An Analytical Approach on Transport Resilience with Smart Transport Systems

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ABSTRACT

As urban areas across the world continue to witness explosive growth, transport operations have become vital to meet the economic needs and social well-being of the populace. Transport operations facilitate the movement of people to their places of employment, to leisure activities, and enable social and cultural interactions. Climate change, natural disasters and temperature rises pose an increasing risk to transport systems and economic growth. Transport resilience is therefore a key agenda item for policy makers. Advances in smart transport systems have meant that such threats can be monitored and managed effectively to increase the resilience. So far there has not been substantial analysis of the benefits of smart transport systems in enhancing transport resilience. This research seeks to make a tangible contribution by a way of a two-step analysis approach. Namely, the research 1) uses a microscopic multimodal traffic flow simulation tool to analyze the impact of incidents and natural disasters on traffic conditions in a target area, and 2) estimates the benefits (e.g., reduced congestion, improved safety and reduced vehicle emissions) by smart transport systems in response to incidents and natural disasters. Given the lack of analysis in this area, it is expected that the research's findings will provide the right directions for policy makers which can make a positive contribution to achieve the 2030 Agenda of Sustainable Development Goals.

Key words: smart transport systems, transport resilience, microscopic multimodal traffic flow simulation, vehicle emissions, natural disaster

1. INTRODUCTION

Transport systems are an engine for trade and the backbone of the global economy. At the national level, the transport sector is an enabler of economic and social development as transport moves people and goods resulting in social and cultural interactions. Rural communities are also dependent on transport systems to connect them to markets and urban centers, thus enabling the development of rural areas. In such an environment, the indispensable role of transport systems is clear, and when transport comes to a halt, all economic and social activities comes to a halt. At the same time, the world today is witnessing rapid urbanization, with over 50% of the global population living in urban areas which is expected to rise in the coming years particularly in Asia (United Nations Department of Economic and Social Affairs, 2019). The rural to urban migration taking place in the developing world, as people move in search of employment and a better quality of life, has resulted in cities that are increasing in size and complexity. Naturally, city infrastructure and resources are increasingly under pressure to meet the demands of residents. Transport systems in particular are getting more complex which is resulting in various traffic issues in cities. To mitigate such negative implications, smart transport systems, including Intelligent Transport Systems (ITS), have been engaged in many cities to manage complex traffic conditions and to keep systems functioning at optimal levels. Among various definitions, smart transport systems, particularly ITS, are defined as an agglomeration of diverse technologies that enhance the sustainability of transport systems in a safer, smarter and greener way (United Nations Economic and Social Commission for Asia and the Pacific, 2019).

While smart transport systems have greatly enhanced the ability to manage intricate transport systems, transport infrastructure is increasingly vulnerable to disruptions from traffic incidents, natural disasters, terrorist attacks and extreme weather conditions. Transport resilience can be defined as "the capability to

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recover from a disruption to an operational level similar to prior to the disruption in a timely manner" (Linkov and Palma-Oliviera, 2017). Ensuring resilient transport systems is therefore a top priority for policy makers around the world as transport networks can be quickly overwhelmed by unexpected events that can bring transport systems to a halt. Examples can be found easily. The 2010 and 2011 earthquakes in Christchurch, New Zealand, resulted in damage to road infrastructure which affected traffic flows in parts of the city (Koorey, 2018). Pacific Island states given their geographic locations are particularly vulnerable to natural disasters such as hurricanes, floods and landslides, which can quickly overwhelm their transport infrastructure resulting in huge economic losses. In Fiji, for instance, the road authority is allotted a third of the government budget (World Bank, 2017), highlighting the importance of road transport networks to the economy. In 2015, an earthquake in Nepal resulted in damage to several key roads which required the deployment of helicopters in some areas to deploy emergency relief (Xie et al., 2017).

Although transport resilience is not the primary goal of smart transport systems, they can play an important role in improving the resilience of transport systems to unexpected events like traffic incidents and natural disasters by enabling restoration of transport operations and services. Smart transport systems can monitor the occurrence of such events on a continuous basis, and alert drivers and passengers in the vicinity of an affected site. By using a variety of data from sensors embedded in emergency vehicles (e.g., ambulances and firefighting vehicles) and infrastructure, smart transport systems can react and assist in post event efforts, thus improving the resilience of transport systems. However, while smart transport systems can contribute to improve transport resilience, there is a gap in research on identifying tangible benefits of such systems for transport resilience.

Further, following the COVID-19 pandemic, transport resilience has been receiving renewed interest as a result of a sharp drop in demand for transport services due to lockdowns. Although social and economic activities have significantly decreased, governments are still required to provide transport services to ensure fundamental social and economic interactions in a limited but safer way. Smart transport systems have increasingly gained attention because the full utilization of these systems could enhance the continuity of transport services during the COVID-19 pandemic resulting in a more resilient transport systems.

In response to growing interests in utilizing smart transport systems for traffic incidents and natural disasters, and the impact of COVID-19 pandemic, it would be worthwhile to explore the advantages of such systems from the viewpoint of transport resilience.

2. PURPOSE AND SCOPE

According to the facts mentioned above, the main purpose of this research was to find tangible evidence on the use of smart transport systems for transport resilience. Particularly, this research focused on traffic incidents and natural disasters, which would significantly affect traffic conditions. Given that it is difficult to reflect unexpected incidents and natural disasters accurately into the research, the simulation approach based on scenarios was used to achieve four objectives:

1. Set up the experiment environment to replicate the reality of traffic conditions with a microscopic multimodal traffic flow simulation tool.
2. Analyze the impact of incidents and natural disasters on traffic condition in a target area;
3. Estimate the benefits (e.g., congestion, safety and vehicle emissions) of smart transport systems in response to incidents and natural disasters.
4. Interpret the findings from the viewpoint of transport resilience.

Note that this research adopted a high-quality of techniques to achieve the above objectives.

3. RELATED STUDIES

Although previous studies regarding the use of smart transport systems for transport resilience have been rarely found, a review of the literature on transport resilience reveals that much of the focus has been on the vulnerability of transport infrastructure to natural disasters, weather-related events or traffic incidents.

Dawson et al. (2016) assessed the extent to which projected sea-level rise was likely to impact the functioning of coastal railway lines in England, in particular segments of the London to Penzance railway line. Vajjarapu et al. (2020) evaluated climate change adaptation policies for urban transport in India with a focus on flooding, and proposed policies to improve the resilience of the city transport infrastructure through flood adaptation strategies.

