Effect of Bus-Stop Spacing on Mobile Emissions in Urban Areas

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ABSTRACT

The operational effect of bus-stop spacing has been a critical issue. Closely spaced bus stops disrupt the traffic flow on the bus route, particularly during peak hours because buses make frequent stops to provide services to customers. The disruption of traffic flow results in energy loss, increased delay/congestion, transit fleet-size requirement and mobile emissions. This paper describes a set of analytical models developed to assess the effect of bus-stop spacing on travel time and mobile emissions in urban areas. It is hypothesized that mobile emissions in urban areas can be significantly reduced if excessive transit-related stops are minimized through optimal spacing of bus stops. As part of the study, a nationwide survey of transit agencies was conducted to determine the prevalent bus-stop spacing policy in urban areas. The survey results show that the average bus stop spacing was approximately 330 meters (m), which is much less than the optimal threshold of approximately 700 m to 800 m obtained from the models described here. The analysis shows that for a typical bus route in an urban area, the peak hourly reduction in mobile emissions from optimal spacing of bus stops is not considered substantial for hydrocarbon, Nitrogen oxides, and carbon monoxide, which actually increased. A substantial reduction was observed for carbon dioxide and fuel consumption. However, for major urban areas with several bus routes, the aggregate system-wide impact for the combined morning and afternoon peak hours is expected to be substantial also for hydrocarbon and nitrogen oxides.

INTRODUCTION

As the federal government's regulations to protect the environment intensify and as transportation funding becomes increasingly competitive, transportation operational issues have been receiving a high level of attention from transportation professionals and decision-makers. The classical operational issues include congestion mitigation, travel-time reduction, air-quality improvement, reduction of operating costs, and safety improvement. Conformance to one or more of these operational issues is a requirement for receiving most transportation-related federal funding.

Public transit is widely considered as being environmentally friendly because of its high loading capacity. The number of passengers carried by a typical bus in some urban areas can exceed the equivalent of 40 passenger cars during rush hours. In most urban areas of the United States buses share the same rights-of-way with other vehicles (namely passenger cars, trucks and motorcycles). Buses are known to make frequent stops, particularly during peak hours, to provide services to transit patrons. As buses stop at designated transit stops, they also impede the flow of traffic, which depending on the traffic intensity can result in congestion and excessive emission of air pollutants on the bus route.

Frequent stops are also costly to the transit operators because travel times are increased, as is the fleet size requirement to sustain the policy headway. Conversely, when bus stops are distantly spaced to avert the problems associated with closely spaced stops, the transit-operators risk providing inaccessible services, which may lead to loss of patrons. Transit operators face the challenging task of increasing fare-box revenue to offset operating deficits. As an effort to encourage transit patronage by providing highly accessible bus services, transit operators typically provide too many stops, particularly at high-density land use locations, which sometimes are counter-productive. Like poorly timed or coordinated traffic signals, overly close bus-stop spacing engenders frequent stops and excessive delay of traffic, resulting in high mobile emissions and vehicle operating costs.

Hypothesis

It is hypothesized here that a significant reduction of mobile emissions can be achieved through proper spacing of bus stops in urban areas.

Nationwide Survey on Bus Stop Spacing

As part of the effort to estimate the operational benefit of optimizing bus stop spacing, a nationwide survey of transit agencies in urban areas was conducted to determine the prevalent bus-stop spacing policy. The summary of the survey results is shown in Table 1. It should be noted that the results of the bus-stop spacing survey, summarized in Table 1, are probably biased because the majority of the responses received came from the western, mid-western, and southern parts of the U.S. Nationwide surveys with adequate representation of the northeastern urban areas (which are the most congested regions of the U.S.) may result in much lower thresholds of average bus-stop spacing than was presented in Table

1. In the City of Baltimore, for example, the average bus stop spacing in some predominantly high-density land use locations was determined to be approximately 160 m.

Using assumed benchmark average bus-stop spacing, a sensitivity analysis was undertaken to estimate the reduction of mobile emissions attributed to optimal spacing of bus stops.

Past Studies

Most of the past studies (1, 2, 3, and 4) on bus stop spacing were implicitly based on the assumption that buses operate on exclusive rights-of-way without interference from other traffic. In addition, the studies focused primarily on determining the optimum spacing of transit-stops resulting in minimized expected cost (including passengers' incurred, and system operating cost). There is no known effort of investigating the potential air-quality benefit of optimizing the spacing of bus stops in urban areas.

STUDY OBJECTIVES

The primary objectives of the study described here are:

(1) To develop a set of models, which can be used as a decision-support tool to determine an optimum threshold for bus-stop spacing in urban areas,

(2) To assess the effectiveness of reducing mobile emissions by optimally spacing bus stops in urban areas, and

(3) To estimate other operational benefits (including reduction in transit-travel time and fleet-size requirement) associated with optimal spacing of bus stops.

MODEL DEVELOPMENT

The model development discussed is based on the following assumptions (some of which are intuitive):

- Buses share the same rights-of-way with passenger cars.
- Merging and lane-change maneuvers are made during the first available safe gap (i.e., a gap greater than the specified critical gap).
- Demand for service at bus stops and the arrival of vehicular traffic on the bus routes can be reasonably represented by the Poisson probability distribution.
- Transit patrons are more interested in minimizing their overall trip time than their out-of-vehicle travel time.
- Transit patrons are more sensitive to out-of-vehicle travel time than in-vehicle travel time.
- Buses stop at designated bus stops only when there is demand for service (boarding or alighting).
- Separate transition lanes are provided at bus stops to enable buses to render services without directly interfering with the through traffic flow. Buses interfere with the through traffic only during deceleration and acceleration from stopping and merging maneuvers, respectively, at designated bus stops. Figure 1 depicts the roadway configuration assumed.
- For every service-related stop, buses decelerate uniformly from cruise speed to a complete stop, open doors, provide service, close doors, accept the first available safe gap to merge into the mainline traffic, and accelerate uniformly to cruise speed as depicted in Figure 2.

Modeling Framework

The modeling process comprises four major steps:

- Estimation of bus-related stops for specified operating conditions
- Estimation of non-transit vehicles affected by bus-related stops
- Estimation of mobile emissions directly associated with bus-related stops
- Estimation of potential reduction of mobile emissions from optimized bus stop spacing.

