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Reducing transit bus emissions: Alternative fuels or traffic operations?

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HIGHLIGHTS

- We estimated the effects of alternative fuels and transit operations on emissions.
- Compressed natural gas (CNG) reduces GHG emissions compared to diesel.
- As congestion levels rise, the emission reductions associated with CNG improve.
- Transit signal priority (TSP) alone can reduce GHG emissions by 14%.
- The benefits of TSP decrease under "extreme" congestion.

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ABSTRACT

In this study, we simulated the operations and greenhouse gas (GHG) emissions of transit buses along a busy corridor and quantified the effects of two different fuels (conventional diesel and compressed natural gas) as well as a set of driving conditions on emissions. Results indicate that compressed natural gas (CNG) reduces GHG emissions by 8–12% compared to conventional diesel, this reduction could increase to 16% with high levels of traffic congestion. However, the benefits of switching from conventional diesel to CNG are less apparent when the road network is uncongested. We also investigated the effects of bus operations on emissions by applying several strategies such as transit signal priority (TSP), queue jumper lanes, and relocation of bus stops. Results show that in congested conditions, TSP alone can reduce GHG emissions by 14% and when combined with improved technology; a reduction of 23% is achieved. The reduction benefits are even more apparent when other transit operational improvements are combined with TSP. Finally a sensitivity analysis was performed to investigate the effect of operational improvements on emissions under varying levels of network congestion. We observe that under "extreme congestion", the benefits of TSP decrease.

1. Introduction

In most metropolitan areas, transit is often considered as a "greener" alternative to the private vehicle in light of its potential to reduce per passenger emissions of greenhouse gases (GHG) and air pollutants. It is important however to note that depending on their operations, technology, age and passenger loading; transit buses could be as polluting as private cars on a per passenger basis (Lau et al., 2012). It is therefore crucial to understand the determinants of transit bus emissions in a local context and evaluate the potential of improved operations and alternative technologies taking into account local traffic conditions and geographic characteristics of the urban area. Few studies have been conducted to date where bus transit emissions are simulated under the effects of alternative fuels and traffic operations simultaneously.

This study aims to quantify transit bus emissions under varying traffic operations as well as explore the effect of alternative technology. It evaluates whether significant emission reductions can be achieved through operational improvements alone as well as the potential of alternative technology under varying traffic conditions. Our research is set in Montreal, Canada where bus operations along a busy transit corridor are simulated in the northbound (NB) and southbound (SB) directions. Instantaneous bus speed profiles are then used to simulate emissions using USEPA's Motor Vehicle Emission Simulator (MOVES) fit with local input data describing the vehicle fleet and ambient conditions (USEPA, 2010a). We evaluate the effects of several transit improvement scenarios including transit signal priority (TSP), bus stop relocation, and queue jumper lane. We also simulate emissions for two different fuels: conventional diesel (currently used) as well as compressed natural gas

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(CNG). Finally, the combination of different fuels and transit operating conditions are compared and evaluated under various congestion levels. Emissions are estimated for GHG (in $CO_{2\text{-eq}}$) and fine particulate matter ($PM_{2.5}$).

2. Context

Existing research in transit bus emissions and performance has typically focused on two dimensions: studying the effects of alternative fuels and of bus operations.

While a breadth of research exists documenting the effects of various alternative fuels (e.g. biodiesel, CNG, LPG, hybrid), of most interest to this research is recent work on the potential of CNG. The principal component of CNG is methane (85–99%), but it may also contain ethane, propane, nitrogen, inert gases, hydrogen sulphide and water vapor (Weaver, 1989; Amrouche et al., 2012). As methane (CH_4) contains one carbon and four hydrogen atoms, the hydrogen/carbon ratio is high. On the other hand, gasoline (C_8H_{18}) and diesel ($C_{15}H_{32}$) have a lower hydrogen/carbon ratio (Semin et al., 2009). As CNG contains relatively less carbon in its chemical composition, it produces less CO_2 compared to diesel during the combustion process (Aslam et al., 2006). CNG also has a higher octane number in the range of 110–130, compared to 95 and 98 for gasoline and diesel respectively (Amrouche et al., 2012). A higher octane number indicates increased compression ratio and hence increased engine efficiency without knocking or denotation. Indeed, CNG is considered as one of the fuels with most potential for application in transit especially that buses operate along fixed routes and therefore, it becomes relatively easy to install refueling stations along the routes (Nylund et al., 2004). Wang et al. (2011) compared on-road emissions and fuel consumption of Euro III, Euro IV, and CNG buses and observed that emissions from CNG buses were lower than Euro IV diesel buses by 72.0% and 82.3% for nitrogen oxides (NO_x) and particulate matter (PM) respectively. Reductions were even higher compared with Euro III diesel buses with 75.2% and 96.3% for NO_x and PM respectively. Jayaratne et al. (2010) monitored exhaust emissions of CNG and ultra-low sulfur diesel buses on a chassis dynamometer. Emissions were measured under idle and steady state conditions with different engine loads at a fixed speed of 60 km/h. Carbon dioxide (CO_2) emissions of CNG buses were found to be lower than diesel buses by 20%–30%. However, emissions of NO_x did not show significant differences due to the large variation between buses. The benefits of using biomethane (bio-CNG) were examined by Ryan and Caulfield (2010) for a portion of the bus fleet in Dublin, Ireland. The authors found that converting from conventional diesel to bio-CNG would reduce emissions of CO_2, carbon monoxide (CO), $PM_{2.5}$, PM_{10} and NO_x by 64%, 71%, 87%, 77% and 87% respectively. Genovese et al. (2011) experimented with a hydrogen-natural gas (HCNG) blend on CNG buses. The authors compared energy and emissions of CNG buses when fueled with HCNG blends with different percentages of hydrogen (5%, 10%, 15%, 20% and 25% by volume). They observed (1) improved energy efficiency in urban driving due to higher hydrogen content in the fuel and (2) significant reduction of CO_2, CO and NO_x emissions.