Other studies have looked at the economic impact of natural disasters, such as earthquakes and sea level rise on transport infrastructure. Market Economics Limited (2017) looked at the impact of the Kaikoura earthquake of 2016 on freight transport and tourism in the Canterbury region of New Zealand. McCarron et al. (2018) assessed the impact of rising sea levels on sea ports in Asia and the Pacific and estimated that it would cost between US$ 31billion and US$ 49 billion to protect and elevate fifty-three of the region's largest port areas to adapt to climate related risks.

On research for the use of smart transport systems to improve transport resilience, although there are few, the research focus has been on how these technologies could be deployed prior to and following a natural disaster. For instance, the use of probe car data, following the 2011 earthquake and tsunami in Tohoku Japan, assisted in post disaster efforts by identifying roads that were operational after the earthquake, and roads that needed to be repaired or inspected (Tanaka et al., 2014). In the United States, Louisiana Department of Transportation and Development collaborated with United States Geological Survey to deploy Information Stations that can gather and transmit data on traffic and water level conditions along frequently used hurricane evacuation routes, enabling monitoring of road and traffic conditions in near real time (Federal Highway Administration, 2003). Federal Highway Administration successfully piloted in 2016 a "Mobile Solution for Assessment and Reporting" which uses mobile applications to collect and upload data needed for the restoration of transport infrastructure following natural disasters (Hendrickson, 2018). This application can respond to the need for speedy damage assessments of transport infrastructure in the aftermath of a hurricane, flood, or storm, and enables transport infrastructure damage to be repaired quickly and restored for normal traffic conditions. It was revealed that the process time by using this application was shortened from 18 hours to 20 minutes on average, resulting in savings of US$ 1.2 million per disaster. Aside from the response to natural disasters, weather incidents have been of great interest to researchers. In Finland, a road weather information system was expected to save an average of 23 minutes per de-icing activity for road maintenance (Pilli-Sihvola et al., 1993). The deployment of weather information controlled variable speed limitations showed relatively good benefit-to-cost ratios ranging from 1.1 to 1.9 (Schirokoff et al., 2006). However, in this analysis, ancillary impacts on pollution were assumed marginal and were not included.

Although it is at an early stage, emerging technologies have been highlighted as a measure for managing traffic operations, particularly including the evacuation. Bahaaldin et al. (2017) revealed that more than 50% of traffic delays could be decreased when the market penetration rate of connected vehicles reaches 30%. Other studies predicted that 20% of delay could be reduced by deploying connected vehicles for the evacuation on short-notice (Intelligent Transportation Systems Joint Program Office, 2015), and 88% of delay and crossing conflicts could be decreased with an autonomous reservation-based intersection control for the evacuation traffic control (Chang and Edara, 2017).

As can be seen from the literature review, smart transport systems can be utilized for reducing the vulnerability of transport infrastructure. However, there remains a gap in the literature quantifying the benefits of smart transport systems for transport resilience. To be specific, studies relating to transport resilience have mostly not explored the options of smart transport systems. Although there are some studies about the use of smart transport systems for traffic incidents or natural disasters, it is not directly linked to transport resilience or is limited and does not take into account detailed benefits including vehicle emissions.

4. METHODOLOGY

Overall approach

In response to the objectives of this research, the multi-level procedure was used which included i) setting up a microscopic multimodal traffic flow simulation tool, ii) establishing scenarios that can evaluate the impact of smart transport systems in traffic condition in a target area, ii) applying scenarios to the experiment environment, iv) calculating benefits by each scenario from the experiment, and v) analyzing the results to see the impact of smart transport systems in a target area. Figure 1 elaborates the details of overall approach.

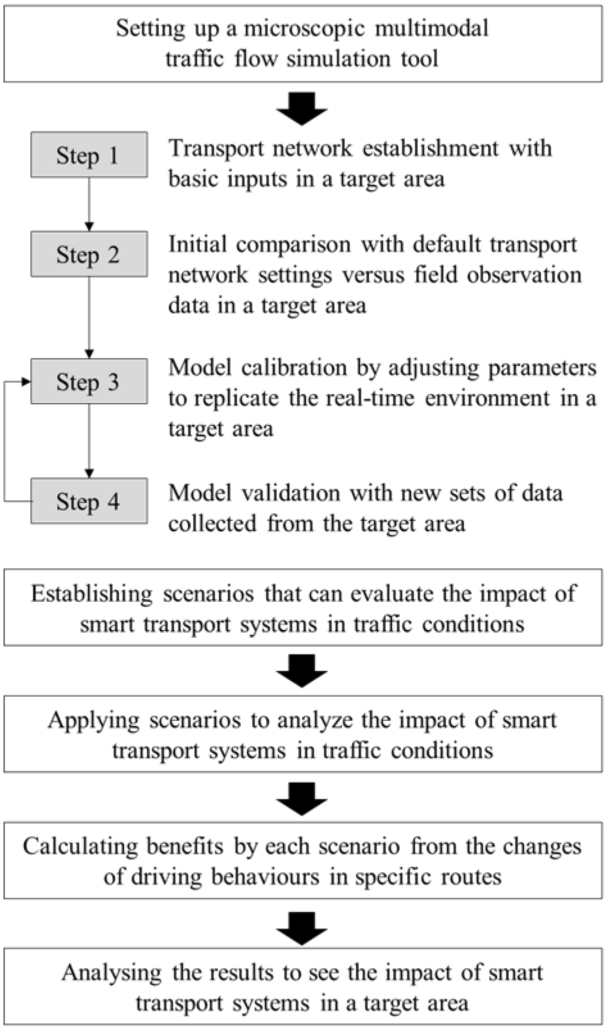


Figure 1: Overall process for the analysis

Approach taken in this research is quite straightforward, except for setting up a microscopic multimodal traffic flow simulation which requires a systematic approach. This has multiple loop processes to replicate the real-world traffic conditions.

Particularly, for step 3, the calibration procedure continues in a loop until signal timings, traffic volume for each intersection, travel speed at all link sections and travel time for all network sections meets specific thresholds. For step 4, travel times from the model are compared point by point with the ones from predesignated matching sections in a target area. Although above steps are described separately, in real setting procedure, calibration and validation steps are interconnected (step 3 is iterated until step 4 is satisfied).

Data sources

Considering that a microscopic multimodal traffic flow simulation tool requires a wide range of data sets, this research chose Broward County in Florida, U.S.A. as a target area where most of data are publicly available. Figure 2 describes a specific research boundary in a target area which consists of six corridors. Six corridors are the East-West direction of Oakland Blvd, Sunrise Blvd, Broward Blvd and Davie Blvd, the North-South direction of State Road 7 and US 1.

