A Model for Estimating NO_x Emission Reductions after Closing Drive-Thrus

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ABSTRACT

In many areas of the United States, air quality challenges are caused by on-road mobile sources. All non-attainment regions must develop strategies so that the regions' air quality can attain the National Ambient Air Quality Standards. With implementation of the new, more stringent 75 ppb ozone standard over the next several years, new innovative strategies for meeting air quality goals must be considered. The North Central Texas Council of Governments (NCTCOG) is considering one such measure. NCTCOG is contemplating a restriction on drive-thru activity. While the exact policy has not been determined, the magnitude of the potential air quality improvement must be investigated. After determining the magnitude of the improvement, other policy issues such as social and public acceptance and feasibility can be examined.

This study develops a methodology for estimating emission benefits associated with drive-thru restrictions by characterizing a drive-thru as an *M*/*M*/1 queuing system. Using data collected from a diesel truck during a field experiment, the researchers formulate emissions factors to represent the emissions associated with different vehicular activities (e.g. moving forward, idling, and moving backward) at the facility. The researchers formulate the emissions attributable to each queuing system state. After collecting arrival and service rates during morning (7-10 a.m) and lunch (11 a.m – 2 p.m.) periods at a fast food restaurant, the team estimates drive-thru emissions during each period. At this site, a drive-thru closure will result in a 61% nitrogen oxide (NO_x) reduction over the morning hours and a 67% NO_x reduction over the lunch period.

INTRODUCTION

According to EPA estimates, in 2003, on-road transportation sources emitted 36% of nitrogen oxides (NO_x), 63% of carbon monoxide (CO), and 29% of volatile organic compounds (VOCs) in the US (figures not including fires) [1]. Despite improvements in vehicle emission control systems and resulting decreases in the amount of pollutants emitted per mile traveled, the total quantity of air pollution from mobile sources has increased in recent years, due to increases in the total number of vehicles on the road and in miles traveled per vehicle. Between 1970 and 2004, total vehicle miles traveled (VMT) in the US increased by 171% [2]. In addition, as industrial sources like electric utilities come under more stringent regulation, on-road mobile sources will compose a larger percentage of the remaining emissions to be controlled.

In development of the 85 parts per billion (ppb) 8-hour ozone State Implementation Plan (SIP) for the Dallas-Fort Worth (DFW) ozone non-attainment region, closing drive-thrus during ozone season was considered. As a short-list measure, closing drive-thrus (fast food restaurants, banks, pharmacies, and dry cleaners) was evaluated for its potential emission benefit, cost effectiveness, implementation feasibility, and social/public acceptance [3]. The measure was not adopted in the final SIP because it was not SIP eligible (i.e. emissions from drive-thrus were not contained in the region's emissions inventory.)

In the analysis of potential SIP short-list measures, emission reductions associated with closing drive-thrus in DFW were estimated to be 0.01-0.05 tons/day NO_x and 0.04-0.19 tons/day VOCs, according to a method given in the Texas Guide to Accepted Mobile Source Emission Reduction (MOSER) Strategies Handbook [3,4]. The MOSER methodology estimates daily emission reductions due to restrictions on drive-thru use in g/day as follows:

$$\text{Daily Emission Reduction} = A - B + C \tag{1}$$

<u>Amount of idling exhaust emissions generated before use-restrictions</u>

$$A = N_v * \mathrm{t_B} * \mathrm{EF_I} \tag{2}$$

<u>Amount of idling exhaust emissions after use-restrictions are in place</u>

$$B = (1 - F_{park}) * N_v * t_A * EF_I \tag{3}$$

$$C = F_{park} * N_v * EF_{HS} \tag{4}$$

where EF_I = Idling emission factor (NO_x, VOC, or CO) (g/veh/hr)
F_{park} = Vehicle fraction that park instead of use drive-thru facility due to restriction
N_v = Average number of vehicles using the drive-thru facility per day
t_A = Time spent in queue after implementation of restriction per vehicle (hr)
t_B = Time spent in queue before implementation of restriction per vehicle (hr)
EF_{HS} = Hot-start emission factor (NO_x, VOC, or CO) (g/veh/trip)

In the SIP analysis for DFW, N_v was assumed to be 100,000, and F_{park} was assumed to be 100% and 50%. Based on information from QSR Magazine [5], t_B was taken as 10 minutes, and t_A was taken as 3 minutes (0.167 hour and 0.05 hour, respectively).. The idling and hot-start emission factors came from MOBILE.

In estimating emissions, MOSER thus accounts for drive-thru idling emissions, and hot start exhaust emissions from vehicles that park; however, the MOSER strategy does not account for emissions associated with backing out of a parking space nor driving within the parking lot of the facility. A literature survey found no models or methodologies besides the MOSER methodology for estimating emission reductions associated with closing drive-thrus.

With implementation of the new, more stringent 75 ppb ozone standard over the next several years, a measure restricting drive-thru activity is likely to be included in the next DFW SIP, since drive-thru emission estimates are now available to include in the region's emissions inventory. Not only DFW but also other ozone non-attainment areas across Texas and around the country may want to consider restricting drive-thru use as a measure to attain the 75 ppb ozone standard.

