Physics-inspired strategies for understanding and optimizing transportation networks

by

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Statement of Originality

I, TAI, Tak Shing, hereby declare that I am the sole author of the thesis and the material presented in this thesis is my original work except those indicated in the acknowledgement. I further declare that I have followed the University's policies and regulations on Academic Honesty, Copyright and Plagiarism in writing the thesis and no material in this thesis has been submitted for a degree in this or other universities.

Abstract

Traffic congestion, which is caused by the increasing number of vehicles, occurs almost daily in urban areas. Owing to the limited space for road expansion, coordinated traffic routing is a better alternative to uncoordinated routing for reducing traffic congestion. In this study, we investigate the characteristics of traffic problems such as phase transitions from the free-flow state to the congested state and the effective dimension of systems, develop methods with random moves in routing to coordinate traffic flow and coordinate traffic flow in network with road blockage. We apply randomness in routing in a two-dimensional cellular automata model to try to sacrifice traveling distance of vehicles to maintain the free-flow state in transportation systems, which can maximize the movement count of vehicles. We then compare two different routing strategies, namely centralized/global routing strategies and individual/adaptive routing strategies, based on the randomness in routing in the model, to maximize the arrival count in the transportation systems. The results show that centralized routing strategies and less greedy routing strategies can be applied to denser networks to reduce traffic congestion. In other words, increasing the randomness in the routing can alleviate traffic congestion problems in denser networks. In addition, in our studies, the effective dimension of transportation systems is reduced from the perspective of physics when traffic congestion occurs. We also employ the cavity approach to obtain optimal diverted routes in networks with road blockage, where vehicles travel from different origins to a common destination. The proposed optimization algorithms for traffic diversion are tested in simulated networks such as random regular graphs with different connectivity and square lattices, and real networks to reveal their effectiveness. When some broken links exist in the networks accidentally, which block the connections between nodes, the results show that the influence of road blockage reduces with the coordination of traffic diversion because the increase in traveling cost can be suppressed. The increase in the connectivity of networks can also reduce the influence of road blockage since it increases the alternative routes for diversion. The coordinated traffic diversions are tested in UK highway networks and the results show that the increase in the traveling cost can be suppressed by up to 66%, compared with the diversions with shortest paths. These studies would help improve traffic coordination in the future, particularly with full driving automation.

Keywords: Statistical Physics, Cellular Automata, Randomness in Routing, Cavity Method, Traffic Diversion

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List of publications

This thesis is submited in the form of folio. The major results are included in the following articles, which are accepted or published in peer-reviewed journals.

1. Tai, T. S., & Yeung, C. H. (2019). Global benefit of randomness in individual routing on transportation networks. *Physical Review E, 100*(1), 012311.

2. Tai, T. S., & Yeung, C. H. (2021a). Optimally coordinated traffic diversion by statistical physics. *Physical Review E, 104*(2), 024311.

3. Tai, T. S., & Yeung, C. H. (2021b). Adaptive strategies for route selection en-route in transportation networks. *Chinese Journal of Physics*.

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List of Abbreviations

$n_{arrival}$	Arrival count of vehicles
CA	Cellular automata model
P	Consecutive steps of movement
ρ_c	Critical density of vehicles
ρ	Density of vehicles
ER (graph)	Erdős–Rényi random graph
g_{lower}	Lower bound of path-greediness
$n_{movement}$	Movement count of vehicles
$g_{optimal}$	Optimal value of path-greediness
g	Path-greediness
γ	Power of cost function
g_{upper}	Upper bound of path-greediness
Δg	Variation in path-greediness

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Chapter 1. Introduction

Traffic congestion is a severe problem among cosmopolitan cities, particularly in urban areas. The problem is deteriorating with the increase in the number of vehicles. The drivers involved in congestion are required to increase their journey time because they need to wait or drive the vehicles slowly. The traffic congestion problem remains unsolved notwithstanding the attempts of governments and researchers to solve it because a substantial amount of investment in infrastructure is required to expand the road capacity or redesign the traffic network. Furthermore, the network cannot be expanded in the denser areas of cities owing to the limited space there and over-expansion of road networks also damage environment (Laurance, et al., 2014). Many vehicles need to wait outside to enter cities. It is observed that the increases in traveling time and cost are influenced by the development of cities.

Many individuals have acknowledged the traffic congestion problems, and many studies have attempted to solve these. Different methods have been proposed to solve these problems, including economic measures. For example, in recent years, governments have proposed different schemes for charging cars that enter denser areas (Transport Department, 2009). There have also been many discussions on the effectiveness of different schemes. Strategies have been proposed to reduce traffic congestion (Wang, Szeto, Han, & Friesz, 2018; Yeung, Saad, & Wong, 2013). Because the strategies help coordinate the vehicles to travel on different routes, these prevent the routes from overloading. That is, these can reduce the likelihood of traffic congestion. The mitigation of traffic congestion helps reduce the journey time and thereby, the traveling cost. Therefore, traffic coordination, which is supposed to incur less expenses, is proposed to divert vehicles to different routes to mitigate congestion. In this article, we propose a traveling strategy. It is combined with methods in statistical physics in an attempt to solve traffic congestion problems.

1.1 Objectives

To study and understand the problems further, the project conducted different simulations and modeling to comprehend the transportation networks and optimize the traffic flow. The project has three objectives:

1. Construct transportation network models and apply routing strategies to study the critical points and phase transitions of traffic congestion.
2. Comprehend the effect of the expansion of road systems and the density of vehicles on transportation networks from macroscopic perspectives.
3. An algorithm is proposed to coordinate traffic flow to attain traffic equilibrium when there are incremental variations in the nodes and links in the transportation networks.

Before introducing the methods, we review the existing methods for solving the problem. The most direct method to reduce traffic congestion is to reduce the number of vehicles. Thus, the prohibition of certain vehicle types is recommended to reduce traffic congestion. The restriction on vehicles can be valid for the entire day or during peak hours. In China, certain vehicles (according to their license) are not permitted to travel on roads on all days (Chen, Zheng, Yin, & Liu, 2020; Pu, Yang, Liu, Chen, & Chen, 2015; Wang, Fu, & Chen, 2010). Because prohibition of certain vehicles may affect certain individuals who are required to use private cars, other methods that do not affect the existing vehicles have been proposed. Traffic diversion is one of the methods used to reduce traffic congestion. Because the vehicles in the network need to be only rerouted, diversion does not significantly affect most drivers unlike vehicle prohibition.

Different models have been recommended to study traffic problems. The interaction of different vehicles can be complex. Thus, the use of models helps individuals comprehend the microscopic and macroscopic behavior of transportation networks. The car-following model (Horn & Wang, 2018; Zeng & Zhang, 2016), cell transmission model (Sumalee, Zhong, Pan, & Szeto, 2011), Biham–Middleton–Levine model (Ding, Jiang, & Wang, 2011), and Nagel–Schreckenberg model (Bette, Habel, Emig, & Schreckenberg, 2017; Jia & Ma, 2011; Kanai, 2010; Liu, He, Luo, Yang, & Zhang, 2015; Simon & Gutowitz, 1998; Tomoeda, Yanagisawa, Imamura, & Nishinari, 2012) can be applied to different cases to study the interaction between different cars. The use of the model can help identify the difficulties caused by traffic problems because there are different types of problems such as lane changing, driving behavior, and road junctions. The solution can then be determined by varying certain quantities in the model, such as the car speed (Zeng & Zhang, 2016), density of cars (Horn & Wang, 2018), traffic light, and connectivity of different points. The Biham–Middleton–Levine model can be used to study dynamic traffic lights (Xie, Jiang, Ding, Li, & Wang, 2013).

The properties of traffic congestion can be identified using the traffic flow theory (Nagel K. , 1996). The formation of traffic congestion can be studied based on the speed and flow of vehicles in the network. The theory indicates that a critical density of vehicles can be determined, at which the vehicles can move freely in the network. Because the vehicle flow is an important criterion for identifying the critical point of the phase transition of the density of vehicles, the flow in networks is discussed in different transportation models. As a result, the discussion of traffic flow is common in transportation studies and a lot of materials are addressing the traffic flow theory (Daganzo C. F., 1997; Kerner B. S., 2004; Treiber & Kesting, 2013). Certain studies used the cellular automata model to study traffic flow. For example, Staffeldt and Hartmann (2019) characterized the flow distribution in a model. Most studies observed that 1) the flow increases with the density of vehicles and decreases beyond a certain density (Sun & Timofeyev, 2014), and 2) in general, the phase of the traffic model transits. Different phases were identified in these studies. For example, the state wherein vehicles move freely in the network is defined as free-flow state, and that wherein the movement of vehicles is restricted by other vehicles is defined as congested state. There have been many discussions on the difference between the free-flow and congested states. For example, Kerner (1997; 2013; 2019) studied the phase transition in the models and indicated that there are three phases in the flow, including a new state called synchronized flow state between the free-flow and congested states. Different studies have discussed phase transitions in traffic flow (Ding, Jiang, & Wang, 2011; Kanai, 2010; Toeh & Yong, 2018). There have been many discussions on the phase transition of traffic flows in highways and their ramp positions (Kerner B. , 2003; Kerner, Klenov, & Schreckenberg, 2011; Tian, Treiber, Ma, & Zhang, 2015). Some researchers recommended a mathematical calculation of the traffic flow in different states of flow (Siqueira, Peixoto, Wu, & Qian, 2016). Scheffer et al. (2009) indicated that there are precursors and signals before the phase transitions. Furthermore, some investigated the relationship between traffic flow and pedestrian density during pedestrian walking (Fujita, Feliciani, Yanagisawa, & Nishinari, 2019; Ma, Sun, Lee, & Yuen, 2018). Most studies show that there is a close relationship between flow and phase transitions and they observed bottlenecks to be one of the factors causing decrease in traffic flow, in addition to increase in vehicle density (Ezaki, Yanagisawa, & Nishinari, 2012; Heliövaara, Ehtamo, Helbing, & Korhonen, 2013; Parisi, Sornette, & Helbing, 2013).