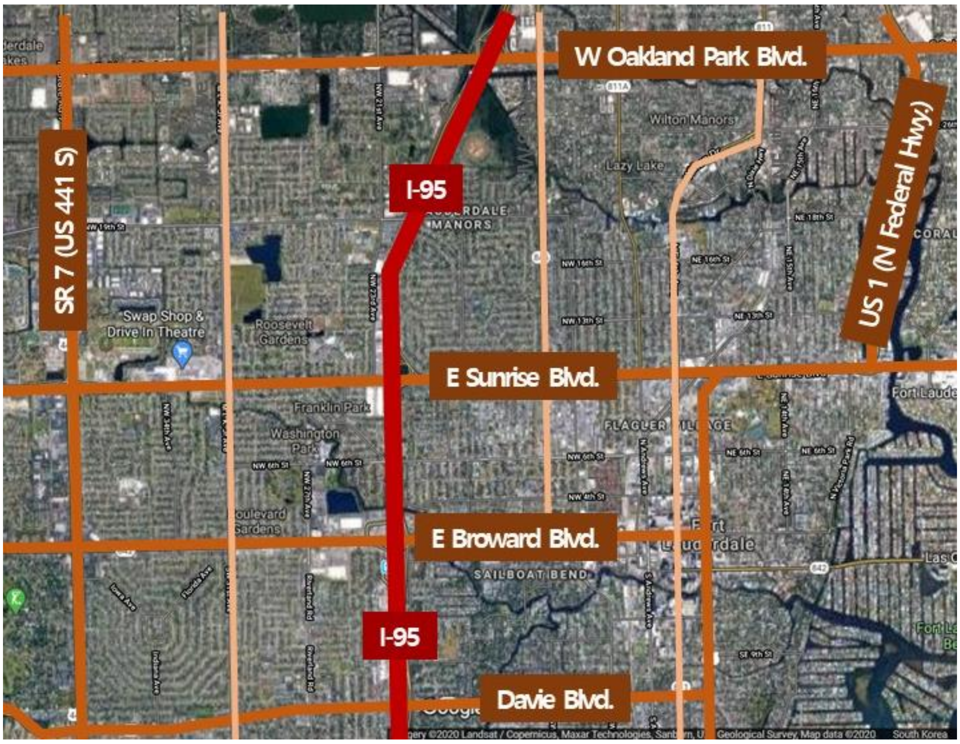


Figure 2: Specific research boundary in a target area

Data sources used for this research are summarized in Table 1. It should be noted that traffic counts including turning movements, which were extracted from different sources, were collected in the same year (i.e., 2013), and the geometry settings were also identical with the year of 2013.

Table 1: Specific data sources for the research

Group	Specific Types	Sources
Geometry	Links, nodes, intersection characteristics, road classifications, stop sign locations, speed limits, conflict areas, right-turn-on-red status	Google Maps (2020)
Traffic signal	Signal timing/heads/displays, detectors and signal controllers in 160 signalized intersections	Broward County (2020)
Public transportation schedule	Railroad/bus stations/stops, lines, service schedules and boarding information in east of I-95 and west of I-95.	
Traffic information	Turning movement field counts for 99 intersections	
	Turning movement counts for 50 intersections	Florida Traffic Online (2013)
	Traffic counts for the other 11 intersections	So et al. (2016)

	Link traffic volumes (annual average daily traffic, vehicle classifications, etc.)	Florida Traffic Online (2013)
	Link travel time in 2010 and 2013	So et al. (2016)

5. APPLICATIONS

Among many microscopic traffic simulation models such as VISSIM, Aimsun (Siemens, 2018), and SUMO (Lopez et al., 2018), VISSIM was ultimately selected for this research as a microscopic multimodal traffic flow simulation tool with two main reasons—i) the capability of modeling detailed driving behavior for various incidents and natural disasters (e.g., Liang et al., 2015), and ii) the flexibility of scenario design for incidents and natural disasters (e.g., Lin et al., 2020).

Transport network establishment

Fundamental transport networks were extracted from the U.S. Geological Survey. Detailed geometries (e.g., 1,300 stop signs, over 4,000 conflict areas) were fine-tuned by aerial images from Google Maps (2020) and by manual investigations of a target area (So et al., 2016). Furthermore, 160 signalized intersections and related traffic links were established; signal timing plans and turning movements were provided by the Broward County Traffic Engineering Division; link traffic volumes were extracted from Florida Traffic Online (2013); and travel time data were collected by manual surveys on the study site (So et al., 2016). Figure 3 shows constructed transport networks in a VISSIM environment.

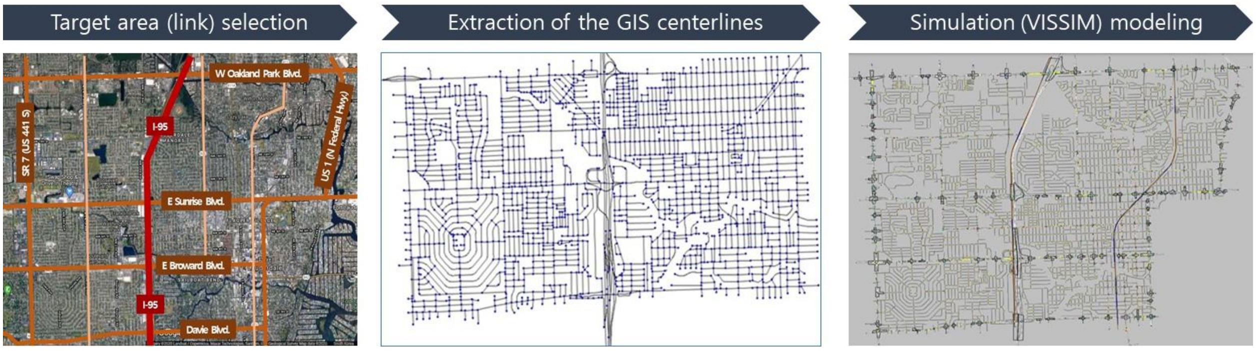


Figure 3: Constructed transport networks

Model calibration and validation

Parameter adjustments

After initial comparison between the default settings of transport networks and field observation data, parameters were adjusted as a first step of the model calibration to replicate the actual traffic conditions. To reflect change in driver's behavior following incidents and natural disasters, two parameter sets were calibrated for normal urban traffic conditions, and for forced merges and lane changes by incidents in terms of car-following and lane change behaviors. Major adjustments are as follows:

Table 2: Parameter adjustments by different situations

Parameters	Default		Urban		Incident	
Safety distance (ft) (additive/multiplicative)	2/3		3.5/4		3.5/4	
	Own	Trailing	Own	Trailing	Own	Trailing
Maximum deceleration (ft/sec^2)	-13.12	-9.84	-13.12	-9.84	-29.13	-29.13
Accepted deceleration (ft/sec^2)	-3.28	-3.28	-3.28	-3.28	-29.13	-29.13
Waiting time before diffusion (s)	60		60		120	
Minimum headway (ft)	1.64		1.5		1.35	
Safety distance reduction factor	0.6		0.5		0.3	

Max deceleration for coop braking (ft/sec^2)	-9.84	-12.84	-29.79

Calibration checks

The remaining procedure for calibration comprises of checking traffic volume, speed and travel time to assure the accuracy of outputs from the experiment.