This study aims to improve on the existing methodology for estimating emission benefits associated with drive-thru restrictions, by measuring real-world emission factors associated with idling, cruising, and backing up. Additionally, this study characterizes the drive-thru as an $M/M/1$ queuing system to more accurately determine customer idling time. The researchers formulate the emissions associated with each queuing system state, and estimate emissions associated with parking. Integrating a queuing system model with emissions that correspond to each the system state should improve the accuracy of emission benefit estimates for closing drive-thrus.

METHODOLOGY

On-Board Data Collection

This study uses a portable emission measurement system (PEMS) to collect field data; this study's PEMS is the Horiba On-Board Measurement System OBS-1300. The OBS-1300 consists of two on-board gas analyzers, a laptop computer equipped with data logger software, a power supply unit, a tailpipe attachment and other accessories. The OBS-1300 collects second-by-second measurements of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), exhaust temperature and pressure, and vehicle position. HC, CO, and CO_2 are measured using heated non-dispersive infrared (HNDIR), and NO_x is measured using a non-sampling type zirconium sensor. Only the NO_x emission results are reported in this paper. The Dallas/Fort Worth (DFW) region must focus on reducing NO_x emissions because the region is NO_x-limited for ozone, which means that reducing NO_x emissions to decrease ozone concentrations is more effective than reducing VOC emissions.

After attempting to rent a diesel vehicle through a rental car company, the researchers selected a 26' International truck model S1900 (around 1983-1985) and installed the OBS on it. The truck's 190 hp diesel engine had 6-inline cylinders with a turbo charger. The diesel truck was chosen because the OBS-1300 only measures NO_x accurately from diesel vehicles; gasoline vehicles with catalytic converters produce an ammonia byproduct that interferes with the NO_x measurements [6]. Although not many 26' trucks are likely to use drive-thrus, its use is still valid because the researchers' interests center on the percent reduction in emissions between vehicles using the drive-thru and parking. The study assumed that this percent reduction in emissions would be similar for all vehicles. The researchers can test this assumption in future studies.

To simulate vehicle movement at a fast-food restaurant, the truck was driven in an empty parking lot. First, the engine was started and emissions were measured while the truck idled for 20 minutes. Next, emissions were measured as the truck accelerated from a stop; traversed a straight-line distance of 20, 40, 60, 80, 100, 125, 150, 175, 200, 250, 300, 350, or 400 feet at an appropriate parking lot cruising speed; and decelerated to a stop. Such acceleration/cruise/deceleration movements would be representative of a vehicle performing the following activities:

- entering the parking lot from a slowed speed (although perhaps not a stop), accelerating and then traversing the parking lot at a constant speed, and decelerating and stopping at the ordering location;
- accelerating from a stop at the ordering location, traveling at a constant speed toward the pick-up window, and decelerating and stopping there;
- all movements within the queue, when the system transitions between states and each vehicle moves forward one car length;
- accelerating from a stop at the pick-up window, traveling at a constant speed toward the parking lot exit, and decelerating to a stop to wait to enter the street.

The research team assumes that turns within the parking lot would not significantly impact emissions or speed, compared with traversing a straight line. Five repetitions were made of the acceleration/cruise/deceleration combinations for each straight-line distance; since thirteen distances were traversed, the researchers collected data for sixty-five runs. Finally, the team measured emissions as the truck backed out of a parking space five times.

Drive-Thru Customer Data Collection

To supplement the emissions data collected in the parking lot, drive-thru customer data was collected at a McDonald’s in Arlington, Texas near the University of Texas at Arlington. The McDonald’s has an ordering location and one pick-up window (no payment window). The following data was collected on a Tuesday/Thursday during the breakfast peak (7-10 a.m.) and lunch peak (11 a.m. – 2 p.m.):

- Time that customer entered the ordering queue;
- Time that customer started to place order;
- Time that the customer took to place an order;
- Time that customer left the pick-up window;
- Time that the customer took to pick up order;
- Number of drive-thru customers arriving hourly.

RESULTS

This section presents the methodology that the research team used to estimate emissions during the breakfast and lunch peaks at a fast food restaurant with a drive-thru. The first section analyzes the data generated during the emissions experiments with the International truck model S1900. This data is used to create emission factors for idling and vehicle movements within the parking lot. The section that follows describes the drive-thru as an $M/M/1$ queuing process. After describing the queuing process, the next section formulates the emissions associated with each queuing system state. The last section compares the emissions reduction that occurs when the drive-thru is closed and all customers must park and enter the establishment.

Emission Factor Estimation

Figure 1 shows NO_x idling emissions in μg/sec as a function of time. Average emissions from 0-5 minutes are 451 μg/vehicle/second. Average emissions from 5-20 minutes are 560 μg/vehicle/second. The engine likely changed to a different operation mode at five minutes. Since idling times in a drive-thru line without any change in location will typically be less than five minutes, an idling emission factor of $EF_I = 451$ μg/vehicle/second will be used.

