC reduces congestion inside the protected sub-network better than PC. Also, it improves the performance of the full network (inside and outside the protected sub-network) in terms of average speed and total delay. Compared to the non-perimeter control case, WTPC increases the average speed of the entire network by 28.61% for rain and 42.64% for snow conditions. Total delay is decreased by 33.26% and 42.02% for rain and snow, respectively.

1 INTRODUCTION

Traffic managers employ various management strategies to maintain safety and improve roadway mobility. This task becomes more challenging with adverse weather, as weather events may increase both crash rates and congestion. According to the Federal Highway Administration (FHWA, 2017), 22% of vehicle crashes are weather-related crashes. Of these, 46% occurred in rainy conditions and 13% in snowy or sleety conditions. Average speed, traffic volumes, saturation flow rates, free-flow speed, and travel time delays are also negatively affected by inclement weather on arterials and freeways. (Romain et al.) found that there is an average decrease of 15.5% in capacity and 9% in free-flow speed and (Agarwal et al., 2005, Maze et al., 2006) reported capacity reductions of 4–30% and speed reduction rates of 3–15% during rainy conditions. (Xu et al., 2013), studied the impact of rain in a network finding that heavy rain and rainstorms reduced the network critical accumulation and maximum production by 10.5%, 16.7% and 21%,

18.7% respectively. (Tsapakis et al., 2013), considered different intensities of rain, snow, and temperature levels to study the effect of weather on travel times in an urban network, finding that total travel time increases due to light, moderate, and heavy rain by 0.1–2.1%, 1.5–3.8% and 4.0–6.0%, respectively. They found light snow increases travel time by 5.5–7.6% and heavy snow increases delays by 7.4 to 11.4%. (Rakha et al., 2008) demonstrated that traffic stream jam density is not affected by weather conditions, and that reductions in free-flow speed and speed-at-capacity increase as the rain and snow intensities increase. Precipitation intensity affects the roadway capacity only during snow. The authors developed weather adjustment factors to calculate the free-flow speed, speed-at-capacity, and capacity as a function of precipitation type, intensity and visibility level.

(Pisano and Goodwin, 2004) introduced the idea of weather responsive traffic management, analyzing the impacts of adverse weather on traffic flow and presenting three categories of operational strategies that may improve safety, mobility and productivity.

The operational strategies are classified into three categories: 1) treatment strategies like coordination with maintenance managers for snow or ice control; 2) control strategies such as signal timing, ramp metering, and variable speed limits; 3) advisory strategies like public notification of road closure and warning systems (Systematics, 2003).

Concerning control strategies, (Goodwin and Pisano, 2004) introduced some successful methods to change signal timings in response to weather. The authors identified the parameters that need to be modified to simulate weather impacts on arterial traffic flow using CORSIM. Their studies revealed that weather-responsive signal timing could improve mobility by increasing average speed and reducing delays. (Papageorgiou et al., 2008) found that variable speed limits decrease the slope of the flow occupancy diagram at under-critical conditions, increase the critical occupancy, and enable higher flows at the same occupancy values in overcritical conditions. These strategies mitigate localized weather impacts on relatively short road segments (Pisano and Goodwin, 2004).

This paper describes the implementation of a weather-tuned control strategy on a macroscopic level. The control strategy is based on the macroscopic fundamental diagram (MFD) also known as the Network Fundamental Diagram (NFD), which gives an aggregated view of the network characteristics: density, flow, and space mean speed. NFD's physical model was initially proposed by (Godfrey, 1900). It was observed with dynamic features in a congested urban network in Yokohama by (Geroliminis and Daganzo, 2008). Their analyses and simulations have shown that NFDs are curves that can be reproduced under homogeneous conditions in urban networks. They have also shown that NFDs are a property of infrastructure and not of demand, which means that the average flow in a network is at maximum for the same density value, regardless of the time-varying origin-destination (O-D) tables.