Estimation of Bus-related Stops

The hourly number of bus-service related stops on the bus route is dependent upon the policy headway, the hourly demand for bus service and the number of designated bus stops on the bus route, and it can be calculated as:

$$\eta_b = q_b \rho_s (N_s + 1) \tag{1a}$$

$$\rho_s = 1 - [\exp(-\lambda_b)]^2) \tag{1b}$$

$$f = 60/h \tag{1c}$$

$$\lambda_b = Q_b/[(f)(N_s + N_{s,c} + 1)] \tag{1d}$$

where

η_b = expected hourly number of stops made by buses at designated stops,
q_b = hourly volume of buses on bus route (expressed in buses/hour),
ρ_s = probability of stopping at designated bus stops,
N_s = total number of designated bus stops (excluding terminals) on bus route,
λ_b = average hourly demand (boarding or alighting) per stop for the operating headway,
Q_b = Total hourly demand for bus service on bus route (expressed in passengers/hour),
f = service frequency (expressed in buses/hour), and
h = operating headway (expressed in minutes).

Estimation of Deceleration-Acceleration Maneuvers of Non-Transit Vehicles

In Figure 2, each bus-related stop is associated with two potential incidents involving impedance to mainline traffic flow. The first incident involves deceleration as bus approaches a designated stop. The second incident involves acceleration as bus merges into the lane of travel after providing service at a designated stop. For each of the two incidents, vehicles arriving and unable to change lanes will momentarily decelerate from cruise speed to avoid collision with bus and then accelerate to cruise speed as bus leaves the travel lane.

The expected number of deceleration-acceleration activity, associated with bus-related stops, involving non-transit vehicles is determined as:

$$\eta_v = \eta_b (t_{d,a})(\lambda)(\rho_{nlc}) \tag{2a}$$

$$\rho_{nlc} = 1 - \exp(-\varphi \delta_v) \tag{2b}$$

$$\lambda = \omega_1 Q_v/3600 \tag{2c}$$

$$\varphi = \omega_2 Q_v/3600 \tag{2d}$$

$$t_{d,a} = u_c(d_b + a_b)/2d_b a_b \tag{2e}$$

where

Q_v = directional hourly volume of non-transit vehicles on bus route,
q_v = directional hourly flow rate of non-transit vehicle on bus-travel lane,
η_v = expected number of deceleration-acceleration activity induced by bus-related stops involving non-transit vehicles,
ω_1 = proportion of directional hourly volume of non-transit on bus-travel lane,
ω_2 = proportion of directional hourly volume of non-transit on lane adjacent to bus-travel lane,
ρ_{nlc} = probability of vehicles unable to change lanes,
λ = arrival rate (expressed in vehicles/sec) of non-transit vehicles on bus-travel lane,
φ = arrival rate (expressed in vehicles/sec) of non-transit vehicles on lane adjacent to bus-travel lane,
δ_v = critical gap (expressed in seconds) for lane-change maneuver,
$t_{d,a}$ = average lost time associated with bus deceleration and acceleration maneuvers,
u_c = cruise speed (expressed in m/s) of vehicles,
d_b = deceleration (expressed in m/s^2)of bus, and
a_b = acceleration (expressed in m/s^2) of bus.

The "2" in (2e) reflects the average condition for a random arrival pattern of non-transit vehicles during bus service-related deceleration and acceleration maneuvers. In other words, vehicles arrive anytime at the same probability within the time window of deceleration/acceleration maneuver, including the beginning and end of the maneuver. The final speed of arriving vehicles ranges from 0 to u_c, depending on the phase of the deceleration/acceleration maneuver the arrival occurs.

The total number of hourly pairs of deceleration-acceleration activities directly associated with bus-related stops is

$$\eta_{tot} = \eta_v + \eta_b \tag{3}$$

Estimation of Mobile Emissions from Bus-related Stops

The Comprehensive Modal Emissions Model (CMEM) (5) package was utilized for estimating the quantity of hydrocarbon (HC), nitrogen oxides (NOx), carbon monoxide (CO), and carbon monoxide (CO_2) directly associated with additional delays from bus-related stops.

The average time of deceleration and acceleration of non-transit vehicles caused by bus-related stop/merge maneuver are determined as:

$$t_d = 0.50u_c/d_v \tag{4a}$$

$$t_a = 0.50u_c/a_v \tag{4b}$$

where

t_d = time of vehicle deceleration (expressed in seconds),
t_a = time of vehicle acceleration (expressed in seconds),
a_v = vehicle uniform acceleration rate (m/s^2), and
d_v = vehicle uniform deceleration rate (m/s^2).

The required time-velocity input data for estimation of the mobile emissions associated with the time of deceleration and acceleration of vehicles during bus-related stops were generated from the expressions:

$$u_d(t) = u_c - (d_v)(t),\ t = 1, 2, \ldots, t_d \tag{5a}$$

$$u_a(t) = 0.50u_c + (a_v)(t),\ t = 1, 2, \ldots, t_a \tag{5b}$$

where

$u_d(t)$ = vehicle deceleration-speed as a function of time (t),
$u_a(t)$ = vehicle acceleration-speed as a function of time, and
u_c = vehicle cruise speed (m/s).

In (5a) and (5b), the speeds are calculated in one second increments for the constrained time period of deceleration and acceleration.

The required velocity-time input data used in CMEM are generated from (4) and (5). Figure 3 depicts the schematic illustration of the velocity-time graph for vehicles arriving during a bus-related stop (deceleration or acceleration) maneuver. For a category of mobile emission, the total amount associated with bus-related stops is determined as:

$$E_i = \eta_v \sum \zeta_k \upsilon_{ij} + \eta_b \upsilon_{ib} \tag{6}$$

where

E_i = estimated total for mobile emission category i, (e.g. HC, CO, NOx or CO_2),
ζ_k = proportion of CMEM vehicle category k (excluding transit vehicles) on bus route, and
υ_{ij} = emission category i obtained from time-velocity data characterizing deceleration-acceleration of vehicle category j during a bus-related stop/merge maneuver, as illustrated in Figure 3.