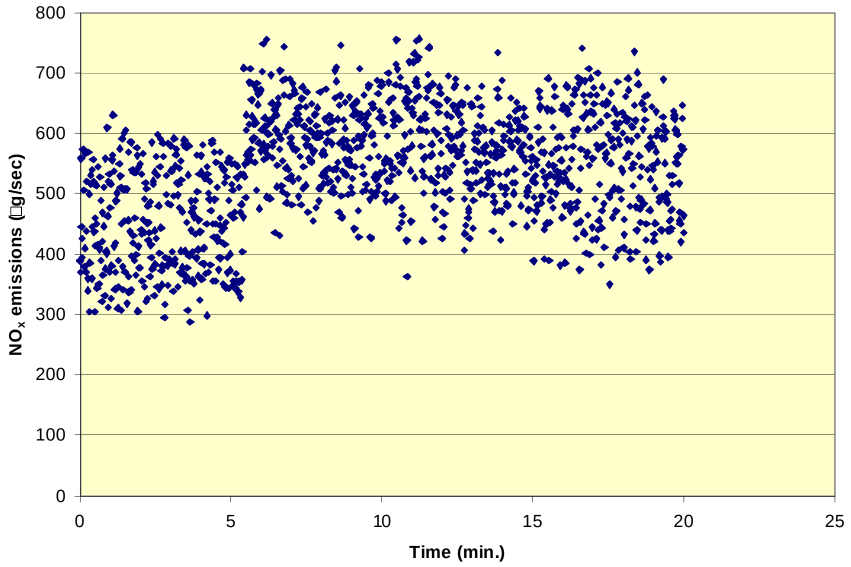

FIGURE 1 NO_x idling emissions (μg/sec) vs. time (min.).

Figure 2 show travel time as a function of parking lot distance traversed. As expected, the travel time increases as the distance traversed increases.

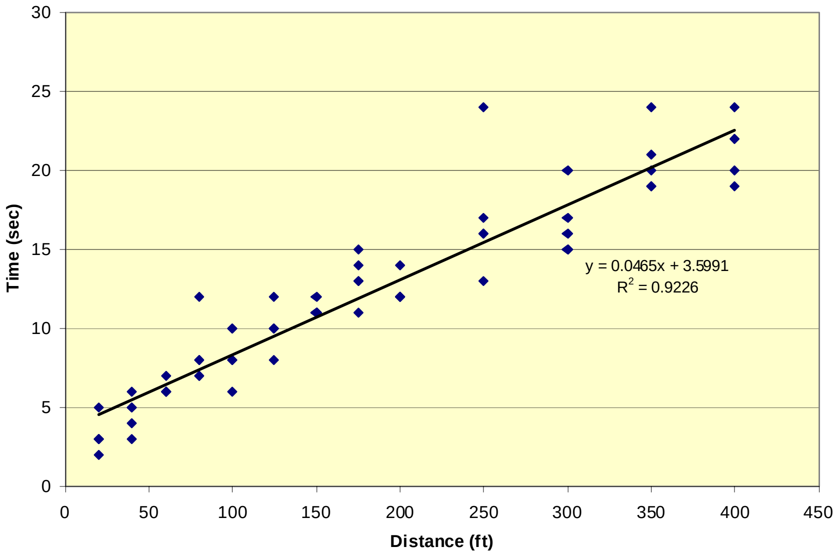

FIGURE 2 Travel time (sec) vs. distance (ft).

Figure 3 shows NO_x emissions in μg/sec for each acceleration/cruise/deceleration combination as a function of straight-line parking lot distance traversed. Since five runs are made for each straight-line distance, five data points are plotted for each distance. The average value from Figure 4 is 767 μg/sec.

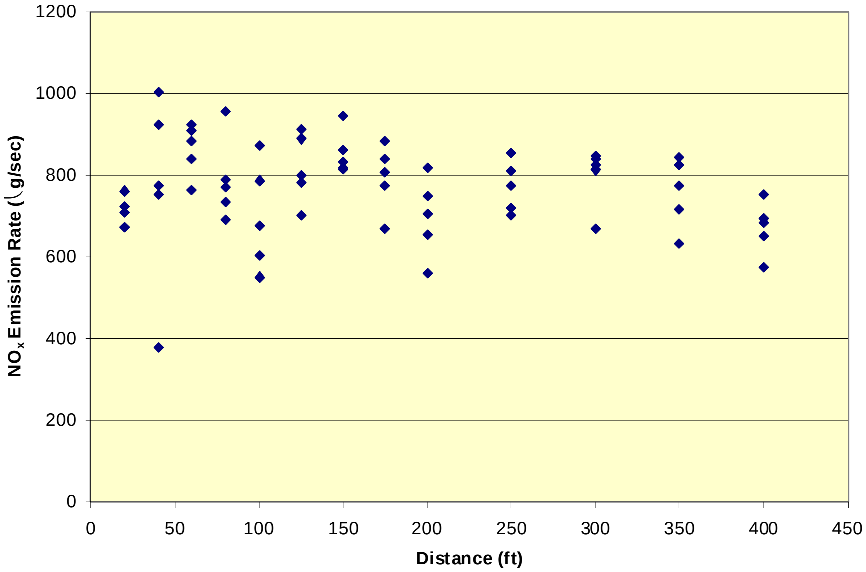

FIGURE 3 Average NO_x emission rate (μg/sec) vs. distance traversed (ft).