The discussion on phase transition in transportation science is inconclusive because Kerner and Rehborn (1997) indicated that there should be phases of free flow, synchronized flow, and jamming, which constitute a three-phase system when we consider traffic flow. They first identified the phenomena on highways with on-ramp sites in Germany (Kerner & Rehborn, 1997). Subsequently, Kerner (1997; 2013; 2019) published a large number of papers to discuss this issue. Other studies also support this theory (Jin, Wang, Jiang, Zhang, & Wang, 2013; Kwak, Jo, Luttinen, & Kosonen, 2017; Shi & Wang, 2013). However, some researchers indicated that the system should have only two phases (free flow and jamming), thereby indicating that the traditional traffic flow theory is correct (Ezaki, Yanagisawa, & Nishinari, 2012; Hao, Jiang, Hu, Jia, & Wu, 2011; Tadaki, et al., 2013). Some researchers discussed whether the phase between free flow and jamming is stable to be observed or not because the metastable states may be observed before the critical density (Helbing & Huberman, 1998; Tadaki, et al., 2013). Kerner indicated that certain popular simulation tools such as VISSIM and SUMO may be unsuitable for studying traffic flow (Kerner B. S., 2013). The discussion on this phase is ongoing.

In addition to the discussion on phase transitions, the trajectory of vehicles is important for understanding transportation systems. Models can be used to study the trajectory of vehicles on highways (Newell, 2002; Sopasakis & Katsoulakis, 2016; Wei, et al., 2017). To further understand the transportation systems, different features such as multiple lanes were included in the models (Nagel, Wolf, Wagner, & Simon, 1998; Simon & Gutowitz, 1998). Moreover, some investigators proposed a two-dimensional model in which vehicles can move in two directions, to study congestion problems (Biham, Middleton, & Levine, 1992). We generally call this the Biham–Middleton–Levine traffic model. Unlike the one-dimensional cellular automata model, the two-dimensional cellular automata model can represent networks in urban areas because each four square lattice of the model is similar to an intersection of streets in the map (Sun & Timofeyev, 2014). As a result, many studies tended to formulate models in two dimensions, and investigated the flow of the model.

1.2 Development and examples of cellular automata models for traffic

In Chapter 2, we apply a model called the cellular automation (CA) model to simulate vehicle movement in a network. The cellular automation model has been studied in different fields. It was first developed by Neumann in 1951 to study biology (Maerivoet & Moor, 2005; Neumann, 1951). Wardrop (1952) introduced the concept of traffic assignment in the field of transportation, and Daganzo and Sheffi (1977) introduced the concept of stochastic user equilibrium to study traffic assignment. Nagel and Schreckenberg (1992) introduced a cellular automation model for traffic that is popular, and the latter journal paper cited it as the Nagel–Schreckenberg model based on the name of the editor. Daganzo (1994) introduced a cell transmission model, which is also popular as a traffic model. The model is discrete and is a commonly used model of statistical mechanics (Schreckenberg, Schadschneider, Nagel, & Ito, 1995). In 2005, Daganzo (2006) demonstrated that the traffic flow of the cellular automata model is identical to the traffic flow in both car-following model and kinematic wave model. The model has undergone many improvements over the years. In Table 1-1, a few examples show the use of the cellular automation model. The cellular automation model is widely used in different computer simulations of transportation networks.

Examples	References
Traffic signal control	(Castillo, et al., 2016; Kramer, Koehler, Fiore, & Da Luz, 2017; Placzek, 2013; Placzek, 2016)
Density estimation	(Chen, Guo, & Wang, 2017; Redeker, 2014)
Lane changing	(Habel & Schreckenberg, 2016; Li, Shao, Wu, Tian, & Zhang, 2016; Rassafi, Davoodnia, & Pourmoallem, 2012)
Driving behavior	(Guzmán, Lárraga, & Alvarez-Icaza, 2015; Xiao & Shi, 2015)
Pedestrian	(Bandini, Crociani, & Vizzari, 2017)
Bicycle	(Chen & Wang, 2016)
Bus lane	(Wu, Deng, Song, Wang, & Kong, 2017)

Table 1-1 Examples of application of cellular automata in transportation

In recent years, Kerner (2012; 2013) indicated that the model may not fully explain existing traffic problems. He recommended that the number of states in a traffic system be three (Kerner B. S., 2016). There are a few discussions on the transition from a free-flow state to a congested state. Further studies have been conducted by different researchers to determine the behavior of the system (Toeh & Yong, 2018). This chapter discusses the number of states in the transportation system.

The update rules of transportation models are generally important because these determine the interaction of vehicles in the models. For example, Watling, Rasmussen, Prato, and Nielsen (2018) recommended a model called the bounded choice model. It integrates the stochastic user equilibrium model and random utility theory framework, and introduces the probability of selection of routes. Some studies combined models with random variables. For example, Ding, Jiang, and Wang (2011) introduced a random update rule in the CA model, and Jabari and Liu (2012) introduced random vehicle time headways. The random update rules can help better understand the influence of the uncertainty of vehicle interaction. Hence, the number of options of routing paths can be increased when we design the routing strategies.

In Chapter 2, we observe how traffic conditions are affected by vehicle paths. We include a parameter called path-greediness, which helps vehicles select paths. The vehicle routes would vary with the values of path-greediness assigned to the vehicles. Specifically, we observe that the selection of routes can affect the traffic conditions of the networks. Thus, the incremental variations in the path-greediness of different vehicles can affect the traffic conditions of the network.

To further investigate how the movement of vehicles affects the overall transportation network, in Chapter 3, we examine how the responses of vehicles can alter the phase of transportation systems. The responses include individual instant responses and the system's response based on its data acquisition and processing. Instantaneous or real-time response in transportation is crucial because it can adapt to the traffic conditions and recommend an optimal solution for routing. The previous chapter and many research articles reveal that the use of optimized routes by vehicles can aid entire networks. Many good and cost-effective solutions for routing optimization exist. However, in reality, the traffic conditions may vary because of certain special events, and a few vehicles may not follow the recommended routes considering their individual losses. In addition, there are certain factors that are beyond the consideration of traffic coordination. Thus, the vehicles in the system can respond in real time to traffic conditions to address these problems. An individual vehicle can determine whether the current setting of route aids it. However, it is inconvenient to study real-time responses because these require a large amount of information including speed and flow. We observe that certain solutions for traffic-data usage and model formulation for studying responses can enable the achievement of better traffic coordination. For example, certain studies proposed the control of traffic lights to regulate the flow of vehicles. In these studies, the traffic light may be changed owing to the traffic conditions (Gholami, Andalibian, & Tian, 2016). This is called adaptive signal control. Signal control can directly affect the flow of vehicles because the flow can increase when a signal permits vehicles to pass, whereas the vehicles must wait when it does not permit passage. Hence, the use of signals can alter the traffic flow of vehicles. Lee, Wong, and Varaiya (2017) recommended signal-control logic to maximize the capacity of a network. Yu, Ma, and Zhang (2018) indicated that a solution with adaptive signal control can reduce the traveling time by 38%. Traffic light signals can be controlled to regulate a group of vehicles. However, there are few studies that provide an understanding of the response of individual vehicles. When we consider the response of vehicles, we observe that random adjustment may occasionally be affected by their original state. Certain studies revealed the presence of a hysteresis effect in a network of random graphs, whereas it was absent for square lattices (Böttcher, Luković, Nagler, & Herrmann , 2017). The hysteresis effect is imposed on the current state by the previous state. When it occurs, two systems with an identical parameter would be different because of the difference in history. As the traffic conditions may be highly complex, in Chapter 3, we test whether the original state causes any difference.

1.3 Methods of traffic coordination

Solving traffic congestion problems is important because traffic congestion has various effects. Different road users can have different routing strategies to reduce these problems, as mentioned in the previous chapter. In Chapter 4, a method is introduced to coordinate the routes in transportation systems, in addition to the routing strategies for individual drivers after road blockage. Traffic coordination involves the coordination of vehicles in transportation systems so that the vehicles can fully use the networks to reduce traffic congestion (Çolak, Lima, & González, 2016). Because a few traffic congestion problems are caused by the overflow of links, the coordination can reduce a part of the loading of the links to reduce the likelihood of traffic congestion (Pi & Qian, 2017; Spiliopoulou, Kontorinaki, Papamichail, & Papageorgiou, 2017). The coordination problem can be a multi-commodity flow problem (Holguín-veras & Patil, 2008). For a more effective study of the problems, we can consider different vehicles as sources and the destination of the vehicles as the sink nodes (Carvalho, Buzna, Just, Helbing, & Arrowsmith, 2012). The formulation of traffic models helps evaluate the effectiveness of different methods and strategies for routing. Furthermore, there are a few existing methods for optimizing the routes of vehicles. For example, the message-passing algorithm is one of the methods used to determine optimal flow solutions for optimization problems in routing. The algorithm generates a message in each link. The message stores flow information. When the messages from different links are used to calculate the state, we can obtain the global optimal values of the traffic flow of the links. With the optimal state of the links, we can assign optimal routes to different vehicles. Some studies applied the algorithm to random graphs (Altarelli, Braunstein, Dall'Asta, De Bacco, & Franz, 2015; Yeung & Saad, 2012). The algorithm originates from the studies of spin glass models or the Sherrington–Kirkpatrick model in statistical mechanics (Sherrington & Kirkpatrick, 1975). Mezard, Parisi, and Virasoro (1986) introduced the cavity method to solve the optimization problems. The minimum energy and ground states of the entire system can be obtained by the zero-temperature cavity method (Mézard & Parisi, 1987; Mézard & Parisi, 2003). These algorithms are similar to belief propagation, which was proposed by

Judea Pearl (1982). Both the cavity method and belief propagation are considered exact in tree networks. These are found to be applicable in loopy networks such as general graphs or random graphs (Bayati, et al., 2008). The results of the studies using these methods show that the optimal solutions of the problems can be obtained (Aurell & Mahmoudi, 2012). Furthermore, most of the results show that the coordination of neighboring nodes can reduce the system cost (Mézard & Zecchina, 2002; Yeung & Saad, 2012). Some researchers proposed a dynamic message-passing approach to solving dynamic resource allocation problems and compared Monte Carlo algorithms with message-passing algorithms in sparse random graphs (Lokhov & Saad, 2017; Angelini & Ricci-Tersenghi, 2019; Yeung, 2019). The results show that the message-passing approach is highly effective for calculating the optimal state of links.