Example 1: Estimation of Mobile Emissions for Specified Operational Condition

This example illustrates the process of estimating mobile emissions associated with the following operating condition:

- Q_b = 350 passengers/hr
- Q_v = 2400 vph
- u_c = 15.6 m/s (56 km/h)
- h_p = 10 min
- N_s = 50
- $a_b = 0.5$ m/s^2
- $d_b = 2.0$ m/s^2
- $a_v = 1.5$ m/s^2
- $d_v = 2$ m/s^2
- δ_v = 2.5 sec
- $\omega_1 = 0.45$
- $\omega_2 = 0.55$
- For illustration purpose, use CMEM vehicle category 9 and 40 to represent passenger cars and heavy vehicles, respectively on bus route.

Problem 1

1. Determine the directional hourly number of vehicle deceleration and acceleration from bus-related stops on bus route.
2. Estimate the directional hourly quantity of mobile emissions directly associated with bus-related stops.

Analysis 1.1: Deceleration and Acceleration

- $\eta_b = (60/h_p)(N_s + N_{s,c} + 1)(1 - [\exp(-(Q_b/[(60/h_p)(N_s + N_{s,c} +1)]]^2)$ or 275 [from (1a) - (1c)].
- $\eta_v = \eta_b[u_c(d_b + a_b)/2d_b a_b)][\ \omega_1 Q_v/3600][1-\exp((-\omega_2 Q_v/3600)\delta_v)]$ or 965 [from (2a) - (2e)].
- $\eta_{tot} = \eta_v + \eta_b$ or 1,240 [from (3)].

Analysis 1.2: Mobile Emissions

- $t_d = 0.50u_c/d_v$ or 4 sec [approximately from (4a)].
- $t_a = 0.50u_c/a_v$ or 5 sec [approximately from (4b)].
- $u_d(t) = u_c - (d_v)(t)$ or $u_d(0)$ = 15.6 m/s (56 km/h), $u_d(1)$ = 13.6 m/s (49 km/h); $u_d(2)$ = 11.6 m/s (42 km/h); $u_d(3)$ = 9.6 m/s (35 km/h); and $u_d(4)$ = 7.8 m/s (28 km/h) [from (6a)].
- $u_a(t) = 0.50u_c + (a_v)(t)$ or $u_a(0)$ = 7.8 m/s (28 km/h); $u_a(1)$ = 9.3 m/s (33 km/h); $u_a(2)$ = 10.8 m/s (39 km/h); $u_a(3)$ = 12.3 m/s (44 km/h); $u_a(4)$ = 13.8 m/s (50 km/h); and $u_a(5)$ = 15.6 m/s (56 km/h) [from (6b)].
- From the generated time-velocity data, the CMEM outputs:
  For vehicle category 9, HC = 0.019 g, NOx = 0.049 g, CO = 1.505 g, CO_2 = 44.136 g.
  For vehicle category 40, HC = 0.083 g, NOx = 0.776 g, CO = 0.195 g, CO_2 = 73.170 g.
- $E_i = \eta_v \sum \zeta_k \upsilon_{ij} + \eta_b \upsilon_{ib}$ [(from (7)], hence:
  E_{HC} = 965[(0.95)(0.019) + (0.05)(0.083)] + 275(0.083) or 0.044 kg/h.
  E_{NOx} = 965[(0.95)(0.049) + (0.05)(0.776)] + 275(0.776) or 0.296 kg/h.
  E_{CO} = 965[(0.95)(1.505) + (0.05)(0.195)] + 275(0.195) or 1.443 kg/h.
  E_{CO2} = 965[(0.95)(44.136) + (0.05)(73.170)] + 275(73.170) or 64.114 kg/h.

In most urban areas, the duration of peak traffic conditions is approximately four hours daily. If a uniform operating condition can be assumed during the peak period, the directional total emissions can be estimated by applying a factor of four to the calculated hourly rates. The resulting quantity of emissions is clearly substantial, particularly for CO and CO_2.

Optimization of Bus Stop Spacing

It has been shown from Example 1 that a direct relationship exists between the frequency of bus stops and mobile emissions. High frequency of bus-related stops results in high mobile emissions. In order to lower mobile emissions in urban areas, particularly those areas categorized as non-attainment, it is necessary to optimize the number of bus stops on the bus route. Based on the results obtained from the aforementioned nationwide survey, most transit agencies use a rule-of-thumb principle resulting in providing more stops than is required, particularly in high-density land use locations. The nationwide average bus stop spacing of 335 m results in average walking distance of 84 m (i.e. 335/4) between bus stops. Based on assumed average walking speed of 1.2 m/s, the average walking time between bus stops is slightly more than 1 minute, which clearly can be increased without having a significant impact on the perceived accessibility of the transit system.

Optimization of bus stop spacing is treated here on the premise of minimizing the average travel time considered important to both the transit users and the operators. There is an indirect relationship between the in-vehicle travel time and bus stop spacing, which is inversely related to the frequency of bus stops. Conversely, there is a direct relationship between the out-of-vehicle travel time and bus stop spacing. The average travel time comprises both the in-vehicle and out-of-vehicle travel time. Therefore, there is an optimal bus-stop spacing that minimizes the aggregate average travel time.

Another important element of transit operations is the fleet size (number of buses) that is required to sustain the transit service being offered. Unlike travel time, which is a continuous variable, the fleet size is a discrete variable, which must assume an integer value. Therefore, the optimization process discussed here involved determining the minimum bus stop spacing associated with the minimum average weighted travel time (AWTT) on bus route and the corresponding sub-optimal fleet size.

Estimation of Travel Time

The travel time comprises in-vehicle travel time and out-of-vehicle travel time, which includes walking, waiting and transfer time. For the purpose of optimizing bus stop spacing, only the component of walking time between bus stops is relevant. All other components of out-of-vehicle travel time are independent of the spacing between stops and are not considered. Thus, transit trip time was determined as:

$$T_{trip} = T_b + T_w \tag{7}$$

T_{trip} = total transit-trip time on bus route,
T_b = bus travel time, and
T_w = walking time between bus stops.