Figure 4 shows total NO_x emissions in μg for each acceleration/cruise/deceleration combination as a function of straight-line parking lot distance traversed. The researchers fit an equation to facilitate the formulation of emission factors associated with the distance that a vehicle travels between stops within the parking lot. Equation (5) can be used to calculate the EF_D for any distance within the parking lot.

$$EF_D = 324\left(d^{0.6527}\right) \tag{5}$$

Where d represents the distance traveled measured in feet, and EF_D is in μg/vehicle.

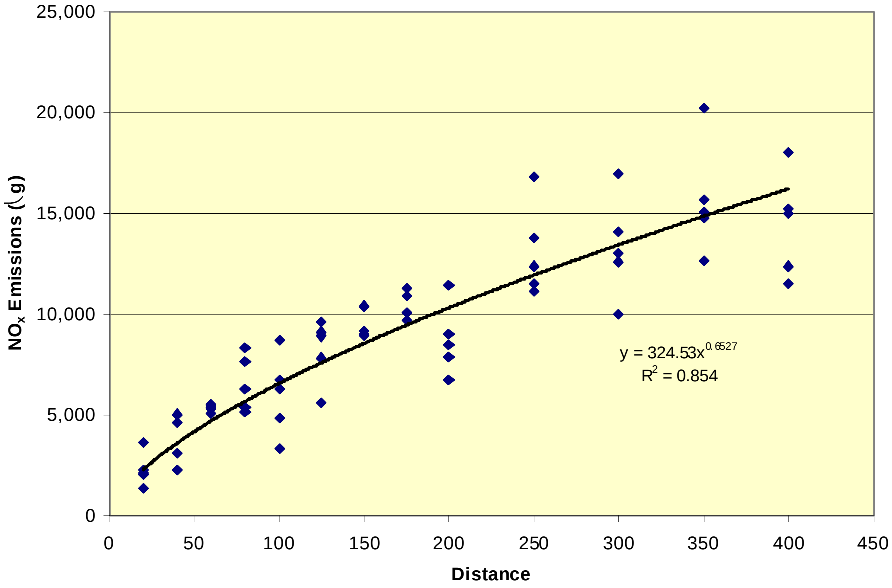

FIGURE 4 Total NO_x emissions (μg) vs. distance traversed (ft)

Figure 5 shows average NO_x emissions in μg/sec as a function of average velocity. Since there was not much variation in vehicle speed, there was not a noticeable change in emission rate with speed. As was the case with emission rate vs. distance traversed, no trend or pattern exists.

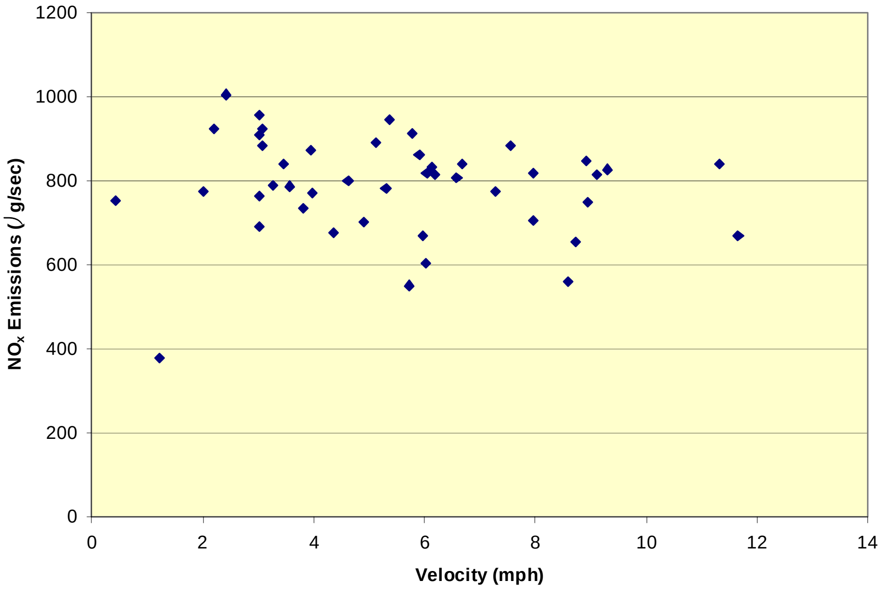

FIGURE 5 Average NO_x emission rate (μg/sec) vs. velocity (mph).

The team has collected five repetitions of the vehicle backing out of a parking space. The average emissions per reverse maneuver are 7345 µg, so a reverse maneuver emission factor of EF_R = 7345 μg/vehicle will be used.

Queuing System Characterization

A restaurant drive-thru may be characterized as a queuing system with a single server. The researchers propose that both the interarrival and interservice times have a negative exponential distribution. Typically, one can use a Chi-Square Test to determine if a data set fits a particular distribution. Unfortunately, this study has limited data collection; therefore, performing a Chi-Square test provides reduced utility. The changing arrival rates during the study period (see Table 1) exacerbate this problem. Additional data collection must be conducted to determine how arrival and service rates vary by time of day because the observed variability may result from the stochasticity in the rates or may represent an actual rate change. At this time, the frequency distributions of the morning and lunch arrivals and services (Figures 6 through 9) show that the interevent times generally follow a negative exponential distribution.

