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# Effects of vehicle–pedestrian interaction and speed limit on traffic performance of intersections

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## HIGHLIGHTS

- Studied pedestrian–vehicle interaction and intersection rules.
- Discovered pedestrian interference on traffic efficiency, energy consumption and safety.
- Studied effects of road speed limit, arrival rates on traffic performance.
- Studied the relationship between traffic safety and efficiency.

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## ABSTRACT

The intersection model consisting of vehicle model, pedestrian model, pedestrian–vehicle interaction model and intersection rules has been presented in this paper. The well-established vehicle and pedestrian movement models in the literature are combined and applied to the intersection system with additional rules. Extensive numerical simulations with different scenarios are carried out. The effects of road speed limit, vehicle arrival rate, pedestrian regularity rate and vehicle rational rate on the intersection performance are quantitatively investigated. Three measures of the traffic performance are studied including transportation efficiency, energy economy and traffic safety. We have found that the energy economy can be achieved with the high transportation efficiency, and that the traffic safety is in conflict with the efficiency. Furthermore, we have found that the pedestrian interference makes the intersection performance worse, resulting in lower transportation efficiency, more energy consumptions and higher safety risk.



## 1. Introduction

As crucial nodes in the city traffic network, intersections have significant impact on the traffic performance. It is necessary to understand different traffic phenomena occurring at intersections in order to achieve transportation efficiency, potential economic and social benefits. Vehicle congestion and pedestrian interference at intersections significantly worsen the traffic performance, particularly in Asian cities with high population density. Over the past decades, a large body of literature has been devoted to the mixed traffic flow, most of which fall into two categories, i.e. mathematical programming approach and simulation-based approach. In order to consider the detailed traffic flow interactions, the simulation-based approach is preferred by many researchers. This paper presents a simulation-based study of vehicle–pedestrian interaction and its effect on traffic performance at intersections.

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Traffic simulations rely on mathematical models of various elements in the traffic system. Car-following models that describe how drivers follow the leading vehicle have been studied for more than half a century. Popular models include Gazis–Herman–Rothery (GHR) model [1,2], safety distance or collision avoidance model, linear Helly model, psychophysical or action point model, fuzzy logic-based model and optimal velocity model [3]. Pedestrian models have been developed to analyze the human behavior. Helbing and colleagues developed the social force model where pedestrians are modeled as particles with different diameters and velocities [4]. Henderson compared pedestrian flow with the model of fluid flow [5]. Cellular automata [6–8], lattice gas model [9,10] and artificial-intelligence-based models also provide accurate descriptions of pedestrian behavior.

A number of models of the interactions among different traffic participants including cars, buses, bicycles and pedestrians *etc.* have been developed [1,6,7,10]. Especially, the interactions between vehicles and pedestrians have received increasing attention in the past decade [11–14]. Shi and colleagues [15] investigated the pedestrian movement and traffic characteristics at an un-signalized mid-block crosswalk in a case study in Beijing, where the random crossing behaviors of pedestrians were involved. Li et al. [16] presented a study of variations of road safety, vehicle speed, fuel consumption and gas emissions due to random street crossings of pedestrians. Jiang et al. [17,18] studied the interactions between vehicles, large objects and pedestrians in a narrow channel with a lattice gas model, and investigated the traffic flow with pedestrians crossing the road [19]. They found that traffic flow is significantly affected by the crossing pedestrians, that lowers the road capacity.

While many studies have been carried out to investigate the vehicle and pedestrian movement, limited researches pay attention to the influence of different traffic variables in the intersection circumstance. In this paper, the well-established vehicle and pedestrian movement models in the literature are combined and applied to the intersection system with additional rules. The effects of different traffic variables, such as interactions between vehicles and pedestrians, road speed limit, vehicle arrival rate *etc.*, on the intersection performance are studied. In general, three categories in the traffic performance are focused on, i.e. road safety, energy economy and transportation efficiency.

(1) Road safety

Traffic safety at intersections is of significant importance to researchers. Intersections are responsible for 47% of all vehicle collisions in the United States in 2010. Signalized intersections accounted for 25% of total vehicles in collisions while unsignalized intersections accounted for 22% of total vehicles involved [20]. Conflicts between different participants in the traffic reduce road safety and result in extra traveling time. Among all kinds of conflicts, the vehicle–pedestrian interaction is considered as the most complex and important issue. Especially at large intersections, traffic performance suffers from the vehicle–pedestrian interaction, traffic signal, long crossing distance for pedestrians, large vehicle flow *etc.*

According to the driving convention in many places such as China, vehicles move on the right side of the road, that leads to high probability of vehicle–pedestrian emergency on the right-turn lanes at the intersection where the vehicles are not regulated by the signal and always allowed to turn right. Furthermore, signal noncompliance behaviors of pedestrians are common at intersections in China. Jiang et al. [21] found 37.07% of pedestrians not following the signal at several intersections in Beijing, China, that results in strong vehicle–pedestrian interactions especially in the right-turn lanes. Ni et al. [22] carried out a field study in Shanghai, China and found that the pedestrians violating signals accounted for 47% of all the total, 44% of the pedestrians who arrived during non-green-light time would cross, and 91% of the pedestrians arriving during flashing green preferred to enter the crosswalk rather than stay and wait for the signal to change green. Yang et al. [23] developed a model of pedestrians' noncompliance road crossing behavior in China with data extracted from videotape, where red light jumpers and violation followers of pedestrians were considered.

(2) Energy economy

Despite the rapid development in transportation system, energy crisis and atmospheric pollution are getting worse. The energy consumption in the transportation sector accounts for more than 27% of the total energy consumption in the US. Vehicles also contribute a lot to air pollution in urban areas [24] and are the source of over 40% of volatile organic compounds (VOC) and hydrocarbons (HC), more than 70% of nitrogen oxides ($NO_x$), and over 90% of the emissions of carbon monoxide (CO) in most European cities, for example. Since vehicle growth is mostly centered in cities, times for commuting and queuing at intersections have increased by multifold, that leads to more fuel consumption and gas emissions [25]. Particularly, vehicle queuing time has increased unprecedentedly at junctions, resulting in more wasted energy by vehicles in idle [26].

A metamodeling-based framework to explore the environment–mobility relationship at signalized intersections, involving experimental design, microscopic simulation and multivariate regression analysis was proposed by Guo et al. [27]. Vehicle fuel consumption and emissions have a close relationship with the driving modes. Rakha et al. [28] found that the vehicle fuel consumption and gas emissions increase significantly when a vehicle is forced to stop. The aggressiveness of braking also considerably makes the vehicle emissions increase. Extra fuel consumption and gas emissions result from the vehicles encountering road-crossing pedestrians when the vehicles have to decelerate to avoid collision and accelerate to the desired speed again afterwards. That leads to more switches of driving modes among cruising, accelerating, decelerating and idling, and consequently more energy consumptions.

(3) Transportation efficiency

Reducing transportation delays and improving traffic efficiency at signalized intersections has long been an imperative issue for researchers. In USA's cities, the congestion cost in 2011 (based on the wasted time and energy) was about $121 billion [29], and it is continuously increasing in the past years. Ji et al. [14] analyzed the traffic efficiency with