The traffic coordination problem can also be considered as a problem of user equilibrium. In general, the user equilibrium state is defined as the state in which the travelers can travel with minimum cost. The state can be used to discuss whether the system can attain its optimal state for travelers. Different mathematical models have been developed to determine user equilibrium. For example, Some researchers recommended a mathematical model for dynamic user equilibrium (Friesz & Han, 2019; Yu, Ma, & Zhang, 2018; Zhu & Ukkusuri, 2017). The studies formulated the problem of minimizing the traveling time of all the drivers in systems. Thereby, the systems help understand their impact when all drivers consider traveling time as the first priority in the journey (Wei & Perugu, 2009). We can also observe that apart from traveling time, traffic flow or combinations of variables such as traveling time–traffic flow can be considered to attain traffic equilibrium (Han, Wang, Lo, Zhu, & Cai, 2017; Zhu & Ukkusuri, 2017). The discussion on the combination of multiple traffic variables can be considered as the traveling cost in the system.

In addition to the consideration of coordination cost, the setting of the model is important. The network structure is one of the important settings of the models. Different network structures or topologies were applied to study the movement of vehicles in the model. A model with the Erdős–Rényi random graph (ER graph) was applied to study the difference in terms of degree of distribution (Maier, 2019). Studies also compared the results obtained using different models with different structures. In a study to understand human assessment, a model applied a network of Erdős–Rényi random graph and square lattice with periodic boundary conditions (Jensen, Tischel, & Bornholdt, 2019). The results showed that models with different network structures generate different results. In addition, the square-lattice structure is also frequently used in different studies. We observe that unlike a random regular graph, the nodes in both square lattices are joined by their nearby nodes. That is, the connectivity of nodes is restricted by their geographical positions. Apart from the graphs, models of random graphs were applied to study phase transitions to find out the relationship between density and traffic load (Barankai, Fekete, & Vattay, 2012; Schrauth & Portela, 2019). Several studies used multilayer networks. Gao, Shu, Tang, Wang, and Gao (2019) recommended a multilayer network for reducing traffic congestion in Railway-Airline and Work-Facebook coupled networks. The concept of multilayer network helps explore the possibility of the relationship between interconnected networks (Domenico, Solé-Ribalta, Omodei, Gómez, & Arenas, 2015; Du, Zhou, Jusup, & Wang, 2016). We can observe that the model results vary across network structures and topologies.

Links in the network are also important elements because these connect all the nodes. A few studies were conducted on the links in networks. Network robustness can be discussed to determine whether the networks are connected effectively and whether networks can survive after attack or link failures (Calvert & Snelder, 2018; Hill & Braha, 2010; Shiraki & Kabashima, 2010; Trajanovski, Scellato, & Leontiadis, 2012; Wuellner, Roy, & D'Souza, 2010). In addition to the study on the links in networks, a few works studied the failure of links (Mieghem, et al., 2011; Liu, Wang, Lai, & Wang, 2012; Ozel, Sinopoli, & Yagan, 2018; Wu, Gu, Ji, & Stanley, 2019). The studies attempted to comprehend the consequences of removing links under cascading failures (Srivastava, Mitra, Ganguly, & Peruani, 2012). This is a common topic in the field of power grids because the removal of the links in a power grid may actually cause blackouts (Ozel, Sinopoli, & Yagan, 2018). Similarly, in transportation systems, when broken links exist, an ineffective diversion of traffic can result in traffic congestion. Hence, an understanding of the robustness of the links may be vital for reducing traffic congestion. Events apart from link failure may also cause traffic congestion. A study shows that an effective traffic diversion can reduce network delay by 21% (Zhou, 2008). Chapter 4 includes a discussion on links to illustrate how the transportation network is affected by the number of broken links. The stability of transportation systems is also important to traffic optimization. A model was used to study the failure of automotive vehicles (Vivek, Yanni, Yunker, & Silverberg, 2019). A system with vehicles that do not follow the optimization rules may cause disarray.

1.4 Research questions

To address these problems, we formulate the following four research questions before conducting the research:

1. How does the randomness in routing reduce traffic congestion?
2. Does traffic congestion show characteristics of phase transitions in terms of statistical physics, and what are the behavioral alterations at critical points?
3. How can the strategies be applied to transportation networks with road blockage to coordinate traffic, compared with existing optimization methods?
4. How can the recommended route diversion algorithms be applied to different types of

networks in the real world?

Certain quantities are commonly considered to compare the results of different studies on transportation systems. Traveling distance and traveling time were considered in the studies on routing problems because these quantities can be measured using both simulation and real data (Huang, Zhao, Woensel, & Gross, 2017; Spiliopoulou, Kontorinaki, Papamichail, & Papageorgiou, 2017). Furthermore, the trajectories and paths of vehicles can be measured to study the interaction of different vehicles in the networks. For example, Gschwend and Herrmann (2019) studied the difference between the shortest path and alternative paths. Some studies also compared the shortest path and the paths generated by optimization to determine the improvement in the methods (Ramasco, Lama, López, & Boettcher, 2010; Solon, Bunin, Chu, & Kardar, 2017). The traveling path is an important factor in determining the effectiveness of optimization methods. Moreover, many studies considered traveling cost as the most important quantity for optimization but the definition of the cost is different from research because the consideration of routing problems may differ. Some may consider the distance, number of lanes, and cost of fuel in the problems (Huang, Zhao, Woensel, & Gross, 2017). The traveling cost is also an important factor in optimization. The symbols and notations of some quantities of interest in the thesis are shown in 2.

Notation	Meaning	Formula
ρ	Density of vehicles	/
$\bar{v}$	Speed of vehicles	$\frac{1}{T-T_e}\frac{1}{N}\sum_{i=1}^{N}\eta_i^t$
$n_{arrival}$	Number of arrivals	/
f or $n_{movement}$	Flow or Number of movement	$\frac{1}{T-T_e}\sum_{t-T_e}^{T}\sum_{i=1}^{N}\eta_i^t$
Average journey/traveling distance		/
Average journey/traveling time		/

Table 1-2 Some quantities of interest

Optimization can be favorable to environmental sustainability because it can reduce the likelihood of traffic congestion, which, in turn, reduces the fuel consumption of vehicles on roads (Meneguette, et al., 2016; Wang, Szeto, Han, & Friesz, 2018). Both economic and emission costs can be reduced when traffic congestion is reduced since vehicles release pollutants and heat to the environment (Erdoğan & Miller-Hooks, 2012; Jabir, Panicker, & Sridharan, 2015; Zhu, Wong, Guilbert, & Chan, 2017). A study showed that the most important source of atmospheric nanocluster aerosols is traffic (Rönkkö, et al., 2017). Therefore, the application of optimization is vital for the environment. To further apply different algorithms, researchers proposed the green vehicle routing problem that helps enhance the consideration of environmental protection of routing problems (Erdoğan & Miller-Hooks, 2012; Montoya, Guéret, Mendoza, & Villegas, 2016). We can observe that traffic coordination helps protect the environment.

Some researchers compared the performance in terms of computational time consumed by computer. Li, Szeto, Long, and Shui (2016) compared the computation time of different methods for different network sizes. They determined that the variance of the result was reduced and that the computational time was shorter. Other studies compared the original methods with the modified newer methods and also identified the modified methods that are better in terms of computational time and reduction in variance (Wang, Chen, & Chen, 2018). A few researchers indicated that three quantities can be measured to determine the performance of different methods: the rate of the optimal solution, simulation time, and difference between the optimal and original solutions (Subramanyam, Wang, & Gounaris, 2018).

Research questions help develop the research. Furthermore, we provide insights into the solution in the subsequent chapters. The results of the three chapters also provide insight into routing strategies, including random update rules and traffic coordination. Both these mainly reduce traffic congestion, reduce traveling time and cost, and better utilize transportation networks. Specifically, in Chapter 2, the results focus on how the randomness in routing induces the reduction of traffic congestion and the features of the phase transitions of transportation systems. The results in Chapter 3 show that a new algorithm with adaptive routing strategies for coordinating the vehicles in a network can be more effective in the free-flow state. In Chapter 4, a method to divert traffic flow in the networks with road blockage is introduced. The results in Chapter 4 show that traffic coordination can reduce the increase in traveling costs when variations or accidents occur in networks. The chapter also shows how traffic diversion can be applied to England's highway networks. The discussion on different traffic quantities across the chapter illustrates how the recommended routing strategies aid transportation networks. The results of the following chapters are included in different manuscripts. Please read the following chapters.

Chapter 2.