TABLE 1. Hourly Volumes Using Drive-Thru

Time	Vehicles
7-8 a.m.	117
8-9 a.m.	98
9-10 a.m.	80
11 a.m.–12 p.m.	71
12-1 p.m.	105
1-2 p.m.	73

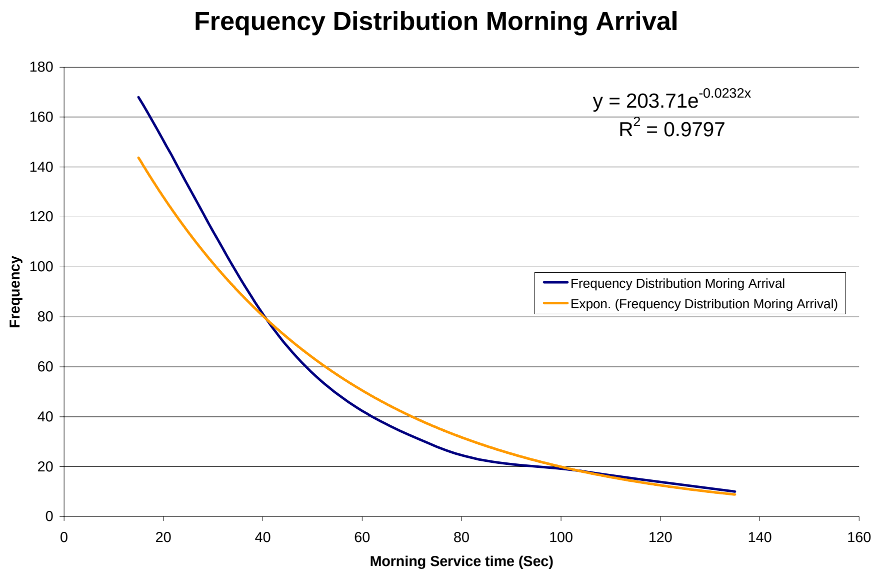

FIGURE 6 Frequency distribution of morning interarrival times

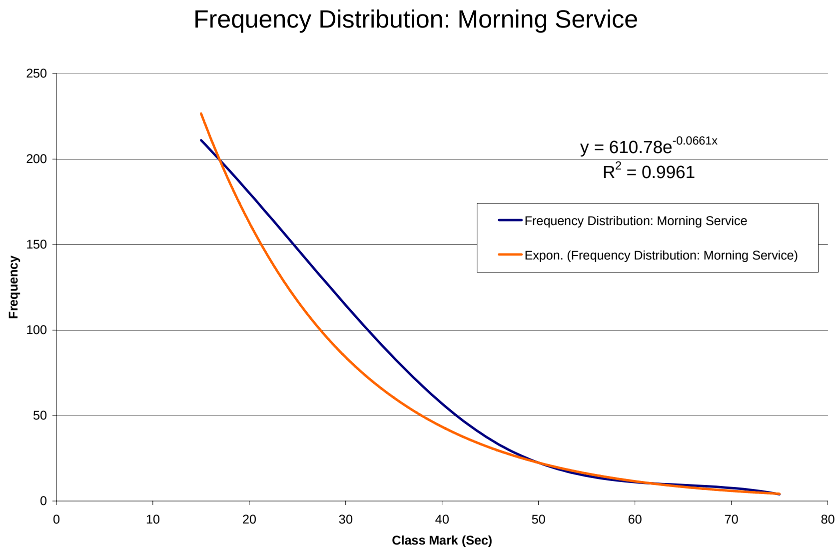

FIGURE 7 Frequency distribution of morning interservice times

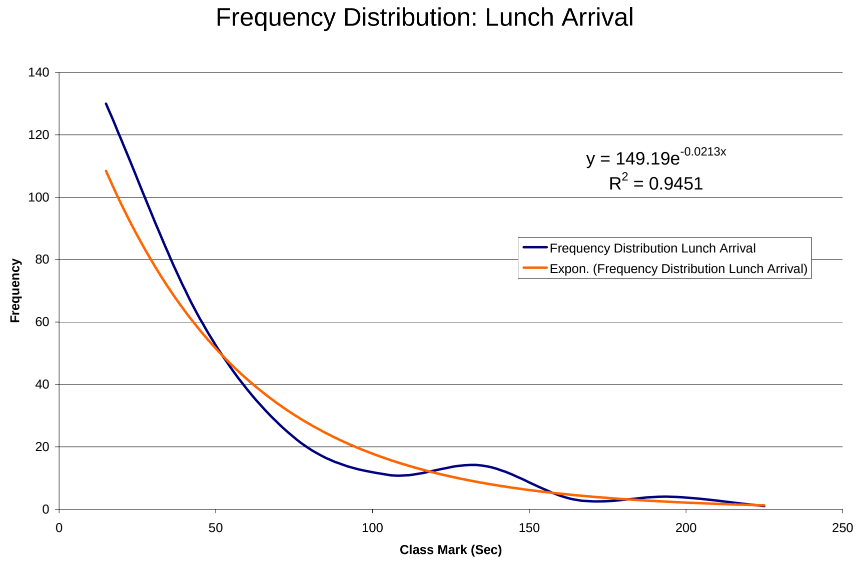

FIGURE 8 Frequency distribution of lunch interarrival times

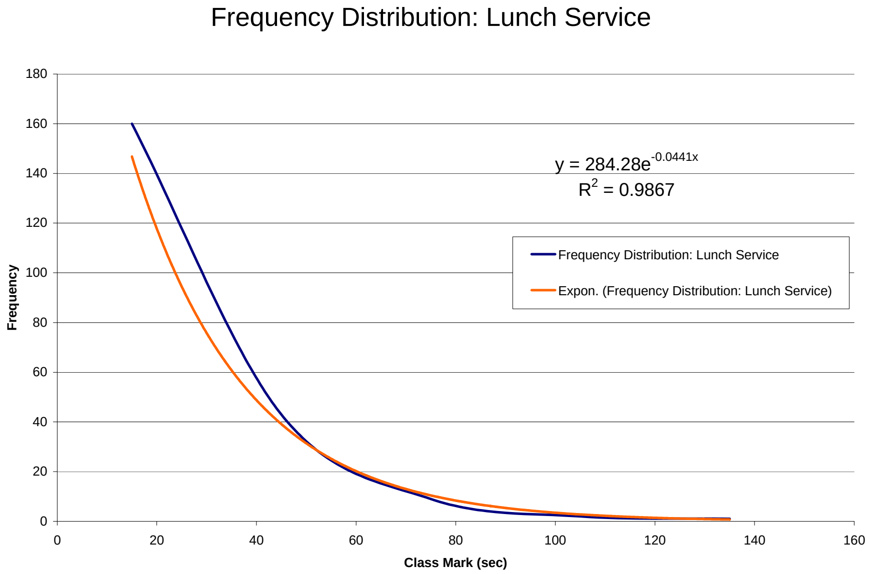

FIGURE 9 Frequency distribution of lunch interservice times

At this time, an assumption of an *M*/*M*/1 queuing system seems reasonable. In this queuing system, both the arrival and service events have a negative exponential distribution of the form:

$$f_T(t) = \begin{cases} \alpha e^{-\alpha t} & for\, t \geq 0 \\ 0 & for\, t < 0 \end{cases} \tag{6}$$

where $1/\alpha$ is the expected time between events. The assumption of a single server is based on the service at the pick up window controlling departure from the system. The service rate may not be constant for each arriving vehicle, but the simplified model is a necessary strategy as a first step in the analysis. Without a baseline queuing system, the researchers will lack a reasonable comparison when considering more complex queuing model forms. A $M/M/1$ queuing system is well known and the formulas associated with them may be found in any operations research textbook. This paper includes some basic terminology and formulas that are used to generate the queuing system state probabilities required for calculating the emissions associated with each system state (see the next section).

A queuing system may be represented by system states where the value of the state is determined by the number of customers in the system. When a new customer arrives, the system transitions to a higher state, and when a customer leaves, the system transitions to a lower state. The mean occurrence rate for an event depends only on the current system state. When assuming steady state conditions, these mean rates remain constant for the system. Table 1 shows that this is not likely the case; however, this assumption greatly simplifies analysis, and for many periods during the day, steady state conditions likely exist. The mean arrival rate is represented by λ, while μ represents the mean service rate. The system utilization factor, ρ, is defined in equation (7).

$$\rho = \frac{\lambda}{\mu} \tag{7}$$