- Traffic volume: Traffic counts from the simulation on six corridors were compared with field data in a target area (4:00 PM to 6:00 PM in 15 minutes intervals). The established experiment produced very close match with field data which at least showed 0.92 R-squared.
    - Oakland Blvd (0.94), Sunrise Blvd (0.92), Broward Blvd (0.92), Davie Blvd (0.96), State Road 7 (0.92) and US 1 (0.94).
- Speed: Simulated vehicle speeds at all segments in a target area were checked with desired speeds observed from the field. That is, the distribution of vehicle speeds in the simulation were adjusted to follow the desired speeds from the field.
- Travel time: Simulated travel times in designated segments (2 per each corridor) in six corridors were compared with actual travel times. R-squared showed at least 0.8 between simulated and observed data.

Model validation

After the calibration procedure, travel time, traffic volume, travel speed and occupancy rate were used to validate the experiment settings in the simulation. Note that new data sets acquired from ITS devices like Bluetooth devices and detectors in five corridors in both directions as one corridor did not have such available data.

- Traffic time: The sections for examination were matched with the locations of Bluetooth devices in the corridors. Although some sections showed the lower R-squared (0.75), most of the sections showed a high correlation (more than 0.8 R-squared) between simulated and observed travel times. This means that the settings of simulation tool are generally able to replicate actual travel time along the major corridors in a target area.
- Traffic volume, travel speed and occupancy rate: Daily traffic data during PM peak hours were used to validate hourly traffic volumes, travel speeds and occupancy rates. Given that these performance measures can vary widely by many factors, validation results are generally not as satisfactory as traffic time. However, the R-squared showed relatively good correlation between simulated and observed performance measures on average (traffic volume: 0.57, travel speed: 0.52, occupancy rate: 0.51).

6. SCENARIO SET-UP FOR THE IMPACT ANALYSIS

In assessing the advantages of smart transport systems for transport resilience, detailed scenarios need to be set up with a VISSIM environment. Selected smart transport systems and necessary assumptions in the scenarios are as follows:

- Four relevant applications were presumed to be operated in a target area considering their roles to maintain smooth traffic conditions in response to any incidents and natural disasters on the roads.
    - Traffic incident management
    - Road weather management

  - Pre-trip traveler information
  - En-route traveler information

- With above applications, two further assumptions were made for traveler information based on default values from the Tool for Operations Benefit/Cost (Federal Highway Administration, 2013).
  - En-route traveler information: Devices provide useful information during 25% of travel time and 10% of drivers act on the information.
  - Pre-trip traveler information: 10% of drivers would access the traveler information and 22% of drivers act on the information.

The target area is prone to being affected by natural disasters, i.e., hurricanes, where various attempts have been made to minimize the impact on traffic conditions through the use of smart transport systems (e.g., Liao, 2017). Besides, the COVID-19 pandemic has been sweeping the world which affects traffic conditions as a result of measures, such as lockdowns and social-distancing, and dealing with patients. As of July 5, 2020, there have been 11,125,245 confirmed cases including 528,204 deaths (World Health Organization, 2020). In this regard, two scenarios were set up to analyze the impact of smart transport systems on transport resilience in a target area.

- Two major roads were closed because of traffic incidents on routes to two hospitals (Broward Health Medical Centers at State Road 7 and Davie Blvd.) which affected the movement of emergency vehicles and/or vehicles transporting the patients.

- A major road to the international airport was closed (Fort Lauderdale-Hollywood International Airport) because of the natural disaster (i.e., hurricane).

The first scenario was to test the response to sudden traffic incidents on the roads under the medical emergency, including COVID-19 pandemic. It was presumed that there was severe traffic congestion due to unexpected incidents (e.g., crashes, breakdowns, road damage, etc.) which would affect traffic conditions significantly. Emergency vehicles and/or any vehicle that transport patients to the hospitals would be particularly affected and transport resilience was tested under this scenario.

The second scenario was based on the fact that the Florida government had decided to close the roads and provide traffic alerts via smart transport systems in response to the Hurricane Irma in 2017 (Liao, 2017). Irma was a category 5 hurricane and the strongest one ever recorded in the Atlantic Ocean outside of the Caribbean Sea and the Gulf of Mexico (Potenza, 2017). In this scenario, it was presumed that the hurricane could affect one of the major transport facilities which could critically break down traffic conditions in a target area.

Two paths were selected—i) the shortest route and ii) the alternative route—to reach each destination. SB-2a/3a, NB-2a/3a and SB-a are the shortest routes, and SB-2b/3b, NB-2b/3b and SB-b are the alternative routes in Figures 4 and 5. Detailed analysis was undertaken with four different cases under each scenario (a total of eight cases) —i) normal situation (Case 1), ii) scenario situation without smart transport systems (Case 2), iii) scenario situation with smart transport systems (10% diversion, Case 3), and iv) scenario situation with smart transport systems (22% diversion, Case 4).