Bus Travel Time

Bus travel time was determined as (5):

$$T_b = T_{a,d} + T_s + T_c + T_m + T_o + T_e \tag{8a}$$

$$T_{a,d} = t_{d,a}[\rho_s N_s + \rho_c N_c + (\rho_s + \rho_c - \rho_s \rho_c)N_{s,c} + 1]/60 \tag{8b}$$

$$T_s = [\rho_s(N_s + N_{s,c} + 1)][((hq_b)\tau + 60k)/3600] \tag{8c}$$

$$T_c = \rho_c(N_c + N_{s,c})[(C - g)]/120 \tag{8d}$$

$$T_m = [\rho_s(N_s + N_{s,c} + 1)][(1 - \exp(-\delta_b\lambda))/\exp(-\delta_b\lambda)][\delta'_b] \tag{8e}$$

$$T_o = (D/u_c) - 0.5T_{a,d} \tag{8f}$$

$$t_{d,a} = u(a_b + d_b)/a_b d_b \tag{8g}$$

$$u_c = \min\{u_o, [2a_b d_b x_s/(a_b + d_b)]^{0.5}\} \quad (8h)$$

$$\rho_c = (C-g)/C \quad (8i)$$

$$\delta'_b = 0.5(\delta_{min} + \delta_b) \quad (8j)$$

where

$T_{a,d}$ = total one-way travel time (expressed in minutes) during bus acceleration and deceleration,
$t_{d,a}$ = bus deceleration and acceleration time (expressed in seconds),
T_s = total one-way delay (expressed in minutes) attributed to bus dwell time at regular bus stops,
T_c = total one-way delay (expressed in minutes) caused by traffic control devices (i.e., traffic signals),
T_m = total one-way delay (expressed in minutes) during bus merging maneuvers,
T_o = total one-way bus travel time (in minutes) at cruise speed,
T_e = total one-way delay (expressed in minutes) from other miscellaneous activities (including layover and circuitous routes) not modeled,
D = one-way terminal to terminal distance in meters,
N_c = total number of other potential stops (i.e., traffic signals locations) on bus route,
N_s = total number of bus stops considered to be isolated from traffic signals on bus route,
$N_{s,c}$ = total number of bus stops located at signalized intersections,
ρ_c = probability of bus stopped by traffic signal,
ρ_s = probability that bus makes a stop at regular bus stop location,
C = average cycle length (expressed in seconds) of traffic signals on bus route,
g = average effective green time (expressed in seconds) on bus route,
δ_b = critical gap (expressed in seconds) for bus merging maneuvers,
δ'_b = average size (expressed in seconds) of rejected gaps,
δ_{min} = smallest gap size (expressed in seconds) in the traffic stream,
u = speed of the bus (expressed in m/s),
u_o = maximum speed (expressed in m/s) permitted on bus route,
τ = average bus service (boarding or alighting) time in seconds, and
k = average time (expressed in seconds) for opening or closing bus door.

In (9e), the expression "$(1 - \exp(-\delta_b\lambda))/\exp(-\delta_b\lambda)$" implicitly assumes the geometric probability distribution in determining the expected number of consecutive gaps rejected by the bus before successfully initiating merging maneuvers at designated bus stops.

Estimation of Walking Time

The average walking time between bus stops was determined as:

$$T_w = [x_s/4u_w]/60 \quad (9)$$

where

T_w = average walking time (expressed in minutes) between bus stops,
x_s = average bus stop spacing in meters, and
u_w = average walking speed in m/s.

The one-way average travel time of transit users was determined as:

$$T_{ave} = 0.5T_b + T_w \quad (10a)$$

$$T'_{ave} = 0.5T_b + \gamma T_w \quad (10b)$$

where

T_{ave} = one-way average travel time expressed in minutes,
T'_{ave} = weighted one-way average travel time expressed in minutes, and
γ = weight reflecting the perceived duration of out-of-vehicle travel time.

The optimum bus stop spacing was determined as:

$$\text{Minimize } T'_{ave} \tag{11a}$$

$$\text{Subject to } h \leq h_p \tag{11b}$$

$$x_s \leq \chi \tag{11c}$$

$$\eta_f \geq (2T_b)/h_p \tag{11d}$$

where

η_f = required fleet size (number of buses in operation),
h = operating headway expressed in minutes,
h_p = policy headway expressed in minutes, and
χ = maximum allowable bus stop spacing expressed in meters.

Sensitivity Analysis

Determining the optimum bus stop spacing for a given operating condition involved a sensitivity analysis requiring gradual variation of bus stop spacing until the weighted average travel time in (11a) is minimized subject to the constraints in (11b) - (11d).

Example 2: Determination of Optimal Bus Stop Spacing

This example illustrates the reduction of mobile emissions from optimal spacing of bus stop based on the following operating condition:

- $D = 14{,}800$ m
- $Q_b = 350$ passengers/hr
- $Q_v = 2{,}400$ vph
- $u_c = 15.6$ m/s (56 km/h)
- $h_p = 10$ min
- $N_c = 25$
- $a_b = 0.5$ m/s^2
- $d_b = 2.0$ m/s^2
- $a_v = 1.5$ m/s^2
- $d_v = 2$ m/s^2
- $\delta_v = 2.5$ s
- $\delta_b = 3.5$ s
- $\delta_{min} = 1$ s
- $\omega_1 = 0.45$
- $\omega_2 = 0.55$
- $\tau = 3$ s
- k = 3 s
- C = 120
- g = 50 s
- $\chi = 1.6$ km
- $u_o = 56$ km/h or 15.6 m/s
- $u_w = 1.2$ m/s
- $Q_v = 2{,}400$ vph
- $\gamma = 2$

- $T_e = 3$ s
- For illustration purpose, use CMEM vehicle category 9 and 40 to represent passenger cars and heavy vehicles, respectively on bus route

Problem 2

1. Determine the optimal bus stop spacing.
2. Estimate the reduction of mobile emissions attributed to optimizing bus stop spacing, if the existing average bus stop spacing is approximately 290 m.