The system idle time, P_0, which is the probability of the system being idle, is defined by equation (8).

$$P_0 = 1 - \rho \tag{8}$$

Equation (9) defines the probability of any system state occurring.

$$P_n = (1 - \rho)\rho^n \tag{9}$$

The researchers calculated separate λ and μ values for the morning and lunch periods. These values, as well as the emission factors and travel times within the parking lot, are summarized in Table 2. These values are integrated together in the next section to determine the emissions attributable to each system state.

Table 2. Queuing System Characteristics and Emission Factors

<table>
<tr><th></th><th>Morning</th><th>Lunch</th><th colspan="3"></th></tr>
<tr><td>Total Study time [Min]</td><td>180</td><td>180</td><td colspan="2">Idle EF (EF_I) [μg/veh/sec]</td><td>451</td></tr>
<tr><td>Total Study time [Sec] (T)</td><td>10800</td><td>10800</td><td colspan="2"></td><td></td></tr>
<tr><td>Total Drive-Thru Vehicles during Study period (V_{DT})</td><td>294</td><td>255</td><td colspan="2">Reverse (EF_R) [μg/veh/reverse]</td><td>7345</td></tr>
<tr><td>Average Interarrival Time [Sec]</td><td>37.5</td><td>42.9</td><td colspan="2">Avg. Time to Travel 100' [Sec] (t_{100})</td><td>9.4</td></tr>
<tr><td>Average Interservice Time [Sec]</td><td>28.6</td><td>33.3</td><td colspan="2">Avg. Time to Travel 80' [Sec] (t_{80})</td><td>9.4</td></tr>
<tr><td>λ [Veh/Min]</td><td>1.63</td><td>1.42</td><td colspan="2">Avg. Time to Travel 60' [Sec] (t_{60})</td><td>7.2</td></tr>
<tr><td>μ [Veh/Min]</td><td>2.11</td><td>1.84</td><td colspan="2">Avg. Time to Travel 40' [Sec] (t_{40})</td><td>5.6</td></tr>
<tr><td>ρ (λ/μ)</td><td>0.773</td><td>0.772</td><td colspan="2">Avg. Time to Travel 20' [Sec] (t_{20})</td><td>4.2</td></tr>
<tr><td colspan="6">Rolling Emissions: $y = 324 * x^{0.6527}$ ($R^2 = 0.854$)</td></tr>
<tr><td>Distance in Ft</td><td colspan="2">EF_D in μg/vehicle</td><td>Distance in Ft</td><td colspan="2">EF_D in μg/vehicle</td></tr>
<tr><td>200</td><td>EF_{200}</td><td>10,209</td><td>100</td><td>EF_{100}</td><td>6546</td></tr>
<tr><td>180</td><td>EF_{180}</td><td>9606</td><td>80</td><td>EF_{80}</td><td>5658</td></tr>
<tr><td>160</td><td>EF_{160}</td><td>8896</td><td>60</td><td>EF_{60}</td><td>4690</td></tr>
<tr><td>140</td><td>EF_{140}</td><td>8153</td><td>40</td><td>EF_{40}</td><td>3599</td></tr>
<tr><td>120</td><td>EF_{120}</td><td>7373</td><td>20</td><td>EF_{20}</td><td>2289</td></tr>
</table>