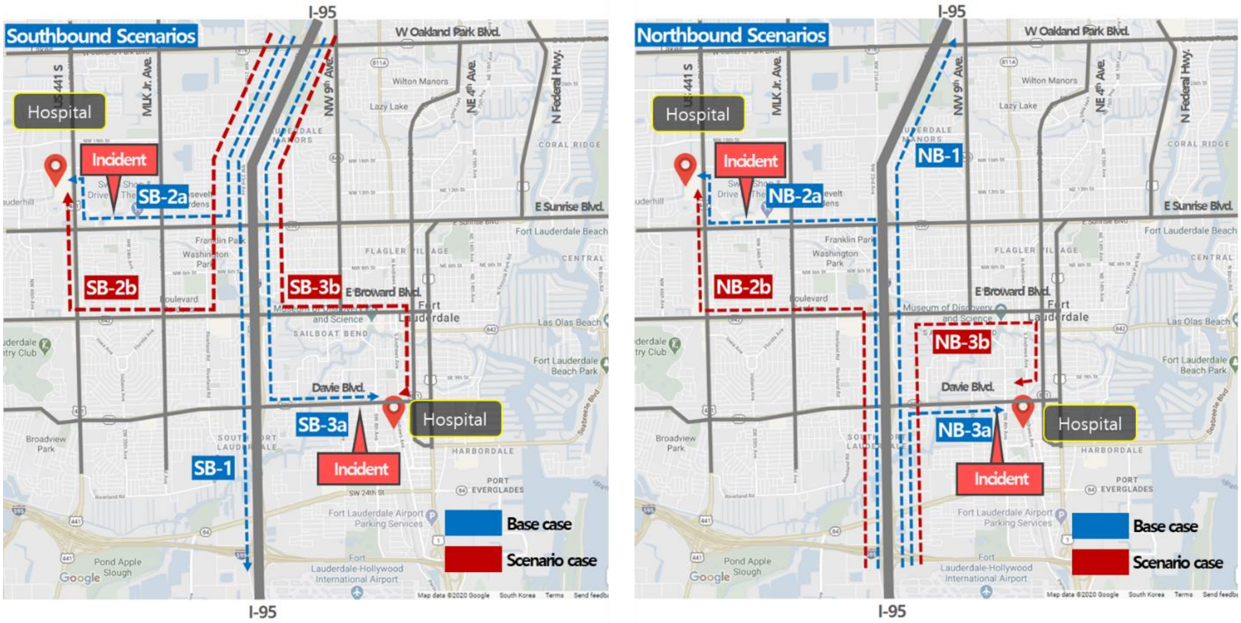


Figure 4: Pictorial description of the first scenario

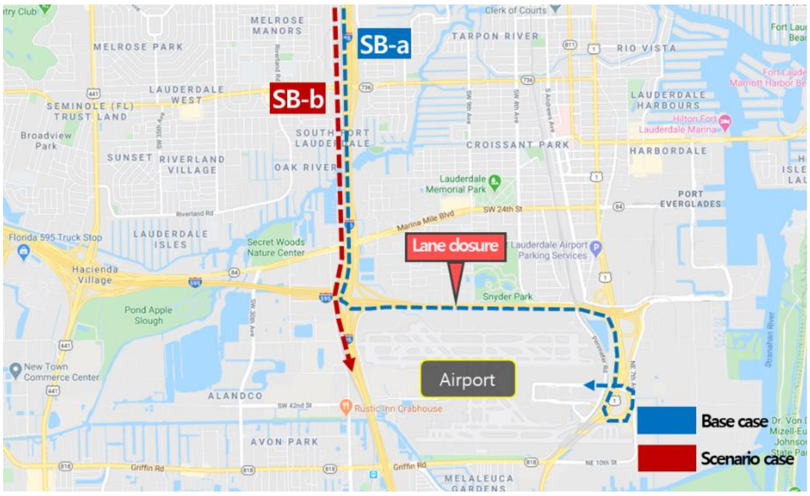
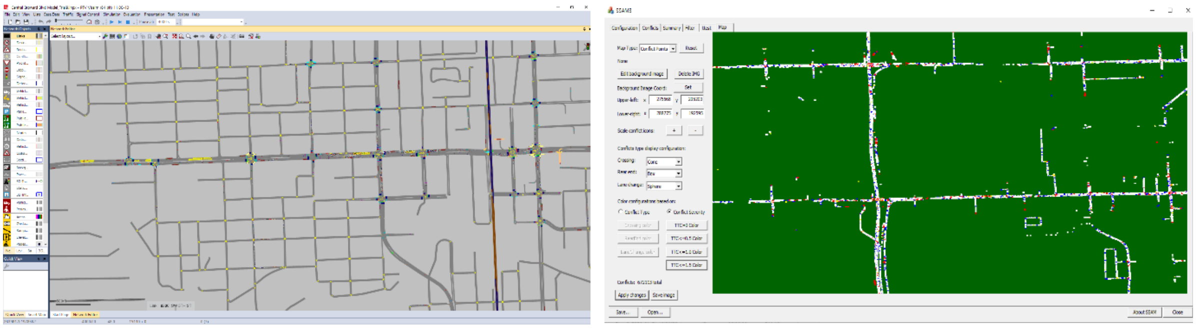


Figure 5: Pictorial description of the second scenario

Note that in the scenarios, the changes in traffic demands during the natural disaster times and COVID-19 pandemic were not considered because of the difficulty to estimate accurate numbers without solid revealed information. It was presumed that traffic demands were unchanged.

Performance measures

The impacts of smart transport systems in incidents and natural disasters were assessed in terms of mobility, safety and sustainability. The mobility impact was assessed by delays, which is one of the representative performance measures for signalized arterials; the safety impact was assessed by traffic conflicts, which is a probability of traffic crashes; and the sustainability impact was assessed by vehicle emissions including CO (g/Km), HC (g/Km), NOx (g/Km) and PM (g/Km). Note that delays and vehicle emissions were extracted directly from the VISSIM while traffic conflicts were estimated by the Surrogate Safety Assessment Model (SSAM) software based on the vehicle trajectories extracted from VISSIM (Federal Highway Administration, 2008) (Figure 6). VISSIM and SSAM are linked in part; VISSIM generates a specific SSAM input file, which is a binary coded output file (.trj) including vehicle trajectories, and SSAM loads the .trj file and estimates the number of conflicts based on various surrogate safety measures including time-to-collision (TTC), post-encroachment time (PET), deceleration rates, and many others. (Federal Highway Administration, 2008)



a) VISSIM run b) Traffic conflict estimation by SSAM

Figure 6: Snapshots of VISSIM Run and SSAM analysis

7. RESULTS AND DISCUSSIONS

Based on the scenarios defined, the impact of smart transport systems in a target area were estimated with suggested performance measures—delays, traffic conflicts and vehicle emissions (CO, HC, NOx and PM). Table 3 presents the experiment results in the first scenario.