Further research has been conducted for the investigation of NFDs using empirical and simulated data. (Buisson and Ladier, 2009) were the first to test how the NFD changes if the congestion is not homogeneous within the network. (Ji et al., 2010) recreated inhomogeneous conditions in an urban freeway traffic simulation with several on-ramps, finding that inhomogeneous congestion leads to a reduction in flow. They presented control strategies to be followed using ramp metering to create homogeneous traffic states. (Mazloumian et al., 2010) and (Geroliminis and Sun, 2011) found that

the spatial variability of vehicle flow density affects the shape, the scatter, and the existence of an NFD. In fact, heterogeneous networks might not have a well-defined NFD, especially in the decreasing part of the NFD, as scatter becomes higher when accumulation increases, leading to the appearance of a hysteresis loop. In order to address this issue, (Ji and Geroliminis, 2012) created clustering algorithms to create homogeneous sub-networks to obtain small variance of link densities within a cluster. This approach is useful for large congested networks with strong heterogeneity. NFD-based traffic flow might then be used in single-region cities (Daganzo, 2007) (Haddad and Shraiber, 2014) or in multi-region cities, each having a well-defined NFD (Aboudolas and Geroliminis, 2013, Haddad and Geroliminis, 2012).

The idea of perimeter control (or gating) based on the NFD consists of attempting to maintain the accumulation around a set point (which corresponds to the maximum throughput) in order to avoid the oversaturation or congestion regime (Figure 1).

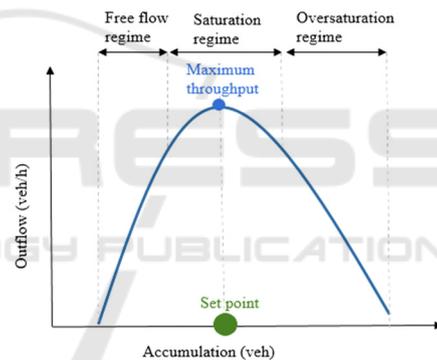


Figure 1: NFD of a network.

(Li et al., 2012) investigated a perimeter control strategy of an oversaturated network using the NFD concept. The optimization goal was to maximize capacity utilization of the network and prevent queue spillback. The phase sequence and offset were optimized by a Genetic Algorithm (GA) to minimize the network delay. They have implemented the signal timing outputs in TRANSYT-7F and showed that their proposed model performs better than TRANSYT-7F in congested networks. However, the approach proposed a fixed signal timing method which is not adapted to the real-time traffic conditions. There are many works in the literature that overcome that issue and operate real time perimeter control. They use different techniques like the standard proportional integral (PI) controller (Keyvan-Ekbatani et al., 2012), Robust PI controller (Haddad and Shraiber, 2014) and Model Predictive

controller (Sirmatel and Geroliminis, 2016). However our focus will be in standard proportional integral Controller because it is simple and computationally cheap.

(Keyvan-Ekbatani et al., 2012) described a simple real-time feedback-based gating concept, which exploits the urban NFD for smooth and efficient traffic control operations. They used a standard proportional-integral (PI) feedback controller, and applied the method to a network in Chania, Greece and tested it using the microscopic traffic simulator AIMSUN. Although simple, the method has been proven to be very efficient. Compared to the non-control case, the average vehicle delay per km was reduced by 35%, the mean speed increased by 39.2% and the total number of vehicles that exit the overall network increased.

The method assumed that the real-time measurements of all links within the protected network are fed to the regulator which is not convenient in terms of implementation cost for a real-time system. (Keyvan-Ekbatani et al., 2013), demonstrated that feedback-based perimeter control is possible with much less real-time measurements than in their previous work.

The aforementioned strategies assume that the gating is applied directly at the border of the protected network. However, in reality, this could not always be satisfied due to some restrictions such as unavailability of proper links to store the gated vehicles. For that reason, (Keyvan-Ekbatani et al., 2015) included a time delay in the feedback-perimeter control strategy so that it handles the metering at some junctions further upstream from the protected network.

All these works assume that the links on which the perimeter control is applied are long enough to handle the queues of the gated vehicles. In order to overcome that limitation and also to obtain a more homogeneous density distribution in PN, (Keyvan Ekbatani et al., 2016) combined the feedback perimeter control strategy with the adaptive traffic signals control. They applied the gating at the borders of the PN and traffic-responsive adaptive signal control strategy inside the PN. The combination of these two strategies led to higher overall vehicle throughputs and hence shorter queues at the boundary of the PN, higher speeds and lower network delays.