Estimating Emissions

Emissions for Customers Using Drive-Thru

The researchers attribute the events that cause emissions to system states within the queuing model. During the transition to a new state, emissions occur as vehicles change locations within the drive-thru. In addition to emissions associated with the transition, the vehicles in the system remain idling except for these transitions. The idling emissions can be combined the transition emissions to calculate the total emissions.

In order to properly quantify the emissions, the site dimensions must be defined.

- L_{IN} – length of driveway from the entrance to the order window, 200 feet
- L_{DT} – length of drive-thru from the order window to the pick-up window, 100 feet
- L_{OUT} – length of driveway from the pick-up window to the exit, 100 feet
- L_V – vehicle length, 20 feet
- T – study period, 10800 seconds (3 hours)
- V_{DT} – vehicle volume (Tables 1 and 2)

Idle Emissions

The idling emissions rely on the probabilities of each system state to determine the total amount of time that the system is in each state, where the state actually corresponds to the number of idling vehicles. The transition times are removed from the total idle time. Equation (10) quantifies the idling emissions, IE_n, for each state.

$$IE_n = \begin{cases} \left(\left(P_n * T\right) - \left(\left(P_{n-1} * V_{DT} * t_{[L_{DT}-(n-1)L_V]}\right) + \left(P_{n+1} * V_{DT} * t_{L_V}\right)\right) * EF_I\right) & for \dfrac{L_{DT}}{n} > L_V \\ \left(\left(P_n * T\right) - \left(\left(P_{n-1} + P_{n+1}\right) * \left(V_{DT} * t_{L_V}\right)\right) * EF_I\right) & for \dfrac{L_{DT}}{n} < L_V \end{cases} \tag{10}$$

where $n = 1$ to ∞

Transition Emissions: Vehicle Arriving

The proposed model assumes that the ordering window is always vacant when a new vehicle arrives; therefore, the emissions in this term relate to a vehicle entering the facility and driving to the end of the queue. An arriving vehicle may stop and place an order before reaching the end of the queue. The arriving transition emissions, ATE_n, are given in equation (11).

$$ATE_n = \begin{cases} \left(P_{n-1} * V_{DT} * \left(EF_{L_{IN}} + EF_{[L_{DT}-(n-1)L_V]}\right)\right) & for \dfrac{L_{DT}}{n} > L_V \\ \left(P_{n-1} * V_{DT} * \left(EF_{[L_{IN}-L_V(n-(1+ROUNDUP(L_{DT}/L_v)))]}\right)\right) & for \dfrac{L_{DT}}{n} \le L_V < \dfrac{L_{DT}+L_{IN}}{n} \\ \left(P_{n-1} * V_{DT} * \left(EF_{L_V}\right)\right) & for \dfrac{L_{DT}+L_{IN}}{n} \le L_V \end{cases} \tag{11}$$

where $n = 1$ to ∞ and all of the emissions factors are for rolling distance, EF_D.

Transition Emissions: Vehicle Departing

The researchers assume that there are no gaps in the queue when a vehicle departs. The emissions associated with a vehicle departing include the vehicle leaving the property and all remaining vehicles pulling forward one car length. In order for a vehicle to leave the system, a vehicle has to be in the system; therefore, the system's losses are proportionally distributed amongst all non-idle states. Equation (12) presents the formulation for the departing transition emissions, DTE_n.

$$DTE_n = \frac{P_{n+1}}{\rho} * V_{DT} * \left(EF_{L_{OUT}} + n * EF_{L_v}\right) \tag{12}$$

where $n = 0$ to ∞ and all of the emissions factors are for rolling distance, EF_D.

The total drive-thru emissions can be calculated using equation (13).

$$E_{DT} = \sum_{n=1}^{\infty} IE_n + ATE_n + DTE_n \tag{13}$$

Table 3 presents the system state probabilities (equation (9)) and the emissions from each state using equation (13). The total morning emissions for the drive-thru are 16.0 grams, and the total lunch emissions are 16.1 grams.