Centralized strategies for individual routing: comprehension and implementation

2.1. Abstract

We introduce a simple model based on two-dimensional cellular automata to study the relationship between the interactions of individual vehicles in transportation networks. We characterize the routing strategies called path-greediness to evaluate the effect on the tendency of vehicles to travel through the shortest path to their destinations. The results show that the effective dimensions of transportation systems are reduced when traffic congestion occurs. The arrival count within a period decreases when the density of vehicles increases. However, the arrival count is larger when a marginal value of path-greediness is applied to each vehicle. This shows that the controlled strategies can coordinate vehicles and thereby, suppress traffic congestion. The adaptive routing strategies can outperform the controlled strategies only in the free-flow state and not in the congested state. Therefore, the use of controlled strategies and adaptive strategies is different across cases.

2.2. Publication

The work is included in the following manuscript:

Tai, T. S., & Yeung, C. H. (2019). Global benefit of randomness in individual routing on transportation networks. *Physical Review E, 100*(1), 012311.

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Chapter 3. Adaptive routing strategies in traffic models

3.1. Abstract

We further examine the effectiveness of adaptive strategies in different traffic parameter settings in transportation systems. In the two-dimensional cellular automata model, the path-greediness of each vehicle that are en route to destinations (introduced in Chapter 2) are updated based on the local traffic conditions. Vehicles attempt to determine the optimal routes and shorter paths to destinations. To prevent entry into a congested area, vehicles occasionally attempt to explore longer diverted paths. The results show that the optimal number of steps to induce an update of path-greediness and the magnitude of the increment in path-greediness depends on the density of vehicles, which also correspond to different states of traffic conditions. We also observe that the coordination of vehicles in denser networks should be gradual and the update of path greediness less frequent.

3.2. Publication

The work is included in the following manuscript:

Tai, T. S., & Yeung, C. H. (2021b). Adaptive strategies for route selection en-route in transportation networks. *Chinese Journal of Physics*.

First Author: Tai Tak Shing

Co-author: Yeung Chi Ho

Chapter 4. Implementation of message-passing algorithm in traffic diversion

4.1. Abstract

Certain special events on transportation networks, such as road accidents and maintenance, cause severe traffic congestion. Route diversions decided by drivers generally deteriorate the traffic condition because the route decisions are not coordinated. In this chapter, we employ the cavity approach/cavity method in statistical physics to obtain the results of the optimal solutions of diverted routes after road blockage. The results show that the traveling path, distance, and cost vary significantly when the number of blocked roads increases. We also observe that in certain cases, the overall traveling cost in a transportation network increases although the overall traveling distance in it decreases. We further examine the traffic diversion on networks with different topologies and connectivity. The results show that the number of alternative routes can generally play an important role in suppressing the increase in traveling cost when a road blockage occurs. To study the effectiveness of the diversion algorithm, we apply it to England's highway network. We observe that the algorithm can suppress the increase in traveling cost by 66% on an average.

4.2. Publication

The work is included in the following manuscript:

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Chapter 5. Discussion

This chapter includes a comparison of results and implication of the studies.

5.1 Why do we need traffic coordination?

The following is an important question: Do we need a traffic coordination scheme in daily life? The answer is yes since it can reduce traffic congestion problem. However, individual drivers do not need to consider whether their routing selection can aid the overall transportation system or not. Instead, individual drivers can follow the routes recommended by different navigation systems and trust that these routes are optimal for the transportation network because the traffic coordination considers the overall advantage of the transportation system (Youn, Gastner, & Jeong, 2008). Many advanced technology companies such as Google and Baidu are testing automated driving. Vehicle autonomy enables the vehicle's built-in system to replace humans to drive vehicles. According to the Society of Automotive Engineers (2016), there are six levels of vehicle autonomy. Full driving automation, where the vehicles do not require human involvement, is the ultimate objective of vehicle autonomy. We can consider that self-driving vehicles would be the most important components of transportation systems in the near future, rather human driven vehicles. Therefore, traffic coordination would become more important when self-driving vehicles dominate the transportation network. Furthermore, traffic coordination schemes consider the minimization of the overall traveling cost of transportation networks but a few vehicles may need to sacrifice their traveling time by adopting travel routes with longer distances according to the schemes. To maximize the efficiency of traffic coordination schemes, all vehicles are recommended to adopt the optimal routes, but it is difficult for certain vehicles to adopt the schemes because other better routing options exist for individuals (Po, Yeung, & Saad, 2021).

This is detrimental to the schemes because variations in a scheme can result in an increase in the overall traveling cost of the vehicles. The disobedience of traffic coordination from individual driver can be reduced when full vehicle autonomy implements. With the vehicle autonomy, the domination of self-driving vehicles can substantially reduce the probability that vehicles do not follow coordinated routes because the systems would control most of the vehicles in the networks, so variations in routes owing to self-centeredness would be prevented. Thereby, traffic coordination schemes would become more effective and, in turn, the advantage and importance of traffic coordination would increase.

5.2 How does traffic coordination aid our daily life?

When two or more vehicles from the same origin travel to the same destination, under traffic coordination schemes, the vehicles may divert to different routes to reduce the traffic flow on each link. Conventionally, the static information such as traveling distance and estimated time can be used to help drivers decide on the route, so highly experienced drivers such as taxi drivers, who drive almost daily, generally have experience of route selecting to prevent traffic congestion or adjust their speed to pass different traffic lights. Furthermore, with the advancements in technology, there has been an increase in the use of navigation systems such as Google Maps, which help a few new drivers to select routes. The navigation systems help drivers identify routes, and provide different real-time information such as the traffic flow or estimated traveling time in different sections of roads to help drivers decide on the best routes. For example, in Google Maps, when a driver enters the starting point and departure point, the application provides a recommended route as default, which it considers as the best. Moreover, the application also provides an alternative route to enable the driver to select when traffic conditions vary. Because the routes are different, the events during the journey can also differ (Izawa, Oliveira, Cajueiro, & Mello, 2017). The traffic coordination is useful for drivers but it is challenging to identify the best route until the vehicle arrives at the destination because traffic congestion or even accidents can occur abruptly during the journey (Wang, Mao, Li, Xiong, & Wang, 2015).

As mentioned earlier, traffic coordination schemes can reduce the impact of traffic congestion. When drivers drive their vehicles on roads, they tend to identify the shortest paths to minimize traveling time. However, it is evident from the results in Chapter 4 that the increase in traveling distance in the event of accidents is large, whereby the increase in traveling time is also large. To reduce this problem, we recommend that traffic coordination be applied to reduce traffic congestion and thereby, the impact of accidents. Traffic coordination can also reduce the overall traveling cost of the transportation system by diverting vehicles to different links. Diversion prevents the concentration of traffic flow on a few major routes. Thereby, the number of vehicles influenced by an accident can be reduced. The applicability of coordination schemes in real networks is evident from the fact that the solutions to traffic congestion are important for economic growth. For example, a study indicated that route optimization can increase network performance by 12% when the model is applied to an urban freeway (Haddad, Ramezani, & Geroliminis, 2013). In Chapter 4, we observe that the increase in traveling cost in networks with road blockage can be suppressed by 66% (Tai & Yeung, 2021a). Traffic coordination helps improve the efficiency of transportation systems. Moreover, cargo logistics is an important source of traffic load. Therefore, a few studies focused on investigations of the routing problems of trucks and the traveling time on the highways between airports and urban areas in Shanghai, Guangzhou, and Beijing, China (Huang, Zhao, Woensel, & Gross, 2017; Wang, Chen, & Chen, 2018; Zhong, et al., 2017). It is evident that in the future, when the demand for cargo logistics would increase, traffic coordination would become more important for diverting and coordinating traffic flow.

Moreover, the likelihood of stop-and-go traffic would reduce with full driving automation.

Many studies on adaptive signal control have been conducted in different networks. Adaptive signal controls reduce the waiting time and queue length by altering the time interval of the signal light at an intersection. This can reduce the traveling time of vehicles (Chacoma, Abramson, & Kuperman, 2021; Li, Jiang, & Wang, 2015). Full driving automation can further improve the optimization of traffic signals. The vehicles controlled by the systems can determine traffic conditions in real time and thereby, make more complex decisions. For example, when the system determines that the waiting queue exceeds the maximum number of vehicles permitted to pass through during the next green traffic light, these could divert the vehicles to other roads so as to reduce the waiting time substantially. In conventional navigation, the systems can only recommend paths that are theoretically the best for drivers because there is no interaction between vehicles. The disadvantage is that these paths can be overloaded when a group of vehicles abruptly travels on these. To better solve the problem, we can enhance the interaction between adaptive traffic signal control and traffic coordination to optimize the traveling paths of vehicles. The optimization can be extended to a group of traffic signal lights. Thus, global optimal solutions can be obtained by traffic coordination schemes. It can also aid long-range traveling. Long-range traveling always occurs in highways because of their large capacity and high speed limits. However, when adaptive traffic signal control is available, we may use non-highway roads as alternatives to divert traffic because the adaptive traffic signal can be controlled to permit vehicles to pass through long roads. Traffic coordination schemes can be more effective because there are more alternative routes (Tai & Yeung, 2021a). Furthermore, the estimated traveling time can be more accurate because the system can consider all the events in the journey. The traveling time, including the waiting times at signals, can be determined before the drive starts. It would aid all road users including drivers and passengers determine the traveling time and organize their work schedule.

5.3 Are there any improvements compared with existing methods?

The advantage of using the CA model is that it enables us to understand the interactions of each vehicle and the role of randomness in routing strategies. In the model, we generate all the vehicles that move in a certain large map, and the movement of vehicles is recorded to determine the traffic patterns. Traffic flow and traffic data aid us to improve certain optimization algorithms. In addition, the simulation helps us to identify unknown patterns in the transportation system. In Chapter 2 and Chapter 3, we introduce the transportation model. There are two routing strategies in the models: centralized and adaptive. We assign the adaptive cases with $\Delta g = 0.04$ and $P = 3$. We observe that in Chapter 3, the cases with $\Delta g = 0.04$ have a higher arrival count $n_{arrival}$ for most density of vehicles ρ, although $n_{arrival}$ is smaller in ρ_c. We also observe that the cases with $P = 3$ have a higher average performance in terms of $n_{arrival}$ than the other cases. We compare the two methods based on the differences in speed, journey distance, journey time, and $n_{arrival}$.