Analysis 2.1: Optimum Bus Stop Spacing

- For $x_s = 290$ m (arbitrarily considered), $N = (D/x_s) - 1$ or 50 ($N_s = 25$ and $N_{s,c} = 25$) [based on the stated bus-stop location policy).
    - $T_{a,d} = t_{d,a}[\rho_s N_s + \rho_c N_c + (\rho_s + \rho_c - \rho_s\rho_c)N_{s,c} + 1]$ or 32.2 min [(8b), (8g) and (8h)].
    - $T_s = [\rho_s(N_s + N_{s,c} + 1)][((hq_b)\tau + 60k)/3600]$ or 4.9 min [(1b), (1d) and (8c)].
    - $T_c = \rho_c(N_c + N_{s,c})[(C - g)]/120$ or 8.5 min [(8d) and (8i)].
    - $T_m = [\rho_s(N_s + N_{s,c} + 1)][(1 - \exp(-\delta_b\lambda))/\exp(-\delta_b\lambda)][\delta'_b]$ or 4.5 min [(1b), (1d) and (8e)].
    - $T_o = (D/60u) - 0.5T_{a,d}$ or 3.7 min [(8b), (8f) and (8h)].
    - $T_e = 3$ min.
    - Therefore, $T_b = 56.8$ min [(8a)].
    - $T_w = [x_s/4u_w]/60$ or 1.0 min [(9)].
    - $T_{ave} = 0.5T_b + T_w$ or 29.4 min [(10a)]
    - $T'_{ave} = 0.5T_b + \gamma T_w$ or 30.4 min [(10b)]
    - $\eta_f = (2T_b)/h_p$ or 12 buses [(8a) and (11d)].

Repeating the above computational steps using different values of x_s, the minimized T'_{ave} and the associated optimal bus stop spacing (x_s*) were determined to be approximately 705 m and 9 buses, respectively. The summary of the analysis is presented in Table 2 and Figure 4.

Analysis 2.2: Reduction of Mobile Emissions from Optimization of Bus Stop Spacing

The average bus stop spacing varies for localities, depending on the levels of land use intensity and demand for transit. Bus stops are more closely spaced in high-density urban areas than in low-density rural areas. Determining the reduction of mobile emissions from optimal spacing of bus stops involves two major steps. The first step is to estimate the mobile emissions associated with the current average bus stop spacing considered as the benchmark. The second step is to estimate the mobile emissions associated with the optimum bus stop spacing as determined in Analysis 2.1. The difference in mobile emissions from the two scenarios of bus stop spacing analysis is the reduction of emissions attributed to optimization of bus stop spacing.

For an urban area, assuming that the benchmark bus stop spacing is 290 m, the resulting mobile emissions are estimated as follows:

- $\eta_b = (60/h_p)(N_s + N_{s,c} + 1)(1 - [\exp(-(Q_b/[(60/h_p)(N_s + N_{s,c} + 1))]^2)$ or 275 [(1a) - (1c)], as determined in Example 1.
- $\eta_v = \eta_b[u_c(d_b + a_b)/2d_b a_b)][\omega_1 Q_v/3600][1 - \exp((-\omega_2 Q_v/3600)\delta_v)]$ or 772 [(2a) - (2e) and (8h)]. Note that η_v is slightly less than previously calculated in Example 1 because u_c is affected by bus stop spacing as can be verified in (8h). In Example 1, it was assumed that $u_c = u_o$ because x_s was not considered.
- $\eta_{tot} = \eta_v + \eta_b$ or 1,047 [(3)].
- $t_d = 0.50u_c/d_v$ or 4 sec approximately[(4a) and (8h)].
- $t_a = 0.50u_c/a_v$ or 5 sec approximately [(4b) and (8h)].

- $u_d(t) = u_c - (d_v)(t)$ or $u_d(0) = 15.2$ m/s (54 km/h), $u_d(1) = 13.2$ m/s (47 km/h); $u_d(2) = 11.2$ m/s (40 km/h); $u_d(3) = 9.2$ m/s (33 km/h); and $u_d(4) = 7.6$ m/s (27 km/h) approximately [(5a)].
- $u_a(t) = 0.50u_c + (a_v)(t)$ or $u_d(0) = 7.6$ m/s (27 km/h), $u_a(1) = 9.3$ m/s (33 km/h); $u_a(2) = 10.8$ m/s (39 km/h); $u_a(3) = 12.3$ m/s (44 km/h); $u_a(4) = 13.8$ m/s (50 km/h); and $u_a(5) = 15.2$ m/s (54 km/h) approximately [(5b)].
- From the generated time-velocity data, the CMEM outputs are:
  For vehicle category 9, HC = 0.005 g, NOx = 0.046 g, CO = 0.104 g, and $CO_2 = 31.040$ g.
  For vehicle category 40, HC = 0.058 g, NOx = 0.513 g, CO = 0.131 g, and $CO_2 = 48.497$ g.
- $E_i = \eta_v \sum \zeta_k \upsilon_{ij} + \eta_b \upsilon_{ib}$ [(from (6)], hence:
  $E_{HC} = 772[(0.95)(0.005) + (0.05)(0.058)] + 275(0.058)$ or 0.022 kg/h.
  $E_{NOx} = 772[(0.95)(0.046) + (0.05)(0.513)] + 275(0.513)$ or 0.195 kg/h.
  $E_{CO} = 772[(0.95)(0.104) + (0.05)(0.131)] + 275(0.131)$ or 0.117 kg/h.
  $E_{CO2} = 772[(0.95)(31.040) + (0.05)(48.497)] + 275(48.497)$ or 36.499 kg/h.

Using the optimum bus stop spacing of 705 m obtained from Example 2, the resulting mobile emissions are estimated as follows:

- $\eta_b = (60/h_p)(N_s + N_{s,c} + 1)(1 - [\exp(-(Q_b/[(60/h_p)(N_s + N_{s,c} + 1))]^2)$ or 126 [(1a) - (1c)].
  $\eta_v = \eta_b[u_c(d_b + a_b)/2d_b a_b)][\ \omega_1 Q_v/3600][1-\exp((-\omega_2 Q_v/3600)\delta_v)]$ or 439 [(2a) - (2e) and (8h)], as determined in Example 1. Note that η_v is same as previously calculated in Example 1 because $u_c = u_o$ for the optimum bus stop spacing of 705 m, as can be verified in (8h).
- $\eta_{tot} = \eta_v + \eta_b$ or 565 [(3)].
- $t_d = 0.50u_c/d_v$ or 4 sec approximately[(4a) and (8h)].
- $t_a = 0.50u_c/a_v$ or 5 sec approximately [(4b) and (8h)].
- $u_d(t) = u_c - (d_v)(t)$ or $u_d(0) = 15.6$ m/s (56 km/h), $u_d(1) = 13.6$ m/s (49 km/h); $u_d(2) = 11.6$ m/s (42 km/h); $u_d(3) = 9.6$ m/s (35 km/h); and $u_d(4) = 7.8$ m/s (28 km/h) approximately [(5a)].
- $u_a(t) = 0.50u_c + (a_v)(t)$ or $u_d(0) = 7.8$ m/s (28 km/h), $u_a(1) = 9.3$ m/s (33 km/h); $u_a(2) = 10.8$ m/s (39 km/h); $u_a(3) = 12.3$ m/s (44 km/h); $u_a(4) = 13.8$ m/s (50 km/h); and $u_a(5) = 15.6$ m/s (56 km/h) approximately [(5b)].
- From the generated time-velocity data, the CMEM outputs are:
  For vehicle category 9, HC = 0.019 g, NOx = 0.049 g, CO = 1.505 g, and $CO_2 = 44.136$ g.
  For vehicle category 40, HC = 0.083 g, NOx = 0.776 g, CO = 0.195 g, and $CO_2 = 73.170$ g.
- $E_i = \eta_v \sum \zeta_k \upsilon_{ij} + \eta_b \upsilon_{ib}$ [(from (6)], hence:
  $E_{HC} = 439[(0.95)(0.019) + (0.05)(0.083)] + 126(0.083)$ or 0.020 kg/h.
  $E_{NOx} = 439[(0.95)(0.049) + (0.05)(0.776)] + 126(0.776)$ or 0.135 kg/h.
  $E_{CO} = 439[(0.95)(1.505) + (0.05)(0.195)] + 126(0.195)$ or 0.657 kg/h.
  $E_{CO2} = 439[(0.95)(14.678) + (0.05)(73.170)] + 126(73.170)$ or 29.232 kg/h.

Therefore,

$\Delta E_{HC} = 0.002$ kg/h
$\Delta E_{NOx} = 0.060$ kg/h
$\Delta E_{CO} = -\ 0.54$ kg/h (increase)
$\Delta E_{CO2} = 7.267$ kg/h

where

ΔE_i = peak hourly reduction of mobile-emission category i associated with optimization of bus stop spacing.

The summary of results obtained from the mobile emissions analysis is presented in Table 3 and Figure 5.

DISCUSSION

It was deduced from the sensitivity analysis using CMEM that maximal production of mobile emissions occurs during acceleration activities, and minimal production occurs during deceleration activities. Consequently, stop-related activities produce higher mobile emissions at high cruise speed than low cruise speed. However, the quantity of emissions produced is directly dependent on the number of vehicular stop maneuvers. Closely spaced bus stops are associated with a higher frequency of vehicular stops than distantly spaced bus stops. Conversely, closely spaced bus stops are associated with lower cruise speeds than distantly spaced bus stops. The two variables, frequency of stops and average cruise speed, which affect mobile emissions, are inversely related. However, the average cruise speed is constrained by the posted speed limit and becomes independent of the spacing between bus stops once attaining the value of the posted speed limit. Consequently, beyond the bus stop spacing at which the average cruise speed corresponds to the value of the posted speed limit, the frequency of stops becomes the dominant operational factor affecting mobile emissions, which generally decrease as the spacing between stops increases. The contributing effect of bus stop spacing on mobile emissions eventually becomes negligible as the spacing between stops is continually increased because of the diminished effect of bus stopping maneuvers on the through traffic as shown in (1) and (2). It is, therefore, not plausible to directly determine the optimum bus stop spacing from mobile emissions. Instead, as demonstrated in this paper, it is desirable to determine the optimum bus stop spacing from minimizing the travel time or other related cost elements, and capturing the associated air-quality benefits by undertaking a comparative analysis.

CONCLUSION

In this paper, it has been demonstrated that, similar to poorly timed traffic signals, improper spacing of bus stops in urban areas significantly disrupt the flow of traffic on the bus route, particularly during peak hours. The disruption of traffic flow from frequent stopping of buses engenders loss of energy from vehicle deceleration and acceleration maneuvers, resulting in increased traffic delay and mobile emissions. The results obtained from a nationwide survey indicate that the average bus stop spacing varies for localities, and decisions on bus stop spacing are usually based on the rule-of-thumb principles. The average bus stop spacing of approximately 335 m determined from the nationwide survey is less than one-half of the optimum threshold spacing of approximately 700 m to 800 m determined from the sensitivity analysis performed for typical urban operating conditions.

It has been demonstrated here that optimization of bus stop spacing benefits the transit users, the transit operators and the environment because the average travel time, the fleet size requirement, mobile emissions (except carbon monoxide), and fuel consumption are all substantially reduced. Optimization of urban bus stop spacing, therefore, is a viable alternative that deserves further exploration, particularly in the non-attainment urban areas of the U.S. mandated by the CAAA of 1990 to embark on mitigation measures to meet the air-quality conformity requirements.

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Table 1 Summary of Nationwide Survey of Bus Stop Spacing

	Minimum spacing (m)	Average spacing (m)	Maximum Spacing (m)
Mean	179.94	336.17	589.29
Standard Error	23.12	25.73	68.51
Median	171	400	501
Mode	91	400	800
Count	18	23	140
Largest	400	528	1200
Smallest	27	36	320
Confidence Level (95.0%)	48.78	53.35	148.01

Table 2 Bus Performance Results of Sensitivity Analysis

Average bus stop spacing, x_s (m)	Total no. of bus stops, N	Average no. of bus stops per kilometer	Average travel time, T_{ave} (min)	Weighted average travel time, T'_{ave} (min)	Required fleet size, η_f (buses)
150	98	6.6	33.9	34.4	13.4 (14)
172	85	5.7	33.0	33.6	13.0 (13)
209	70	4.7	31.7	32.4	12.4 (13)
243	60	4.1	30.6	31.5	11.9 (12)
290	50	3.4	29.4	30.4	11.4 (12)
361	40	2.7	28.0	29.3	10.7 (11)
477	30	2.0	26.4	28.1	9.9 (10)
705	20	1.4	24.9	27.3	9.0 (9)
822	17	1.2	24.6	27.5	8.7 (9)
1,346	10	0.7	24.8	29.4	8.0 (8)
1,644	8	0.5	25.3	31.1	7.9 (8)