Three operational strategies with potential to reduce transit emissions are evaluated in this paper: Transit signal priority (TSP), queue jumper lanes, and bus stop location. While a breadth of research has been conducted to evaluate TSP, the results remain inconclusive. TSP is an operational strategy that provides priority to transit vehicles so that they can pass an intersection easily. Detectors are used to sense the presence of the bus and concurrent actions are followed to give the green phase to the bus. The most quantified benefit of TSP includes reduced travel time by minimizing delay at intersections (Sunkari et al., 1995; Baker et al., 2002). This potentially translates to reducing drivers' workload, fuel consumption, emissions, and maintenance costs (Wang et al., 2008). Rakha and Zhang (2004) identified the impacts of TSP on a signalized intersection and concluded that (1) it provides benefits to transit vehicles, (2) at low level demand, it provides marginal benefits to the whole network, (3) the system wide impact of TSP is directly proportional to transit frequency, (4) benefits depend largely on the base signal timing plan and (5) near-side bus stop location has significant impacts on the TSP benefits. Dion et al. (2004) quantified the benefits of TSP in terms of delay and emissions and found that emission reductions of hydrocarbons (HC), CO and NO_x are not significant. The study concluded that vehicle emissions are not only a function of vehicle stops and travel time, but also of the individual driver behavior and variability of travel speeds. Finally it was observed that TSP can become ineffective during peak hours as the buses are not able to cross the signal due to longer queue lengths at intersections (Balke et al., 2000; Head, 1998; Nowline and Fitzpztrick, 1997).

As transit buses emit high amounts of pollutants while idling, queue jumper lanes are another strategy which entails a short stretch of a special lane (such as right turning lane) near an intersection so that buses can bypass the waiting queue. Zhou (2009) evaluated the performance of jumper lanes with TSP under various traffic volumes and bus stop locations and found that the jumper lane TSP can reduce bus delays by 3–17 percent compared to a mixed-lane TSP with a far-side bus stop. The reduction benefit becomes higher when the traffic volume on the street increases.

Finally, the locations of bus stops potentially affect delays, travel time, and emissions. Often, bus stops are located at far-side (downstream of the intersection), at near-side (before the intersection) and at mid-block (between two intersections). When a bus approaches a bus stop three actions are completed: deceleration, dwell, and acceleration; bus emissions during these events are high. Saka (2003) conducted a study to examine the effect of bus stop spacing on emissions in urban areas and suggested an optimal spacing of 700–800 m. However, the study could not detect any plausible association between bus stop location and emissions. Recently, Li et al. (2012) observed that in the case of a far-side stop, if the bus receives red light while approaching an intersection, the emissions could be increased by 100%, and the emissions at a near-side location could be reduced by using intelligent transportation systems (ITS).

3. Description of the study corridor

The study corridor is called the Cote-des-Neiges (CDN) corridor situated in the Cote-des-Neiges/Notre-Dame-de-Grace and Ville-Marie boroughs in Montreal. It runs North-South with respect to the downtown (located south of the corridor). The length of the corridor is about 5.1 km with various grades ranging from −17% to +8%. The corridor has a high frequency of buses (4–5 min) during peak periods compared to other routes and it has one of the highest transit ridership in Montreal making it a candidate for infrastructure or operational improvements by the transit operator. It has significant differences in traffic flow between the northbound (NB) and southbound (SB) directions as well as between morning and afternoon peak periods. As such, the high passenger ridership, frequent bus service, and distinct directional traffic flow make it an ideal corridor for scenario analysis using a traffic simulation model. Moreover, our study corridor has a total of 64 links with different levels of traffic congestion and grade. Combining both directions, we observe a significant variability in link congestion levels with average speeds ranging between 1.11 mph and 17.74 mph.

Three buses operate along the corridor (1) route 165 that runs during the day, (2) route 369 that follows a night schedule and (3) route 435 that operates only during peak periods on weekdays. In