We observe that the arrival count of different cases is more effective for evaluating the performance of different strategies. In Chapter 2, it is highlighted that the cases with controlled path-greediness g have an optimal g for different vehicle densities. Because the optimal g of the models is different from ρ, we assign different values of g to test whether the cases have the highest value of $n_{arrivals}$. To examine the optimal g in the controlled cases, we determine the maximum value of $n_{arrival}$ by starting the cases with different g values, to narrow the possible range of ρ to obtain ρ_c. $g_{optimal}$ can then be obtained by determining the maximum value of $n_{arrival}$ between g_{lower} and g_{uppper}, since $n_{arrival}$ keep increasing when $\rho < \rho_c$. When the difference in $n_{arrival}$ value between g and g_{lower} is less than 1×10^4, we terminate the calculation and assign $g_{optimal} = g$.

Compared with the cases with controlled g, the cases with adaptive g have a higher arrival count $n_{arrival}$ when $\rho < 0.3$. However, we observe that when $\rho > 0.3$, the $n_{arrival}$ in the cases with adaptive g is smaller than that in the cases with controlled g where $g < 0.3$. Meanwhile, this value of g decreases when ρ increases. We observe that the value $\rho = 0.3$ occurs where the traffic conditions vary from a free-flow state to a congested state (Tai & Yeung, 2019). As a result, the cases with controlled g outperform the cases with adaptive g when $\rho > \rho_c$ and in the event of a congested state.

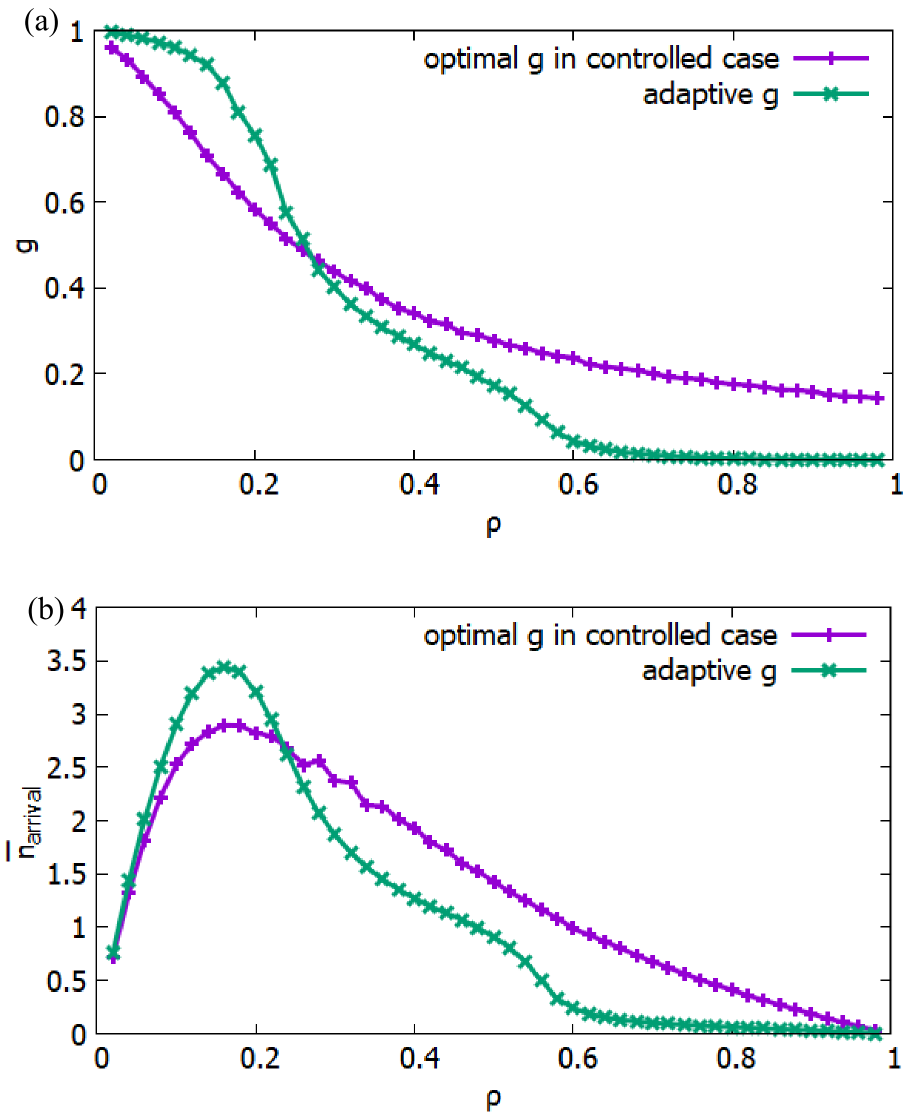

Figure 5-1 Simulation result of (a) path greediness g and (b) arrival count $\bar{n}_{arrival}$ as a function of density of vehicles ρ. The optimal g in the controlled cases is compared with the g in the cases with adaptive g. Source: Tai and Yeung (2019)

Figure 5-1 shows that both of the $n_{arrival}$ and the optimal g in the controlled cases decreases when ρ increases. The $n_{arrival}$ and optimal g in the cases with adaptive g also decreases when ρ increases. However, the rate of decrease is higher, particularly when $\rho > p_c$. In addition, we observe that for a large ρ such that $\rho > 0.3$ (which corresponds to the transition of the free-flow state to the congested state), the value of g in the controlled cases is relatively higher than that in the adaptive cases. The results in Chapter 3 also show that $n_{arrival}$with an optimal value of g in denser networks cannot be higher than that of vehicles with controlled g in denser networks. This indicates that the controlled cases have better coordination among vehicles in the denser networks because the $n_{arrival}$ here is larger than that in the adaptive cases (Tai & Yeung, 2021b). It is evident that the centralized routing strategies are significantly more important in denser networks, particularly for vehicles that are always self-interestedly driven by the shortest paths.

The coordination of diverted traffic can be complex since traffic networks can be large. In Chapter 4, we propose an algorithm for optimizing traffic diversion by simplifying the calculation of equation of cost function. The algorithm makes use of existing data in original networks to reduce the number of vehicles involved in the calculation. The results show that the average computation time can be reduced by approximately 80%, compared with using the original algorithm, in network with road blockage (Tai & Yeung, 2021a). That is an advantage to use our proposed algorithm to solve traffic diversion problems.

5.4 What are the differences between shortest paths and coordinated paths?

To evaluate the effectiveness of the routing strategies, we compare the differences in traveling distance between vehicles that travel by shortest paths and those that travel by coordinated paths, with the cost function $f(I_{il}) = I^{\gamma}$. The shortest path is a link that connects the origin and destination with the minimum distance. The vehicles generally travel on the shortest path because the journey time is generally minimum. For simplicity, in the cases of routing by shortest paths, we assume that all individual vehicles travel over the shortest distance. Therefore, when $\gamma = 1$, the routes become the shortest paths between the origin and destination. In the case of routing by coordinated paths, we formulate a cost function and minimize the traffic flow in each link. When $\gamma = 2$, the drivers tend to select different less-used routes because the increase in cost is significant while driving on the same routes. We attempt to minimize the traffic flow because in traffic flow theory, if a large number of vehicles use the links together, the links may be overloaded and cause traffic congestion. Therefore, we introduce traffic coordination to reduce the probability of overloading of the links and study how the traveling distance and cost vary in the coordination.

To study the effectiveness of the routing strategies, we examine the dependence of the average traveling distance in different routing strategies. The results of a previous study showed that for the London subway network, the average path obtained by coordinated paths to divert traffic flow is longer than that obtained by shortest paths by $5.8 \pm 0.1\%$ (Yeung, Saad, & Wong, 2013). Furthermore, the average cost obtained by coordinated paths to divert traffic flow is less than that obtained by the shortest paths by $20.5 \pm 0.5\%$ (Yeung, Saad, & Wong, 2013). To study the effectiveness of the routing strategies, we apply the algorithm to random regular graphs to obtain the average distance and average traveling cost by coordination and shortest-path routing. As shown in Figure 5-2, the average traveling distance for the cases where the vehicles travel by the shortest paths is shorter than that for the cases where the vehicles travel by the coordinated path with different ρ. On an average, the average path obtained by the coordinated paths is longer than that obtained by the shortest paths by $5.23 \pm 0.8\%$ in the cases with $k = 3$ and $4.83 \pm 0.5\%$ in the cases with $k = 4$. It is evident that the vehicles in the cases with coordinated routing strategies need to travel on longer paths to reduce the traffic flow in each link because certain vehicles may divert to longer paths to reduce the loading of links that are always occupied by a larger number of vehicles. Chapter 2, Chapter 3 and Chapter 4 illustrate that the traveling distance of vehicles when routing strategies are applied is longer than that of vehicles that travel on the shortest paths.