Table 3 Emission Results of Sensitivity Analysis

Average bus stop spacing, x_s (m)	Total no. of bus stops, N	Average cruise speed, u_c (km/h)	Hourly number of stops made by buses, η_b	Hourly number of non-transit vehicles affected by bus-related stops, η_v	HC Index (kg/h)	NO_x Index (kg/h)	CO Index (kg/h)	CO_2 Index (kg/h)	Fuel Usage Index (kg/h)
150	98	6.6	411	904	0.020	0.167	0.085	30.700	9.741
290	50	3.4	275	772	0.022	0.195	0.117	36.499	11.585
477	30	2.0	182	594	0.021	0.178	0.120	37.374	11.863
705	20	1.4	126	439	0.020	0.135	0.657	29.232	9.561
1,346	10	0.7	66	231	0.011	0.071	0.345	15.360	5.024

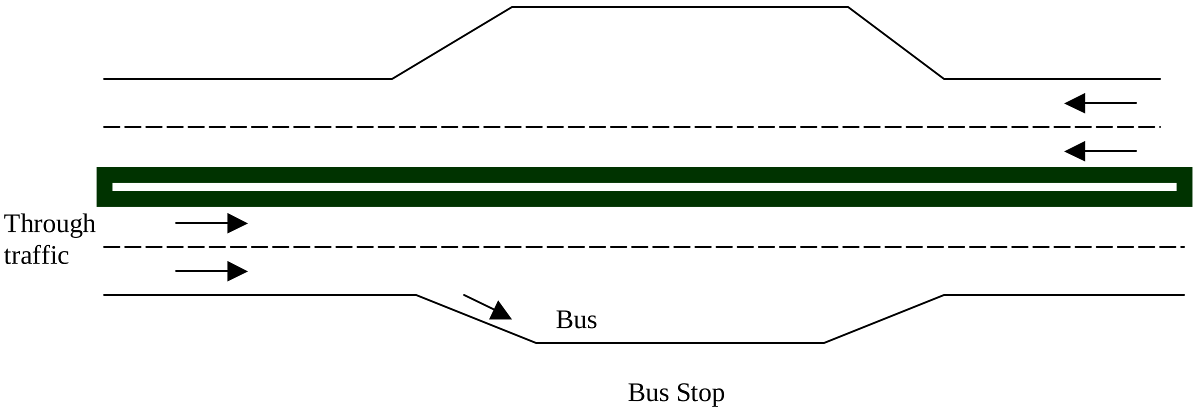

Figure 1 Schematic illustration of the configuration of bus route

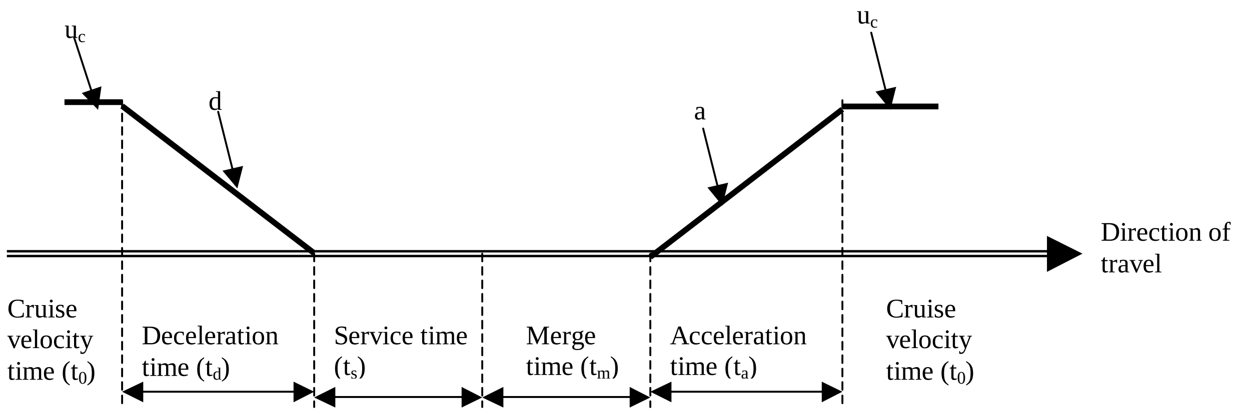

Figure 2 Schematic illustration of bus velocity profile at bus stops

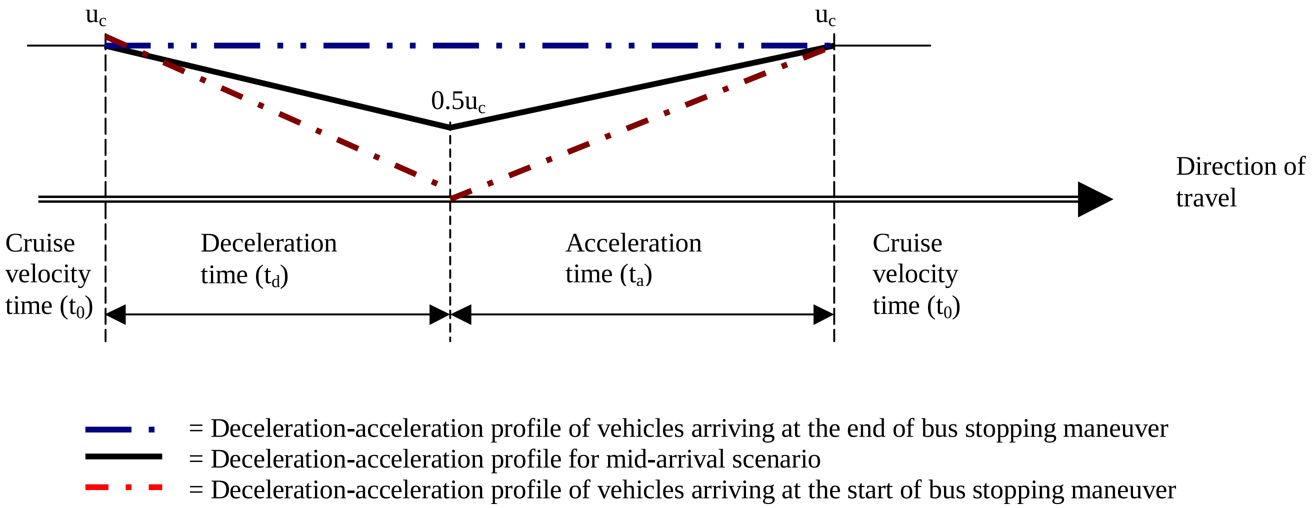

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Figure 3 Schematic illustration of time-velocity relationship for estimation of mobile emissions