(Keyvan-Ekbatani et al., 2017) proposed strategies for queue and delay balancing at the gated links under perimeter control. Their approaches could be used for flow distribution among the gated links, especially in multi-region perimeter control as

they reduce the impact of queuing on NFDs of the regions.

All of the mentioned works are very interesting and effective. However, they do not consider the effect of weather on the NFD. Also, they did not test the efficiency of the control method for different weather conditions which are the objectives of this paper. Consequently, the objectives and the contributions of this work are as follows: (1) Implement a feedback-based standard proportional integral perimeter control (PC) strategy in the INTEGRATION micro-simulator. (2) Study its impacts on the protected network's (PN's) NFD and on the full network (FN) for different weather conditions. The full network is the zone inside and outside the protected network. (3) Develop a weather-tuned perimeter control (WTPC) strategy and evaluate its impact on the NFD of the PN and on the performance of the FN. (4) Compare the WTPC with the PC and the non-control (NPC) cases. (5) Validate the obtained results of the WTRC by testing it for different rain and snow intensities.

2 NETWORK DESCRIPTION AND MACROSCOPIC FUNDAMENTAL DIAGRAM

2.1 Network Setup

The modelled network was used for studying the impact of the implemented PC strategy on the NFD. For that reason, a PN was identified; this is the sub-network that needs to be protected from congestion. The PN corresponds to the zone surrounded by the green rectangle in the middle of the network in Figure 2.

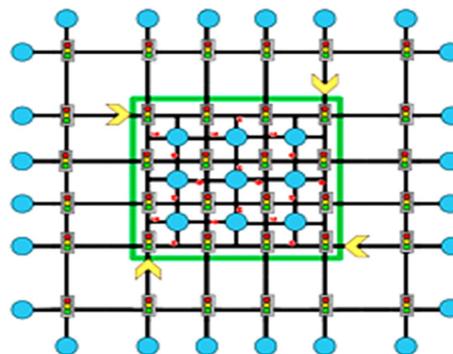


Figure 2: Grid network modelled in INTEGRATION.

The PN contained 91 links, as shown in Figure 2. The yellow chevrons represent the four links where gating was applied. The gated links were long enough such that they were able to accommodate the queues caused by gating without spilling back onto other links. Future work will integrate queue spill back prevention strategies. All links were one way and each link had only one lane.

The full network (FN) comprised 36 signalized intersections running on a fixed-time plan. The origins and destinations are represented by blue circles (Figure 2). Loop detectors were placed on each link in the network to collect the needed measurements, and those measurements were collected every cycle (60 s in this study). The traffic demand was loaded for 75 minutes, with demand increasing during the first 37.5 minutes, and decreasing during the second 37.5 minutes, representing realistic demand behaviour. In order to ensure that the network was empty at the end of the simulation, the total simulation time was set to be 176 minutes (approximately 3 hours). A feedback dynamic traffic assignment was activated to reflect realistic driver behaviour during congested conditions.

2.2 NFD Equations Derivation

In this work, the NFD is presented based on the total time spent (TTS) and the total travelled distance (TTD), which are calculated from the loop detectors measurements. The TTS (in veh.h/h) corresponds to the number of vehicles in all the network links and is calculated using Equation (1).

$$TTS(k) = \sum_{z \in Z} \frac{T \cdot \widehat{N}_z(k)}{T} = \sum_{z \in Z} \widehat{N}_z(k) \quad (1)$$

where z is the link; Z is the set of measurements links, $k = 0, 1, 2, \dots$ is an index reflecting the cycle number; T is the duration of the cycle; $\widehat{N}_z(k)$ is the measured number of vehicles on link z during cycle k . It is calculated by Equation (2).

$$\widehat{N}_z(k) = L_z \cdot l_z \cdot k_j \cdot \frac{o_z(k-1)}{100} \quad (2)$$

where L_z is the length of link z ; l_z is the number of lanes on link z ; k_j is the jam density; o_z is the measured time-occupancy (in %) on link z during cycle k .

The TTD (in veh.km/h) corresponds to the length weighted sum of the corresponding network link flows. It is calculated using Equation (3).

$$TTD(k) = \sum_{z \in Z} q_z(k) \cdot L_z \quad (3)$$

where $q_z(k)$ is the measured flow on link z during cycle k .