Table 3: Summary of findings from the first scenario

Scenario 1		**Case 1**	**Case 2**	**Gap (Case 1 – Case 2)**	**Case 3**	**Gap (Case 2 – Case 3)**	**Case 4**	**Gap (Case 2 – Case 4)**
Average delay per vehicle (Seconds)	**All roads in a target area**	286.4	310.3	**23.9 (8.4%)**	309.9	**-0.4 (-0.13%)**	306.1	**-4.3 (-1.4%)**
	SB-1	247.3	258.3	**11.1 (4.5%)**	255.3	**-3.0 (-1.2%)**	251.3	**-7.0 (-2.7%)**
	SB-2a+SB-3a	553.3	1,376.5	**823.2 (148.8%)**	1,177.5	**-199.0 (-14.5%)**	700.4	**-676.1 (-49.1%)**
	SB-2b+SB-3b	397.2	396.0	**-1.2 (-0.3%)**	398.5	**2.4 (0.6%)**	413.9	**17.9 (4.5%)**
	NB-a	60.7	62.3	**1.6 (2.6%)**	62.0	**-0.3 (-0.4%)**	62.3	**0.1 (0.1%)**
	NB-2a+NB-3a	731.4	1,344.7	**613.3 (83.9%)**	1,253.2	**-91.5 (-6.8%)**	1,072.5	**-272.2 (-20.2%)**
	NB-2b+NB-3b	430.2	456.6	**26.4 (6.1%)**	530.5	**73.9 (16.2%)**	610.8	**154.2 (33.8%)**
Total number of conflicts	**All roads in a target area**	602,484	672,113	**69,629 (11.6%)**	667,583	**-4,530.0 (-0.7%)**	636,539	**-35,574.0 (-5.3%)**
	SB-1	111,833	119,875	**8,042 (7.2%)**	119,844	**-31.0 (-0.03%)**	118,302	**-1,573.0 (-1.3%)**
	SB-2a+SB-3a	5,320	24,930	**19,610 (368.6%)**	23,932	**-998.0 (-4.0%)**	18,022	**-6,908.0 (-27.7%)**
	SB-2b+SB-3b	3,023	2,993	**-30 (-1.0%)**	3,533	**540.0 (18.0%)**	4,203	**1,210.0 (40.4%)**
	Sum of SB	120,176	147,798	**27,622 (23.0%)**	147,309	**-489.0 (-0.3%)**	140,527	**-7,271.0 (-4.9%)**

	NB-1	58,352	73,923	**15,571 (26.7%)**	70,293	**-3,630.0 (-4.9%)**	65,332	**-8,591.0 (-11.6%)**
	NB-2a+NB-3a	4,882	9,884	**5,002 (102.5%)**	9,401	**-483.0 (-4.9%)**	6,332	**-3,552.0 (-35.9%)**
	NB-2b+NB-3b	3,492	3,383	**-109 (-3.1%)**	3,493	**110.0 (3.3%)**	3,622	**239.0 (7.1%)**
	Sum of NB	66,726	87,190	**20,464 (30.7%)**	83,187	**-4,003.0 (-4.6%)**	75,286.0	**-11,904.0 (-13.7%)**
Average emission per vehicle (g/km/vehicle)	CO (g/Km)	898.234	1,080.737	**182.504 (20.3%)**	999.811	**-80.9 (-7.5%)**	986.931	**-93.8 (-8.7%)**
	HC (g/Km)	24.098	28.985	**4.887 (20.3%)**	26.885	**-2.1 (-7.2%)**	26.768	**-2.2 (-7.6%)**
	NOx (g/Km)	75.897	91.213	**15.315 (20.2%)**	85.184	**-6.0 (-6.6%)**	86.685	**-4.5 (-5.0%)**
	PM (g/Km)	0.688	0.826	**0.138 (20.0%)**	0.780	**-0.05 (-5.5%)**	0.824	**-0.002 (-0.3%)**

In all aspects of delays and conflicts, after incidents happened (Case 2), they were noticeably increased in the shortest route by increased traffic congestion: 148.8% (SB-2a+SB-3a) and 83.9% (NB-2a+NB-3a) in average delay per vehicle, and 368.6% (SB-2a+SB-3a) and 102.5% (NB-2a+NB-3a) in total number of conflicts. After applying smart transport systems (Case 3 and Case 4), average delay per vehicle was reduced by 49.1% (SB-2a+SB-3a) and by 20.2% (NB-2a+NB-3a) at maximum with traffic/weather information and optimized strategies. For the total number of conflicts, similar findings were observed—maximum reduction of 27.7% (SB-2a+SB-3a) and 35.9% (NB-2a+NB-3a). It was noted that Case 4 showed superior outcomes in both measurements. Congestion and safety might not be direct proxies for transport resilience. However, they can be indirect means to understand how fast traffic conditions can be restored in status quo as less delays and potential conflicts between vehicles would lead to less required time for returning to the original state which would result in secondary impact to the society and environment.

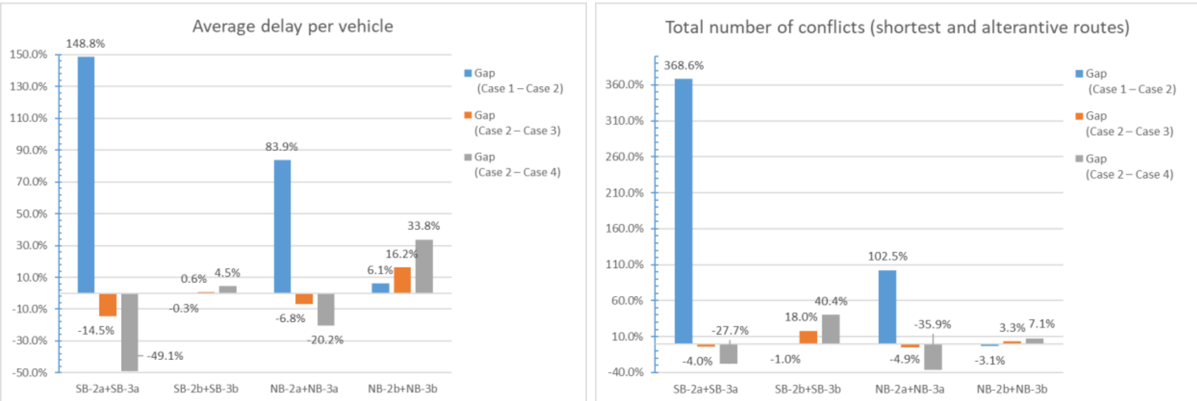


Figure 7: Average delay per vehicle and total number of conflicts in the first scenario#1

Aside from that, one interesting result was found from the alternative routes (SB-2b/3b and NB-2b/3b) (Figure 7). After introducing smart transport systems, there were increases in both measurements which were suspected to be affected by vehicles that were originally planning to use the shortest routes. Because of smart transport systems, they had the information about incidents and options to avoid that. The alternative routes would be one of the options they could choose. Given that the shortest routes showed the positive impact on two measurements, while the alternative routes had the negative impact, it was necessary to check the overall impact in transport networks in a target area.