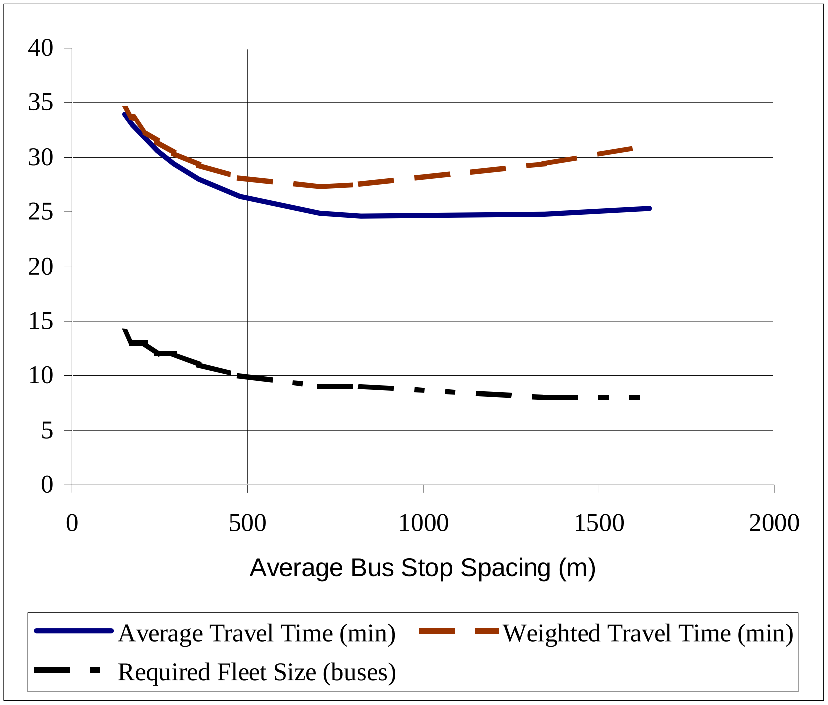

Figure 4 Relationship between bus stop spacing, travel time and fleet size requirement developed from Table 2.

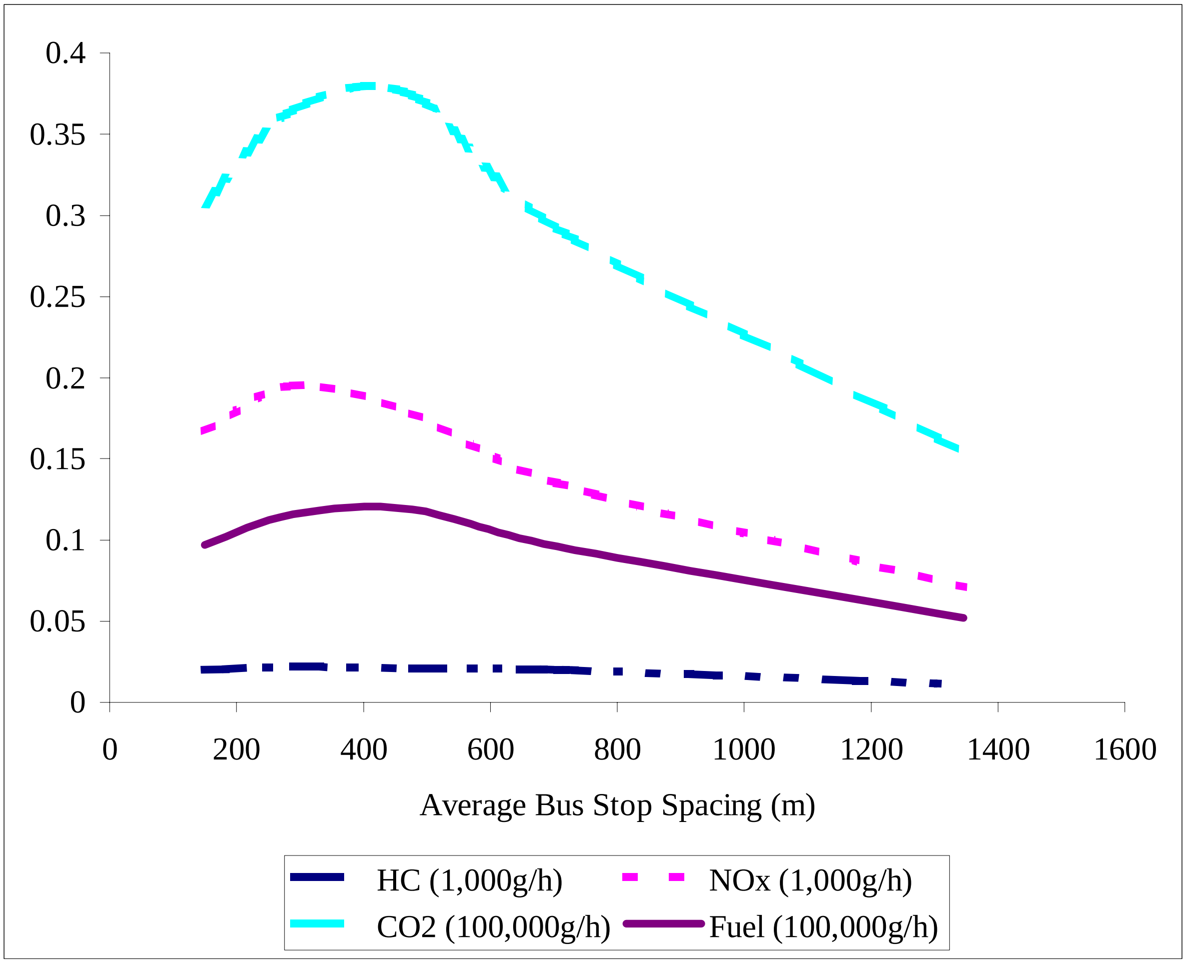

Figure 5 Graphical illustration of relationship between bus stop spacing and mobile emissions from Example 2.