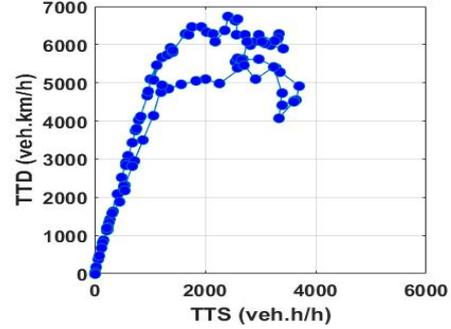


Figure 3: NFD of the protected network (PN).

Running a simulation in INTEGRATION, we obtain the NFD presented in Figure 3. The maximum throughput occurs in a TTS range of [1800, 3000]. Note that the NFD has a decreasing area corresponding to the congestion regime, indicating the need for a control strategy to mitigate congestion in the PN.

3 IMPLEMENTATION OF THE PERIMETER CONTROLLER (PC)

3.1 Mathematical Modelling

In order to avoid congestion inside the PN, a PI PC is applied based on the NFD. The idea of the PC is to maintain the TTS around a set value \widehat{TTS} , which corresponds to the maximum TTD. In our case, $\widehat{TTS} = 2000 \text{ veh.h/h}$, which is within the range of the TTS values corresponding to the maximum TTD [1800, 3000].

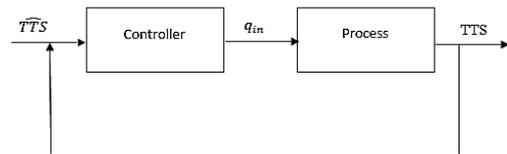


Figure 4: System and feedback controller structure.

The system and feedback controller structure is represented in Figure 4. The process, shown in Equation (4), is what happens in the PN—its input is q_{in} , which corresponds to the PN's entering flow,

and its output is TTS. Further details about the derivation of the process of Equation (4) can be found in (Keyvan-Ekbatani et al., 2015, Keyvan-Ekbatani et al., 2012).

$$\Delta TTS(k+1) = \mu \Delta TTS(k) + \zeta \cdot \Delta q_{in}(k) \quad (4)$$

where $\Delta x = x - \bar{x}$ and \bar{x} corresponds to the steady state variable used in the model linearization. The desired steady state is common in control engineering, and in this case, it corresponds to the region where the TTD is maximal. Note that $\overline{TTS} = \overline{TTS}$. μ and ζ are two model parameters that can be found using a least squares approximation of the simulated data (q_{in} , TTS) around the maximum TTS range.

The controller's inputs are TTS and \widehat{TTS} , and its output is the ordered flow that should enter the PN. Equation (5) corresponds to the proportional-integral feedback regulator equation.

$$q_{in}(k) = q_{in}(k-1) - K_p(TTS(k) - TTS(k-1)) + K_I(\widehat{TTS} - TTS(k)) \quad (5)$$

where K_p and K_I are the proportional and integral gains, respectively. These can be found by manual fine-tuning or using control engineering methods. More details about finding these gains can be found in (Keyvan-Ekbatani et al., 2012, Keyvan-Ekbatani et al., 2015).

The controller ordered flow q_{in} is distributed among the gated links. The flow entering the PN from each gated link has to be between two bounds: q_{min} and q_{max} . These bounds can be calculated based on the minimum and maximum green times, respectively.

The controller always works in the background and the fixed signal timings are set for all signals. Once the TTS is close to (i.e., 85% of) the set value \widehat{TTS} , the controller is activated and the signal timings are calculated based on the controller ordered flow q_{in} . When the TTS decreases, to less than 85% of \widehat{TTS} , the controller is deactivated and the signals display the fixed timings again.

3.2 Use of the Perimeter Control (PC) for Clear Weather Conditions

Since INTEGRATION is a stochastic micro-simulator, simulations were run for the PC case and the NPC case using five different random seeds. The parameters used in these simulations are as follows: $\mu = 0.678$, $\zeta = 0.0973$, $K_p = 6.96$, $K_I = 3.31$, $\overline{q_{in}} = 1826.66 \text{ veh/h}$, and $\widehat{TTS} = 2000 \text{ veh.h/h}$.

Table 1: Performance metrics of the PC for the FN using five different seeds.