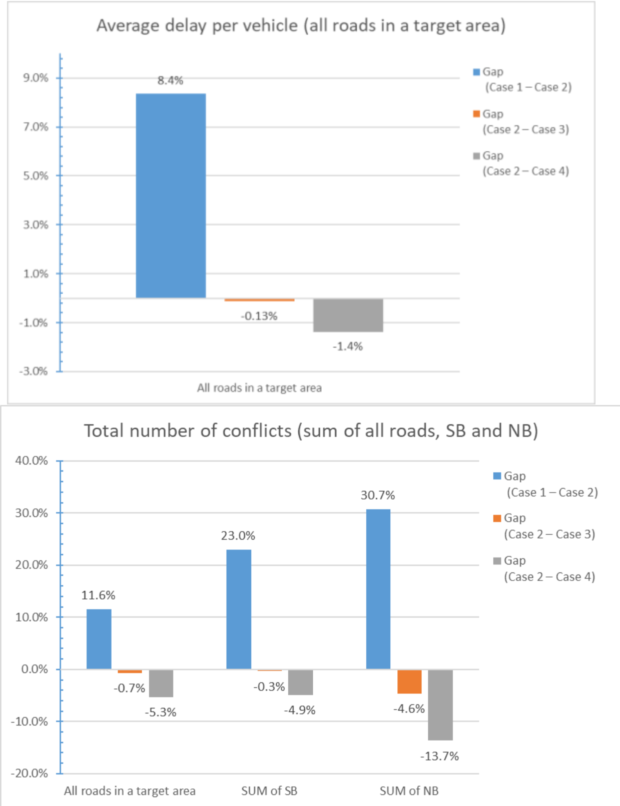


Figure 8: Average delay per vehicle and total number of conflicts in the first scenario #2

As shown in Figure 8, average delay per vehicle and total number of conflicts in all roads in a target area were decreased up to 1.4% and 5.3%, respectively. Particularly, total number of conflicts in three northbound routes showed 13.7% reduction. Even though the decrease rate in delay looked relatively small (1.4%), smart transport systems brought crucial resilience impact considering the delay in the original state (286.4 seconds) and the one after applying the systems during incident period (306.1 seconds). Namely, in all roads in a target area, only 19.7 seconds delay gap per vehicle was produced between the original and incident states by smart transport systems, which eventually would contribute to increase the transport resilience.

More importantly, in terms of the average emission per vehicle, after incidents occurred (Case 2), all elements (CO, HC, NOx and PM) were increased by around 20% but it was considerably reduced by 7.5% (Case 3) and by 8.7% (Case 4) at maximum by the reduction of delays with smart transport systems (Figure 9).

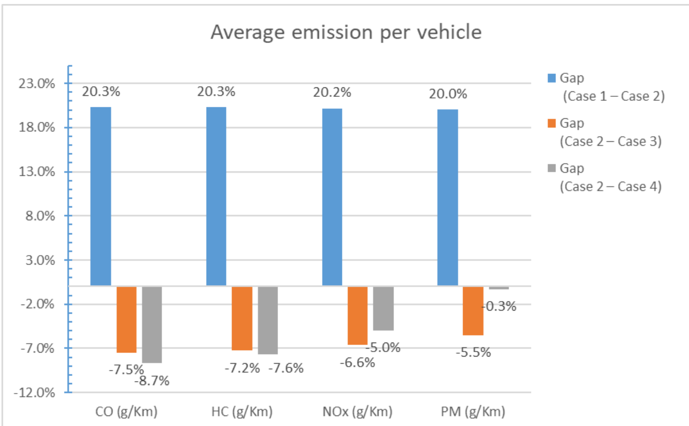


Figure 9: Average emission per vehicle in the first scenario

Given that transport resilience is directly related to environmental externalities, these exceptional improvements through smart transport systems can show to what extent such systems could contribute to the society and environment. The results from the second scenario are summarized in Table 4.

Table 4: Summary of findings from the second scenario

Scenario 2		**Case 1**	**Case 2**	**Gap (Case 1 – Case 2)**	**Case 3**	**Gap (Case 2 – Case 3)**	**Case 4**	**Gap (Case 2 – Case 4)**
Average delay per vehicle (Seconds)	SB-a	717.6	1,651.6	**934.0 (130.2%)**	1,472.1	**-179.5 (-10.9%)**	1,373.5	**-278.1 (-16.8%)**
	SB-b	479.4	549.4	**70.0 (14.6%)**	509.4	**-40.0 (-7.3%)**	497.1	**-52.3 (-9.5%)**
Total number of conflicts	SB-a	2,403	6,012	**3,609 (150.2%)**	4,933	**-1,079.0 (-17.9%)**	4,122.0	**-1,890.0 (-31.4%)**
	SB-b	130,293	140,221	**9,928 (7.6%)**	138,042	**-2179.0 (-1.6%)**	13,3009.0	**-7,212.0 (-5.1%)**
	Sum of SB	132,696	146,233	**13,537 (10%)**	142,975	**-3,258.0 (-2%)**	137,131	**-9,102.0 (-6.2%)**
Average emission per vehicle (g/km/vehicle)	CO (g/Km)	1,119.199	1,549.703	**430.503 (38.5%)**	1,257.128	**-292.6 (-18.9%)**	121.9	**-1,427.8 (-92.1%)**
	HC (g/Km)	30.077	41.611	**11.534 (38.3%)**	33.818	**-7.8 (-18.7%)**	32.7	**-8.9 (-21.5%)**
	NOx (g/Km)	95.137	131.336	**36.198 (38.0%)**	107.256	**-24.1 (-18.3%)**	103.8	**-27.5 (-20.9%)**
	PM (g/Km)	0.869	1.195	**0.326 (37.5%)**	0.984	**-0.2 (-17.7%)**	1.0	**-0.2 (-20.4%)**

Likewise, average delay per vehicle and total number of conflicts were notably increased up to 130.2% (SB-a) and 150.2% (SB-a), respectively, in Case 2. However, the reduction rates by smart transport systems in Case 3 and Case 4 struck the eyes in both the shortest and alternative routes: up to -16.8% (SB-a) and -9.5% (SB-b) in average delay per vehicle, and -31.4% (SB-a) and -5.1% (SB-b) in total number of conflicts. Note that the Case 4 results showed a higher decrease (almost doubled) in terms of both average delay per vehicle and total number of conflicts, compared to the Case 3 results.