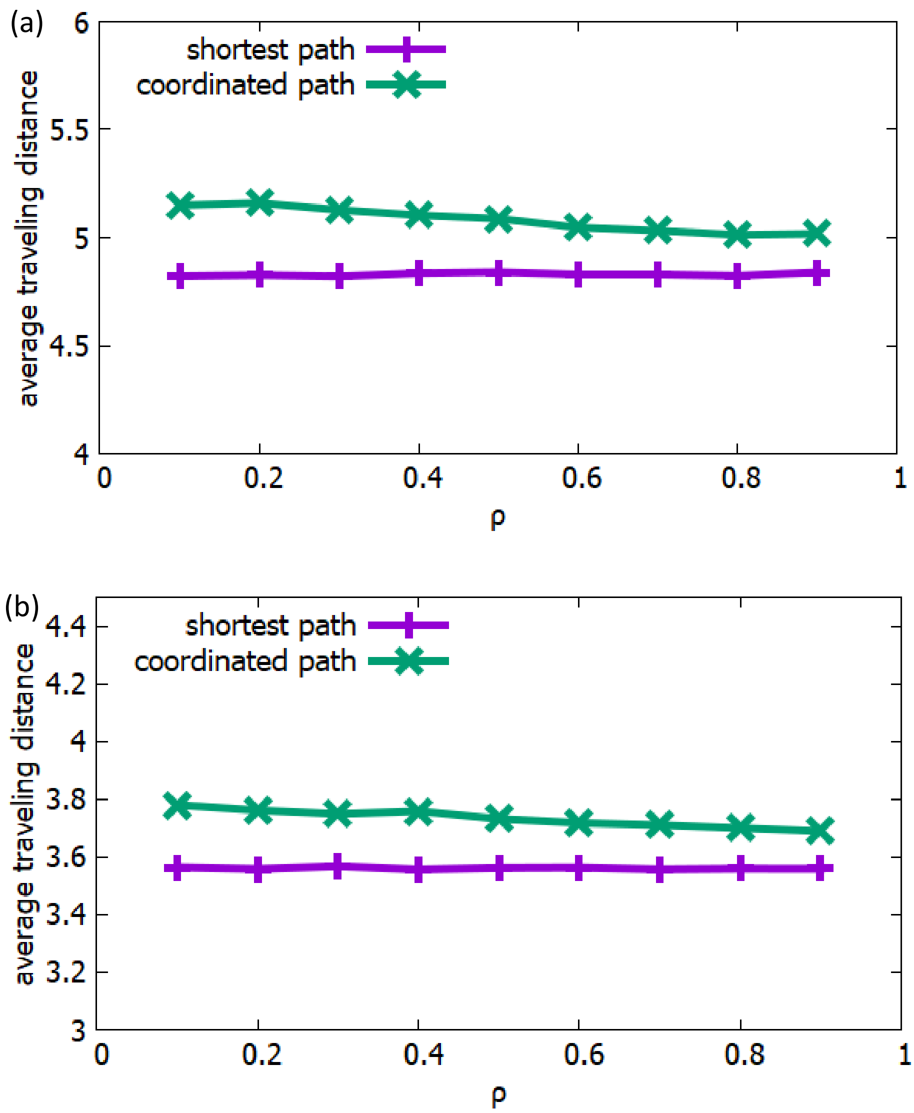

Figure 5-2 Simulation results of average traveling distance as a function of density of vehicles in the cases of coordination by shortest paths, compared with that in the cases of traffic coordination in the network with $N = 100$, (a) $k = 3$, (b) $k = 4$, and random graph averaged over 1000 instances.

We further examine the dependence of the average traveling cost on different strategies. As shown in Figure 5-3, the average traveling cost of the cases with the vehicles travelling the shortest paths is smaller than that of the cases with the vehicles travelling by the coordinated path for different ρ. On an average, the average traveling cost obtained by the coordinated paths is less than that obtained by the shortest paths by $13.4 \pm 2.84\%$ in the cases with $k = 3$ and $14.7 \pm 2.64\%$ in the cases with $k = 4$. It is evident that coordination can reduce the traveling cost of the network. From both Figure 5-2 and Figure 5-3, the average traveling distance in the cases involving traveling strategies that seek the shortest path is shorter. However, the average traveling cost is higher. This shows that the links in the network are more straightforwardly overloaded compared with the cases with traffic coordination schemes. Rather, with traffic coordination, the likelihood of traffic congestion reduces when the average number of vehicles per link decreases.

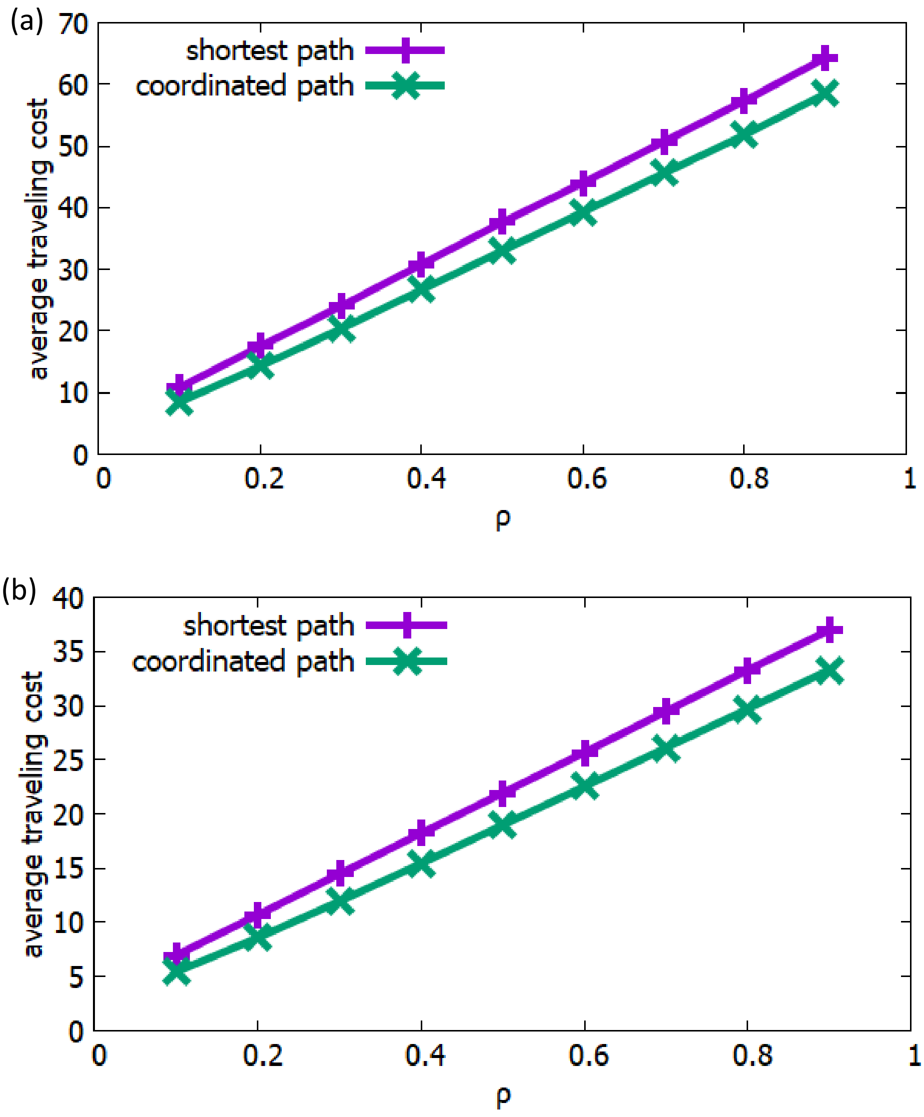

Figure 5-3 Simulation results of average traveling cost as a function of density of vehicles in the cases of coordination by shortest paths, compared with that in the cases of traffic coordination in the network with $N = 100$, (a) $k = 3$, (b) $k = 4$, and random graph averaged over 1000 instances.

We further test the traffic coordination scheme in popular traffic simulation software: SUMO. We created simulated networks and set speed limit of all links to be 50km/h. In network 1, as shown in Figure 5-4(a), three streams of traffic flow with 180 vehicle per hour (veh/hr) are converged in a mainstream so the influx of traffic flow is 540 veh/hr. In network 2, as shown in Figure 5-4(b), three streams of traffic flow are also converged in a mainstream but one of the streams are diverted to 2 sub-streams with 90 veh/hr while others keep constant. The results, as shown in Table 5-1, show that there is around 1.2% difference in traffic flow between network 1 and 2., using flow=density x velocity ($q = k\bar{v}$) and density = occupancy / default vehicle length (i.e. 5m). We can see the difference in the traffic flow is small and within the error. Since the networks may be simple so we may not see the advantages of coordination in the networks. We will go on to test in more realistic networks.

