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Traffic signal control with partial grade separation for oversaturated conditions

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ABSTRACT

Increasing individual vehicular traffic is a major concern all around the world. This leads to more and more oversaturated intersections. Traffic signal control under oversaturated condition is a long-lasting challenge. To address this challenge thoroughly, this paper introduces grade separation at signalized intersections. A lane-based optimization model is developed for the integrated design of grade-separated lanes (e.g. tunnels), lane markings (e.g. left turns, through traffic, right turns, etc.) and signal timing settings. We take into account two types of lane configurations. One is conventional surface lanes controlled by signals, and the other is grade-separated lanes. This problem is formulated as a Mixed Integer Linear Program (MILP), and this can be solved using the regular branch-and-bound methods. The integer decision variables help in finding if the movement is on grade-separated or surface lanes, and also the successor functions to govern the order of signal display. The continuous variables include the assigned lane flow, common flow multiplier, cycle length, and start and duration of green for traffic movements and lanes. The optimized signal time settings and lane configurations are then represented in Vissim simulation. Numerical examples, along with a benefit-cost analysis show the good savings of the proposed optimization model for oversaturated traffic conditions. The benefit-cost ratio for installing 4 grade-separated lanes (as a tunnel) at a heavily oversaturated intersection (intersection capacity utilization rate equal to 1.57) exceeds 5.4.

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1. Introduction

The traffic congestion index has been growing steadily over the past 20 years in most of the urban and suburban areas of United States, according to the 2012 Urban Mobility report (Schrank et al., 2012). In 1982, the average personal delay was 16 h per year; by 2012 that figure had doubled, and the total delay for all travelers reached 38 h. The amount of fuel wasted due to the idling engines in traffic jams was 2.9 billion gallons, and the total cost due to traffic congestion was more than 121 billion dollars and nearly 820 dollars for each commuter. Consequently, there will be an increase in vehicle hour delay by a number of folds which will cause the decrease in the level of service even after adding new road lines. Traffic congestion mitigation has been the primary task of the federal, state, and local transportation agencies.

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Intersections are vital nodal points in a transportation network, and the efficiency of their traffic signal control greatly influences the entire network's performance. The evidence shows that more than 90% of the surface road congestion in an urban street network occurs at or near intersection areas. Traffic signal control is a fundamental element in the traffic control and management system and plays an important role in traffic operation and control. According to the Federal Highway Administration (FHWA), over 75% of the 350,000 traffic signals in the United States could be improved by updating the equipment or by simply adjusting the timing (Paulson, 2002). Retiming traffic signals alone can produce a benefit-cost ratio as high as 40–1. That is, for every $1 invested in optimizing the timing of traffic signals, $40 is returned to the public in time and fuel savings (Sunkari, 2004).

Traffic signal control under oversaturated conditions is a well-known challenging problem and has been studied over past decades (Gazis, 1964; Daganzo, 1996). However, very limited progress has been made for this challenge since the traffic demand exceeds intersection capacity too much in oversaturation. In this paper, the proposed solution to address this issue is to use grade separation. Grade separation increases roadway safety and mobility. The crossing traffic is removed from the intersection, thus eliminating the possibility of collisions between those streams of vehicles. Pedestrians are given greater protection from cars, as there will be only less number of traffic movements to cross and more refuge points can be provided at multiple locations. The Highway Safety Manual of American Association State Highway and Transportation Officials (AASHTO) reports that converting an at-grade, 4-leg intersection to a grade-separated interchange reduces injury crashes by 57%. Converting a signalized intersection into a grade-separated interchange reduces injury crashes by 28%.

Most importantly, intersections are a large cause of congestion on arterial streets. Signal time given to each direction dramatically decreases a road's capacity, increasing the possibility of congestion and queues. This planned stop-and-go condition greatly increases travel time for all drivers. Tunneling one of the streets will reduce the conflict caused by intersecting roadways. The reduced interference will increase the road capacity. Grade-separated intersections substantially increase capacity by eliminating delay caused by the previous intersection. Traffic moves freely, and any needed signal timing can be increased by the lack of a traditional intersection, as signals may only be necessary for accessing the exit and entrance ramps of the interchange. Removing at-grade intersections with heavy traffic substantially increases speed and throughput. Street traffic moves freely over interchange ramp or in tunnel, reducing wait times and increasing travel speed and capacity of the roadway.

In this paper, to mitigate oversaturated intersection while considering the cost of full grade separation, we resort to adding additional intersection capacity by introducing partial grade separation (PGS), which allows one or multiple lanes grade-separated from other surface lanes and prevents them from being controlled by signals. A typical PGS example is building a tunnel under intersections. In this case, the tunnel increases the throughput of the intersection permanently. Compared with traditional traffic signal control, signal control with PGS helps in smoothing traffic flow with fewer interruptions, achieving higher overall speeds, and also increasing the capacity of intersection by many folds. Further, we can adopt higher speed limits on grade-separated lanes. In addition, fewer conflicts between traffic movements reduce the risk of accidents. However, PGS will likely attract more volumes during peak hours. The demand elasticity of intersection design with PGS will be not considered in the scope of this paper. This paper aims to develop a mathematic model to design traffic signals with PGS and examine its long-term benefit.

The proposed partial grade separation (PGS) scheme has been widely implemented in practice (Meconstructionnews, 2016; Shin et al., 2008; Hughes et al., 2010). However, no prior research has systematically modeled traffic signal control for PGS. The practice lacks a systematic tool to both design the intersection lane markings and signal timing under PGS and to evaluate the benefit/cost ratio in order to determine when the decision should be made to invest additionally for PGS on existing intersection. To fill this gap, this paper models the problem using a mathematic formulation, proposes new parameters to be considered, and assesses the benefit gained from the grade separation.

Here this paper considers the design problem of a signalized intersection with PGS, which adopts both the traffic signal system and grade separation, as shown in Fig. 1. A partially grade-separated intersection would be more cost effective and also efficient than full grade separation. Except for grade-separated lanes, all other movements will be controlled by the sig-

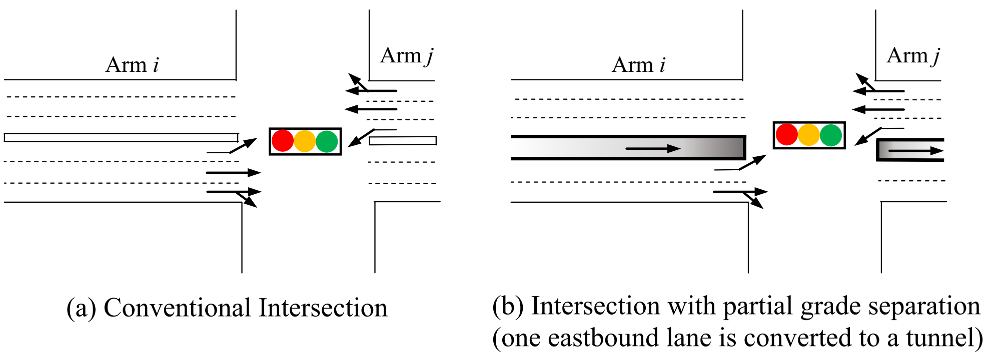

Fig. 1. Lane configuration with and without grade separation.

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