	Average	Max	Min
NPC: Speed (km/h)	16.00	16.97	14.182
PC: Speed (km/h)	18.89	19.33	18.23
Difference (%)	18.75	35.34	7.75
NPC: Delay (s)	261.31	340.95	220.65
PC: Delay (s)	187.34	194.45	183.25
Difference (%)	-26.25	-12.59	-46.12
Completed trips	9068	9079	9053

Table 1 shows that the PC improved the performance of the full network FN. On average, it increased the average speed by 18.75% and decreased the total delay by 26.25% compared to the NPC case.

For the performance inside the PN, Figure 5 clearly shows that the control algorithm decreased the congestion. Note that the decreasing NFD area in Figure 5(a) no longer exists in Figure 5 (b).

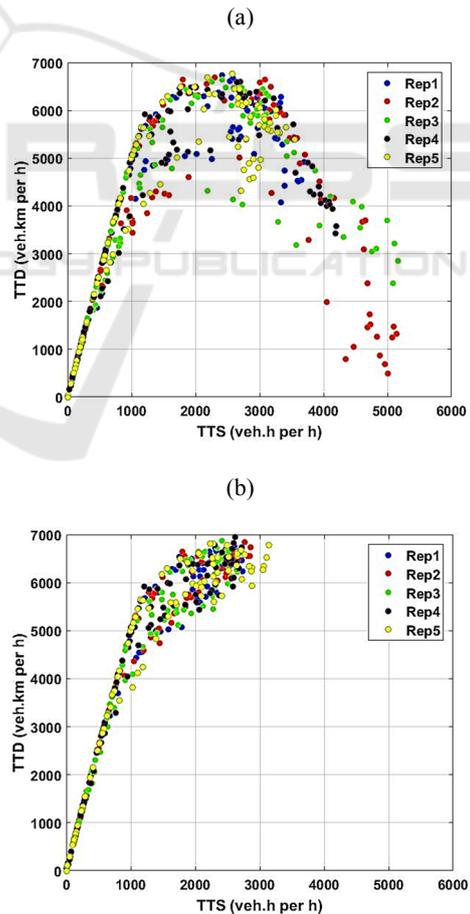


Figure 5: (a) NFD using 5 different seeds for NPC; (b) NFD using 5 different seeds for the PC.

4 PC AND WTPC FOR INCLEMENT WEATHER

4.1 Weather Modelling in INTEGRATION

Rakha et al. studied the impact of weather on free flow speed, speed at capacity and capacity. They developed weather adjustment factors (in Equation (6)) to compute these three traffic stream parameters based on precipitation intensity i (cm/h) and visibility level v (km) for each of the rain and snow cases (Rakha et al., 2008, Rakha et al., 2012).

$$WAF = a_1 + a_2i + a_3i^2 + a_4v + a_5v^2 + a_6iv \quad (6)$$

In this work, the calibrated model parameters a_1 through a_6 are chosen to be the Twin Cities parameters because it has the highest WAF (Table 1 in (Rakha et al., 2012)). These WAF are multiplied by the clear conditions speeds and capacity.

The authors also modelled vehicle deceleration and acceleration behaviour for inclement weather. They provided rolling and friction coefficients for different roadway surface conditions (including wet and snowy surfaces).

In order to model different weather conditions in INTEGRATION, the set of inputs containing the free flow speed, speed at capacity, capacity, rolling coefficient and coefficient of friction are calculated and given to the software.

The PC uses for inclement weather the same set of parameters used for clear weather conditions which is the following: $\mu = 0.678$, $\zeta = 0.0973$, $K_p = 6.96$, $K_l = 3.31$, $\bar{q}_{in} = 1826.66 \text{ veh/h}$, and $T\hat{T}S = 2000 \text{ veh.h/h}$.

However, the WTPC uses a specific set of parameters for each weather condition. For clear weather, it uses the parameters defined above: $\mu = 0.678$, $\zeta = 0.0973$, $K_p = 6.96$, $K_l = 3.31$, $\bar{q}_{in} = 1826.66 \text{ veh/h}$, and $T\hat{T}S = 2000 \text{ veh.h/h}$. The obtained re-tuned parameters are $\mu = 0.755$, $\zeta = 0.214$, $K_p = 3.17$, $K_l = 2$, $\bar{q}_{in} = 1600 \text{ veh/h}$, $T\hat{T}S = 2000 \text{ veh.h/h}$ for the rain conditions and $\mu = 0.0864$, $\zeta = 0.758$, $K_p = 0.114$, $K_l = 1.2$, $\bar{q}_{in} = 1613 \text{ veh/h}$, $T\hat{T}S = 2000 \text{ veh.h/h}$ for the snow conditions.