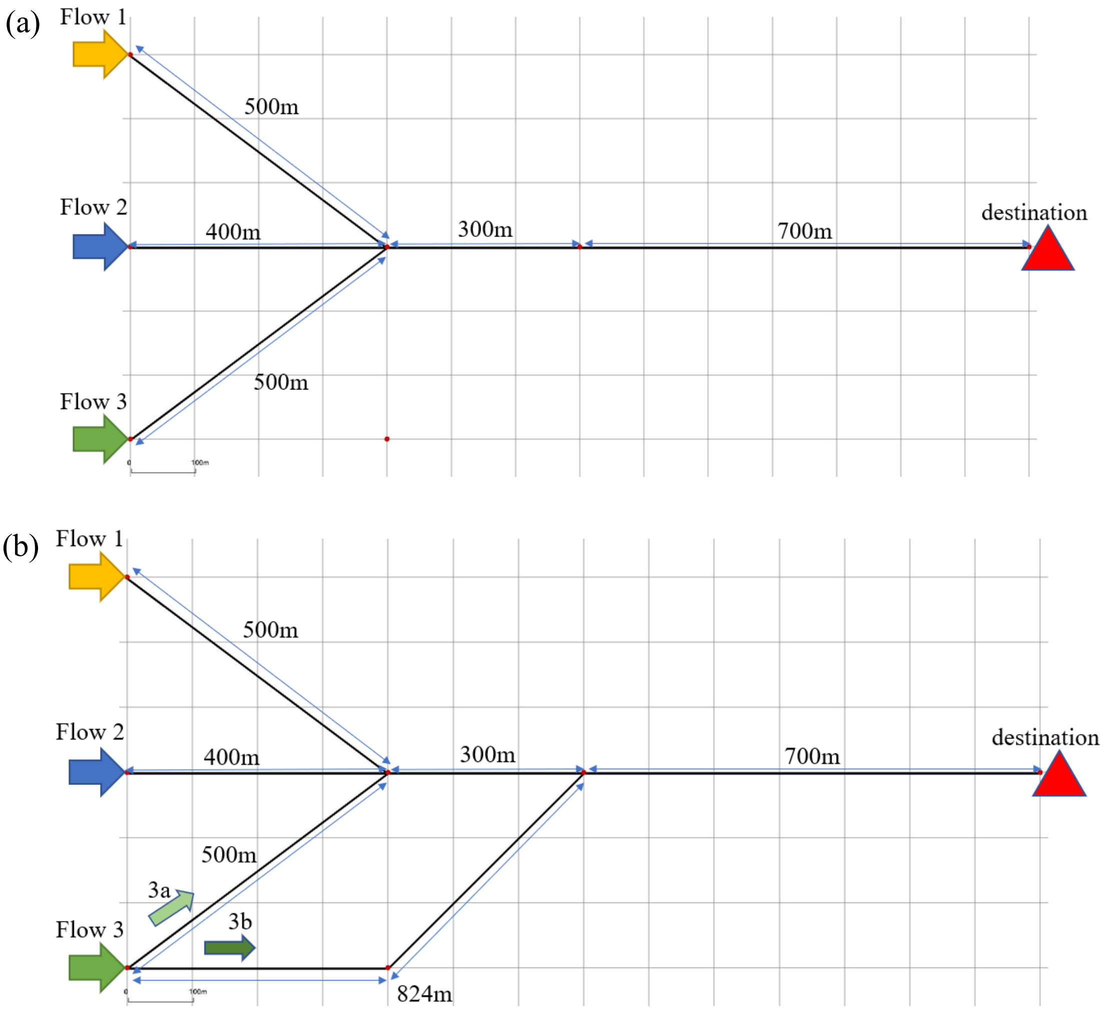

Figure 5-4 Simulated networks in SUMO, labelled as (a) Network 1 and (b) Network 2

	Mean speed	Occupancy	Flow (Estimated)
Network 1	12.40 m/s	0.0602	0.148825±0.002526 veh/s or 535.8± 9.09 veh/hr
Network 2	12.46 m/s	0.0594	0.147319±0.002309 veh/s or 530.3± 8.31 veh/hr

Table 5-1 Simulation results of Network 1 and 2 in SUMO. The results are recorded from the last 700m from the destination of the network and split 1-hour simulation into over 33 instances, where each instance is averaged the mean speed and occupancy within 100 seconds.

To determine whether traffic diversion helps reduce the likelihood of traffic congestion, we test the traffic coordination scheme in a real network. Because traffic congestion may be significantly related to the density of vehicles, we define different states in which the likelihood of traffic congestion is as follows:

Color	Definition
	Low probability of traffic congestion Medium probability of traffic congestion High probability of traffic congestion

Table 5-2 Probability of traffic congestion

We then demonstrate the effectiveness of traffic diversion on England's highway network. If we adjust the level of density of vehicles representing the probability of congestion in Table

5-2, we observe that several links near the congested links (highlighted in red) have higher traffic flow. As shown in Figure 5-5(a), in the original network, there is a long chain (highlighted by red) in the case with $\gamma = 1$. Therefore, severe traffic congestion is likely in those links. However, when we apply the traffic coordination scheme (i.e., the case with $\gamma = 2$), as shown in Figure 5-5(b), the traffic flow can be distributed to different links. This would substantially reduce the probability of traffic congestion. Furthermore, we set 40 links as broken links to determine how the traffic flow would vary. In Figure 5-6, we observe an increase in the number of broken links that enhance the probability of traffic congestion, in both the cases. The case with $\gamma = 1$ shows severe traffic congestion that is higher than that for the case with $\gamma = 2$. This can be verified by counting the number of red and yellow links. To summarize, the traffic coordination scheme can be effective in both original networks and networks with broken links.

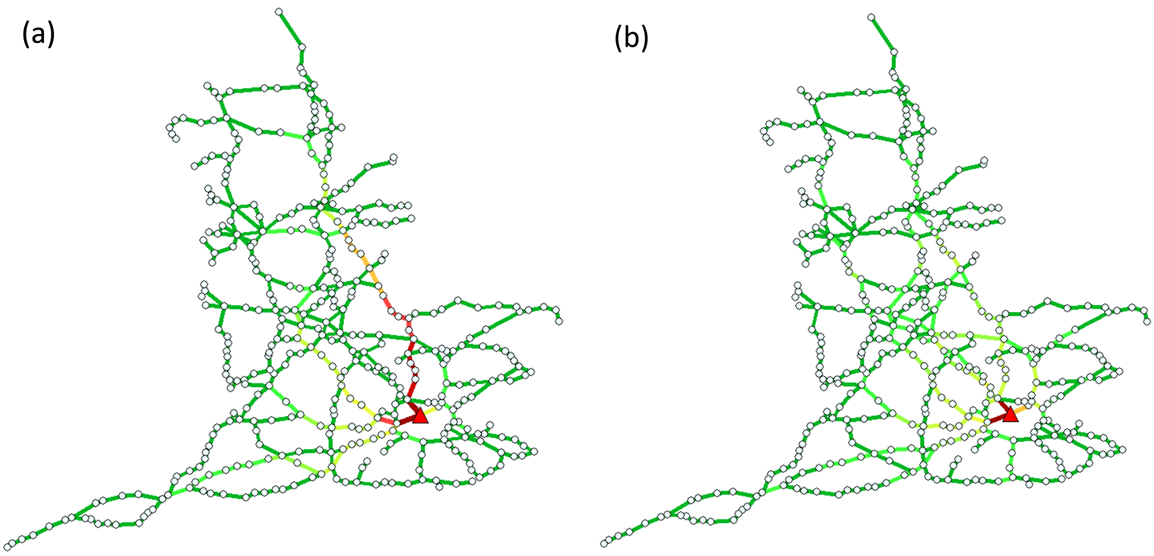

Figure 5-5 Traffic flow in the cases with (a) $\gamma = 1$ and (b) $\gamma = 2$ in the original network (i.e., B = 0). The case with $\gamma = 1$ is more likely to have traffic congestion in the network.

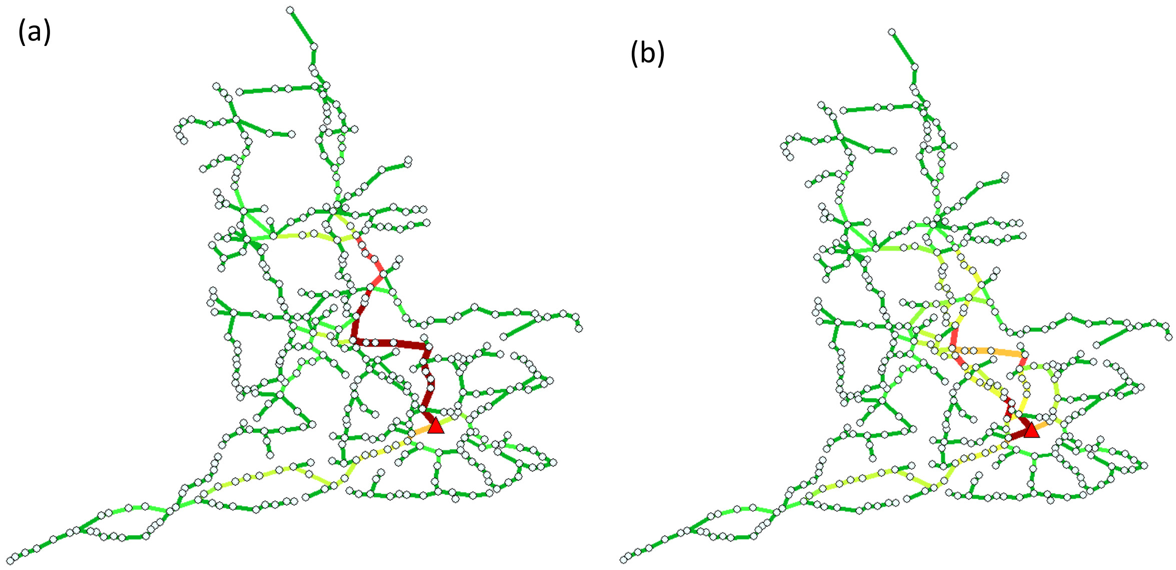

Figure 5-6 Traffic flow in the cases with (a) $\gamma = 1$ and (b) $\gamma = 2$ in the network with 40 broken links (i.e., B = 40). The case with $\gamma = 1$ has more severe traffic congestion in the network than the case with $\gamma = 2$.

Our results in Chapter 4 also show that the traffic diversion scheme can reduce the increase in traveling cost when several broken links are applied in the network, by approximately 60% (Tai & Yeung, 2021a). The application of traffic coordination in real networks would increase their resilience irrespective of their topologies.