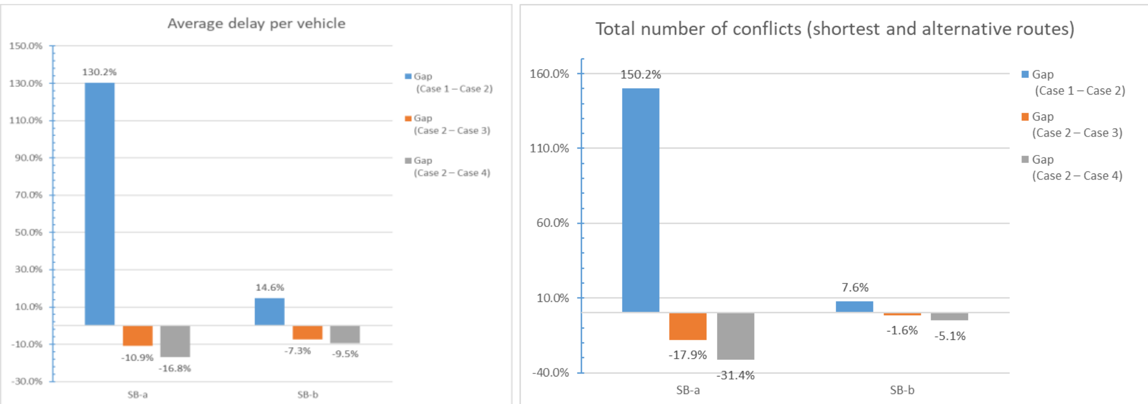


Figure 10: Average delay per vehicle and total number of conflicts in the second scenario

Looking into the average emission per vehicle, the road closure by the hurricane would noticeably result in increased emissions in a target area which was much higher than the one by the incident in the first scenario. Around 38% increase was observed in all aspects of emission-related elements, such as CO, HC, NOx and PM. Interestingly, the positive effects of smart transport systems to mitigate vehicle emissions were outstanding, which were 18.9% (Case 3) and 92.1% reductions (Case 4) for CO (g/km) at maximum. From the viewpoint of transport resilience, it is quite meaningful because limiting vehicle emissions from the transport sector is an essential element of building more resilient transport systems to climatic events. As shown in Figure 10, smart transport systems could cut down vehicle emissions at least by 17.7% when a particular negative event happens.

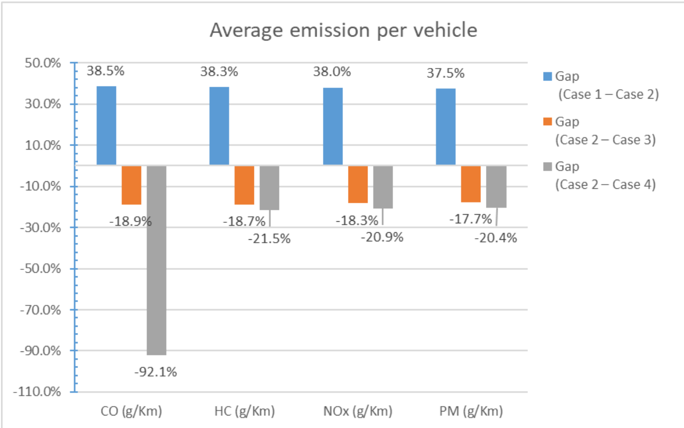


Figure 11: Average emission per vehicle in the second scenario

It was noted that comparing to the results from the first scenario, smart transport systems could contribute more to mitigate vehicle emissions which were caused by increased delays from the natural disaster (i.e., hurricane) (Figure 11). Given that damage to transport networks by natural disasters can comprise an important share of destruction in transport resilience, findings from the second scenario can encourage the use of smart transport systems to reinforce resilient transport systems.

8. CONCLUSION

Efficient transport systems are instrumental in enhancing resilience by meeting the demand for mobility and connectivity in a society. Existing transport systems are however vulnerable to climate change and extreme weather conditions. The vulnerability of transport systems can already be seen in the rise in traffic incidents and natural disasters around the world. At the same time, smart transport systems have increasingly gained attention as one of the feasible solutions to address such challenges. Yet, the supporting evidence is scarce with details lacking on the extent such systems can contribute to enhancing transport resilience.

In this regard, this research attempted to quantify the benefits of smart transport systems to transport resilience across the three dimensions of mobility, safety and sustainability. To replicate actual conditions in a real world, a simulation-based methodology was applied which assessed the impact of smart transport systems on traffic issues and natural disasters in given scenarios. Four smart transport systems, including traffic incident management, road weather management, pre-trip and en-route traveler information, were presumed to be used with two scenarios (four cases) to test their capability for transport resilience in a target area (Broward County, Florida, U.S.A). To sum up, the results revealed that the traffic incident and natural disaster seriously affected traffic conditions by increasing delays, traffic conflicts and vehicle emissions which could deteriorate the transport network resilience. After deploying smart transport systems, all cases showed a positive impact on the shortest paths to the destinations. Emphasizing on the effects for vehicle emissions which are directly linked to the environmental issues, the first scenario for traffic incidents showed a reduction of 7.5% (Case 3) and of 8.7% (Case 4) at maximum with smart transport systems. The impact from the second scenario was greater, which was 18.9% (Case 3) and 92.1% reductions (Case 4) at maximum. This is because there were fewer alternative routes in the second scenario where the impact of the natural disaster (i.e., hurricane) was greater while the positive effect due to smart transport systems was higher than the ones in the first scenario.

Although transport resilience may not be assessed only on the performance measures selected in this research, significant changes on these measures indicate that smart transport systems could help restore traffic conditions or at the least prevent situations from deteriorating. More importantly, given that reduced vehicle emissions could contribute to more resilient transport systems, such significant impacts on vehicle emissions are very meaningful. As found from one case, providing smart transport systems on the primary route might worsen the traffic situation on the alternative route because of increased traffic influx by detours. However, in spite of such case, an improvement to vehicle emissions in the overall transport network was found in both scenarios which strongly supports the critical role of smart transport systems for environmental issues. Such findings can be a good reference to apply smart transport systems for increasing transport resilience in cities or countries of the Asia-Pacific region which are vulnerable to traffic incidents with high crash rates and/or natural disasters like earthquakes or tsunami. This will be a cost-effective solution without significant infrastructure investment.

This research could be further enhanced with additional considerations. There was an assumption regarding the compliance rate of drivers by smart transport systems which was based on the previous research. However, given that traffic incidents and natural disasters have different influential areas and magnitudes of impacts, that assumption needs to be more customized as the compliance rate can vary by traffic conditions and the types of smart transport systems. Even though most effective applications of smart transport systems were employed in this research, other applications including emerging technologies (e.g., connected vehicles) can be considered to evaluate transport resilience to traffic incidents and natural disasters. In terms of the geographical size of a target area, it could be extended to the state or national level as transport networks are organically connected which will eventually affect overall transport resilience. In addition to quantifying delays, traffic conflicts and vehicle emissions, it would be valid if actual values to return to the normal state (i.e., recovery time) following traffic incidents or natural disasters are estimated. Technically, the approach would not be easy, but it would be of great interest to researchers and policy makers in this field. Lastly, although smart transport systems showed good results in increasing transport resilience in this research, the operation and maintenance costs for these systems need to be considered when adopted in cities or countries.

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