The NFD plots of the PN for both rain and snow conditions are presented in Figure 6(a) and (b). The blue curves correspond to the NFDs for the NPC, the

red to the NFDs for the PC, and the green curves to the NFDs for the WTPC. As the curves show, the values of TTS for the WTPC case were lower than those for the PC and NPC cases, indicating that the WTPC performed better than the PC in decreasing congestion inside the PN.

The results of Table 2 show that the WTPC algorithm outperformed the PC algorithm for both the rain and snow cases in terms of increasing the average speed and decreasing the total delay of the FN (not only PN). Compared to the NPC case, the WTPC increased the speed by 28.61% and the total delay by 33.26% for the rain conditions. For the snow conditions, an improvement in the range of 42% is shown for both the average speed and total delay.

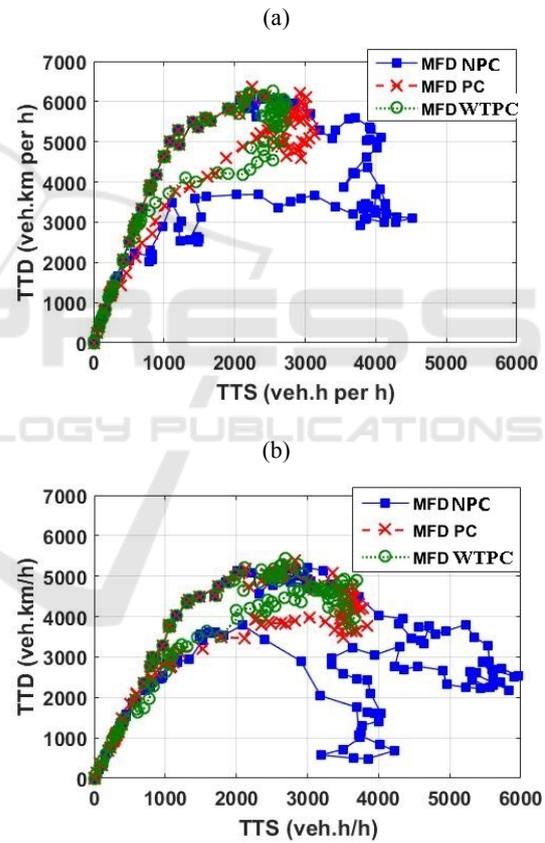


Figure 6: (a) NFD for rain; (b) NFD for snow.

In order to further test the efficiency of the WTPC, simulations for different rain and snow intensities were performed for the NPC, PC, and WTPC cases.

Table 2: Performance Metrics on the FN for the NPC, PC and WTPC Cases.

Performance metrics	Strategy	Rain		Snow	
		Value	% Difference w.r.t NPC	Value	% Difference w.r.t NPC
Avg. Speed	NPC	11.23	-	6.52	-
	PC	13.75	22.43	8.85	35.73
	WTPC	14.44	28.61	9.30	42.64
Avg. Total Delay	NPC	402.52	-	803.42	-
	PC	283.73	-29.51	478.27	- 40.47
	WTPC	268.65	-33.26	465.77	- 42.02

Table 3: Performance metrics of the FN with respect to (w.r.t) NPC for the PC and WTPC cases for different rain and snow intensities.

Performance Metrics	Strategy	Moderate Rain	High Rain	Moderate Snow	High Snow
% Difference in Avg. Speed	PC	21.14	17.95	49.82	48.25
	WTPC	30.50	24.68	59.62	53.24
% Difference in Avg. Delay	PC	-33.97	-23.62	-50.3	-46.74
	WTPC	-39.97	-31.57	-54.87	-49.06