5.5 Limitations

The algorithm is effective for solving routing problems. However, the cavity method originally solves the problems in networks with tree structures, but not loopy networks. Therefore, the solutions for loopy networks may not be determined (Ramezanpour & Moghimi-Araghi, 2015). In addition, we apply a small bias in all the links such that each link generates a highly marginal unique value. Therefore, when the messages of the links pass through the different links, marginal differences can be counted to ensure that the routes of individual vehicles are unique by eliminating the multiple solutions in the network (Mézard, Parisi, & Zecchina, 2002). With this improvement, we observe the convergence of the algorithm to be approximately 99.4%. This implies that solutions can be obtained for most of the problems. However, we observe that the convergence rate decreases when the network is a square lattice because the square lattice is a highly loopy network. To increase the convergence rate, we introduce another convergence criterion to examine whether the system converges. In most cases with a convergence rate of 99.4%, we use message convergences by testing the messages $E_{\mathrm{i}\to\mathrm{l}}^{\mathrm{V}}(I_{il})$ in Equation (14) or $\widetilde{\mathrm{E}}_{\mathrm{i}\to\mathrm{l}}^{\mathrm{V}}(I_{il})$ in Equation (17) within consecutive 10^2N steps (see Chapter 4). To increase the convergence rate, we implement another convergence criterion called path convergence by testing the I_{il}^* in Equation (15) and ΔI_{il}^* in Equation (19) within 10^3N consecutive steps in Chapter 4. The path convergence rate increases to 100%. However, there is an increase by 0.41% in the average optimal traveling cost. This implies that some of the solutions found by path convergence may be sub-optimal solutions. To continue the computation of the optimal solutions, we use message convergence as the criteria for convergence and forgo the convergence rate. The mystery of the cavity method for computing loopy networks would be one of the research directions in the future. Whether the messages in the loopy networks are randomly converged or whether only the messages in a few loopy networks can converge could be discussed.

The algorithm proposed in Chapter 4 is useful for coordinating traffic diversion. For algorithmic efficiency, the original method has already reduced the configuration space from 3^M to $2M+1$, by using the convexity of the cost functions (Yeung & Saad, 2012). We further narrow the space from M to Ω, where $\Omega \leq M$ when B is small in the networks with broken links (Tai & Yeung, 2021a). The proposed algorithm with Ω can take the advantage in the network with a few broken links, but it may not reduce the computational time in the networks with a large number of broken links.

Moreover, in our theoretical framework of Chapter 4, the joint distribution of $P[E^V(I), \tilde{E}^V(I)]$ has been taken into account in the diversion. The variable ΔI is obtained to show the changes of traffic flow before and after links are broken in the network. However, in our model, we cannot measure the time of recovery of traffic flow to understand how long the dynamic responses take. Since the theoretical frameworks we adopted for theoretical analyses and derivation of algorithms are originated from the study of the equilibrium state of spin glasses, and these frameworks cannot obtain the non-equilibrium or relaxation dynamics of the systems, we can only identify the final configurations of optimized traffic patterns, without the dynamics in between equilibrium states. In other words, we consider a steady flow originates from different nodes and find the optimal solution in the network, but there are no temporal records in the diversion. The model mainly focuses on the coordination of diversion in static routes.

5.6 Implications

In many studies, the density of vehicles is an important parameter. Discussions on the density of vehicles in transportation studies are frequent because the high density of vehicles is a key cause of traffic congestion. In these studies, we generally cannot directly prohibit vehicles from traveling in the networks because it is difficult to substantiate which vehicles are necessary to travel. Moreover, we generally assume the density of vehicles to be a fixed value because we attempt to reduce the traffic congestion during peak hours, which represents the maximum traffic flow in a certain period. Although the demand for traffic varies across time, the coordination of peak hour traffic is important in the traffic coordination scheme. Furthermore, the promotion of the use of public transport can also be a measure to reduce the number of vehicles (at least a few private cars) in the network and thereby, solve traffic congestion problems. The public transports may need to travel with fixed routes, which may not be beneficial to traffic coordination scheme since we cannot optimize their routes.

However, the optimization of the traffic would still be an important issue in transportation studies because public transportation modes such as buses or minibuses are parts of transportation networks and we can consider them in the coordination schemes in order to divert other transports. In addition to reducing the number of vehicles on the major routes in urban areas, the traveling paths of vehicles can be optimized to reduce the traffic flow on certain major routes. This would substantially reduce the probability of traffic congestion.

The number of alternative routes can determine how serious the problems are. In the CA model, each site is connected with four neighbors, showing that the vehicles in the site have at least one more direction to travel, and in Chapter 4, we can see that when the connectivity of networks increases, the impact of broken link reduces. The connectivity of the networks is vital to reduce traffic congestion problems. We can foresee that in the real network structures, both of the centralized traveling strategies or coordinated traffic diversion have the advantage when they are implemented in networks with more alternative diverted routes. However, the intersection of the real network is not always equal to four and probably less than four on average, the advantage of the centralized traveling strategies may become smaller. The centralized traveling strategies are still good in city streets' traffic since the intersections of the networks of city traffic is in degree four.

Meanwhile, the public wish to be informed whether capacity of transportation networks can be increased. We observe that one of the characteristics of peak hours in many cosmopolitan cities is traffic congestion. Cities have peak hours on almost all weekdays. Severe traffic congestion, which hinders the forward movement of vehicles, can cause a gridlock, wherein the vehicles are confined to a congested area because these lock each other. This is a severe error because no vehicle can leave the congested area because of the unavailability of space for vehicles to move. Therefore, the occurrence of gridlock is catastrophic if there is excessive delay in the identification of overcrowded traffic flow by commuters. However, we observe few gridlocks in reality. The first reason for this is that the police can control traffic manually. The involvement of the police can prevent a group of drivers from joining a congested cluster and thereby, prevent deterioration of the congestion problem. Second, drivers would circumvent travel to severely congested areas. Experienced drivers would be aware of the time and location wherein an area would experience traffic congestion because of peak hour traffic flow.

However, we observe that certain cases can cause a gridlock in the simulation. Gridlock would occur without human-induced corrections. We foresee self-driving vehicles occupying a significant share of the total number of vehicles in the network. The routing strategies would determine the routes of most vehicles. Are the routing strategies effective for preventing gridlock in the absence of human involvement? A model was used to study the failure of automotive vehicles in the network of Manhattan, New York (Vivek, Yanni, Yunker, & Silverberg, 2019). Although fully automotive vehicles can aid the transportation network, scientists should also consider abrupt failures of the transportation system and prepare a contingency plan for it. For example, Zhang et al. (2019) studied the scale-free traffic resilience of the networks of Beijing and Shenzhen, and Sumalee, Zhong, Pan, and Szeto (2011) applied the study of freeway flow in Los Angeles. The studies demonstrate the amount of additional traffic flow that a network can sustain. Moreover, it is more effective to convert the driving experience of frequent drivers into traveling strategies in transportation systems. Transportation systems can receive a substantial amount of information (such as vehicle queue) from the network by using different sensors. The information helps determine the routes of vehicles in the networks because we need to optimize the traffic flow in the network, which presently consists mostly of human drivers.

We anticipate that in the future, with full automation, all negligent driving behaviors including illegal parking, stoppages in restricted areas, violation of traffic light signals, and speeding, which impair transportation networks, can be reduced substantially. Traffic coordination schemes could become an important part of transportation systems and thereby, contribute to the development of cities.

Chapter 6. Conclusion

In this thesis, we study the optimization and coordination of transportation systems and networks. The cellular automata model is discussed in Chapter 2 and Chapter 3, and a mathematical model using the cavity method is discussed in Chapter 4.

In Chapter 2 and Chapter 3, the results of the two-dimensional cellular automata model show that the interaction of vehicles in transportation networks is vital for controlling traffic conditions. With the increase in the number of vehicles, transportation networks become crowded, and traffic congestion occurs. Chapter 2 illustrates that if we need to reduce traffic congestion, we can reduce the tendency to travel to the destinations of vehicles. That is, the vehicles can travel to the destination over longer paths, rather than the shortest paths, to reduce the probability of causing traffic congestion in the networks. Chapter 3 illustrates that individual routing strategies do not always favor transportation networks, particularly denser networks. This is because the arrival count in denser networks with decentralized routing strategies is less than that in networks with centralized routing strategies, as shown in Chapter 2. Therefore, different strategies should be applied based on the density of vehicles and the different states of transportation systems.

The traffic flow or movement of vehicles in the two-dimensional cellular automata model shows that there is a critical point in the increase in density of vehicles. At this point, the movement of vehicles decreases substantially. Thus, we can observe that the system transits from a free-flow state to a congested state. Furthermore, in the congested state, the effective number of dimensions is reduced to one. However, it is evident that the degree of freedom in free-flow states can be identical to that for the original number of dimensions because the rescaled movement count collapses at different parameters. Traffic congestion is accompanied by a phase transition.

Our physics-inspired message passing algorithm for coordinating diverted traffic in different type of graphs in Chapter 4 is one of the significant results. To study the effect of unforeseen road blockages in the networks, randomly selected links are disconnected. The disconnections represent road blockages. The incorporation of road blockages reveals that the routing strategies are critical to the reduction of traffic congestion because both traveling distance and cost are substantially higher in the absence of routing strategies. The number of broken links can affect the variation in traveling cost because more vehicles need to be diverted when there are more broken links. The results also show that when the connectivity of networks increases, the increase in the traveling cost because of broken links reduces. In addition, the network topology affects the increase in traveling cost depending on the number of alternative routes that can be generated from the networks. However, an increase in the traveling cost does not always increase the traveling distance. As shown in Chapter 4, certain cases show that the traveling distance of vehicles can decrease when road blockage occurs. Therefore, the optimal solutions for traveling cost may not be optimal for traveling distance. We also tested the algorithm in the UK highway network. The results in Chapter 4 show that the increase in traveling cost after road blockage can be suppressed by 66%. This shows that the resilience of the networks can be increased by routing strategies.

To conclude, we studied various approaches to suppress traffic congestion in this work. We formulated a two-dimensional cellular automata model to study the interaction between vehicles and to apply less greedy routing strategies to reduce traffic congestion. Moreover, we applied the cavity approach to random regular graphs and real networks to coordinate traffic flow with road blockage. The results show that traffic coordination can substantially reduce the increase in traveling cost after blockage. These methods and results help improve comprehension and enhance the development of traffic coordination, particularly for full driving automation in the future.

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