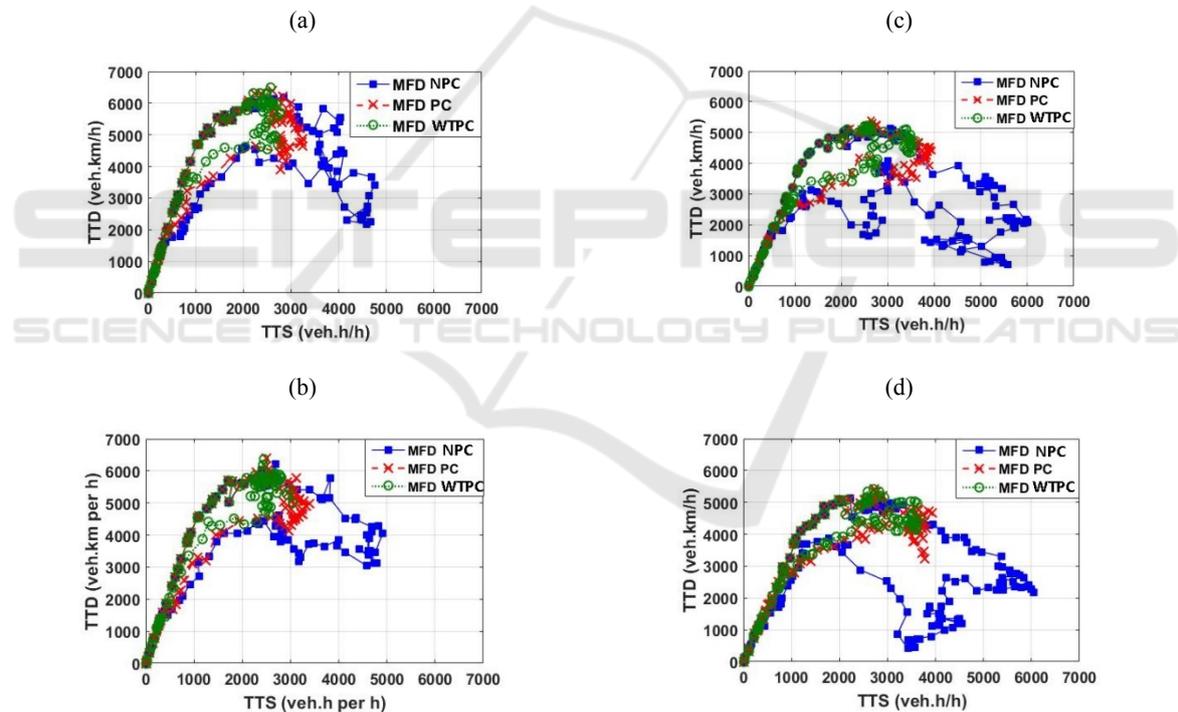


Figure 7: (a) moderate rain, (b) high rain, (c) moderate snow, (d) high snow.

5 VALIDATION FOR DIFFERENT RAIN AND SNOW INTENSITIES

Two different precipitation intensities were chosen for each weather conditions. Each weather condition was run with its corresponding set of parameters as

described above. No further parameter tuning is done. Depending of the weather (clear, rain or snow), the corresponding set of control parameters is loaded to INTEGRATION for the WTPC. For the PC, the same set of parameters tuned originally for clear weather conditions is loaded to INTEGRATION whatever the weather is.

Table 3 shows the relative difference of each performance metric for the PC and WTPC with respect to NPC for different rain and snow intensities. All the results show that the WTPC outperformed the PC in improving the mobility of the entire transportation system.

The PN NFD plots of each scenario are presented in Figure 7. In all the plots, the green curves corresponding to the WTPC have the lowest *TTS* values, which means that they were the most effective in reducing the congestion inside the PN.

6 CONCLUSIONS

A Perimeter Control (PC) strategy based on the NFD was implemented in the INTEGRATION micro-simulator. It was tested for different weather conditions and was proven to be efficient. Because the method was proven to be efficient, and due to the need for a macroscopic weather responsive traffic management strategy, a weather-tuned perimeter control (WTPC) model was developed and tested for different precipitation types (rain and snow) and intensities. The WTPC was shown to outperform the regular PC in decreasing congestion inside the protected network (PN), in increasing the average speed and in decreasing the total delay of the full network (FN).

An application of this work in a real network will be a future objective. Another future objective will be combining this control strategy with a routing strategy to manage the queues on the gated links. A generalization of this work will be done so that it could be applied to any network.

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