TABLE 3. System State Probabilities and Emissions

System State	Prob.	Morning	Lunch	Emission in g	Morning	Lunch
0	P_0	0.227	0.228	E_0	0.45	0.37
1	P_1	0.182	0.172	E_1	1.00	0.92
2	P_2	0.139	0.134	E_2	1.23	1.22
3	P_3	0.105	0.104	E_3	1.42	1.44
4	P_4	0.080	0.081	E_4	1.48	1.53
5	P_5	0.061	0.064	E_5	1.45	1.53
6	P_6	0.046	0.050	E_6	1.30	1.41
7	P_7	0.035	0.039	E_7	1.14	1.27
8	P_8	0.027	0.030	E_8	0.99	1.13
9	P_9	0.020	0.024	E_9	0.84	0.98
10	P_{10}	0.015	0.018	E_{10}	0.70	0.85
11	P_{11}	0.012	0.014	E_{11}	0.59	0.73
12	P_{12}	0.009	0.011	E_{12}	0.49	0.62
13	P_{13}	0.007	0.009	E_{13}	0.40	0.52
14	P_{14}	0.005	0.007	E_{14}	0.50	0.50
15	P_{15+}	0.029	0.016	E_{15+}	2.08	1.12
SUM		**1.000**	**1.000**		**16.0**	**16.1**

Emissions for Parking Customers

The parking customers' emissions depend on the parking location, which determines the distance traveled by the parking vehicle. This study has not completed a detailed analysis of parking space utilization; therefore, the researchers have made some assumptions regarding the lot's utilization. Given that the facility has thirty-two parking spots, the study assumes that all of the parking locations are utilized with a uniform probability. The study assumes that the parking vehicles enter and leave through the same driveway, and none of the parking spaces are pull through (i.e. one reverse maneuver occurs). Furthermore, the researchers assume that a parking space is always available for a customer; there is no blocking or balking. Without an analysis of the interior operations, the researchers cannot determine the hot soak time for each parking vehicle. Future research will measure hot start emissions as a function of hot soak time and determine this time based on the interior queuing system and dining behavior.

The equation for NO_x emissions from parking customers is given by equation (14).

$$E_P = \sum_{i=1}^{m} P_i * V_P * \left(2EF_{L_i} + EF_R\right) \tag{14}$$

Where E_P = Total customer parking emissions
P_i = Probability of customer selecting parking spot i
V_P = Volume parking at facility during study period (vehicles)
EF_R = Reverse emission factor (μg/veh) = 7345 μg /vehicle
EF_{L_i} = Rolling emission factor to distance L_i (μg/vehicle)

Table 4 specifies the number of parking spaces at each distance; recall that each space has an equal probability of selection. One should note that the probability associated with selecting different spaces may or may not differ by time of day and demand. The table also shows the emission factors associated with rolling distance from the entrance to the space, and the total emissions for the morning and lunch periods. When all of the drive-thru customers switch to parking, the morning emissions are 6.2 grams and the lunch emissions are 5.4 grams.

TABLE 4. Emissions for Parking Customers

Distance (Feet)	Parking spaces	EF_D (μgm/vehicle)		Emissions (grams)	
				Morning	Lunch
75	6	E_{75}	5425	1.00	0.87
100	10	E_{100}	6546	1.88	1.63
125	16	E_{125}	7572	3.31	2.87
Total				**6.2**	**5.4**

Reduction in Emissions due to Drive-Thru Closure

Based on existing drive-thru emissions, the percent reduction in emissions due to closing a drive-thru can be calculated as follows:

$$\text{Percent Reduction} = (E_{DT} - E_P)/E_{DT} * 100 \quad (15)$$

This calculation assumes that $V_{DT} = V_P$, or that every customer that previously used the drive-thru will now park (i.e. there is no reduction in customers). This is a conservative assumption (minimizes potential reductions due to closing the drive-thru), because in actuality, some customers may simply choose not to stop at the facility if the drive-thru is closed. However, this assumption also minimizes the negative impacts to the business. Closing the drive-thru will result in a 61% NO_x reduction over the three morning hours, and it will result in a 67% NO_x reduction over the three-hour lunch period.

CONCLUSIONS

This research represents an important step in verifying the potential emission reductions due to drive-thru closures. The reductions in NO_x emissions are in the range of 60-70% for the morning and lunch study periods. Given thousands of drive-thru locations scattered throughout the region, these reductions are likely significant and may be included in the region's SIP. This research establishes drive-thru closure as an effective strategy for reducing NO_x emissions; however, there remain numerous opportunities for further investigation into this topic.

Future efforts must address the planning agencies' next concern, which will likely focus on the policy's viability, especially in terms of the business and public response. Surveys can help address these concerns; however, a pilot study combined with surveys may be more effective. Part of this study must focus on any financial impacts on the businesses.

To broaden this research's impact, future studies should examine the potential regional impacts associated with a drive-thru closure program. One of the first keys to this effort is developing new emission factors that better represent the region's vehicle fleet as opposed to a single diesel truck; these fleet emission factors may be derived from MOBILE or through additional field experiments. If the observed benefits remain similar, this policy has the potential for extensive success. Part of extending the research to the entire region includes identifying the different types of drive-thrus throughout the region. Each drive thru type may have very different characteristics and behaviors. Perhaps of most interest will be if any have different queuing system structures; however, another important issue relates to daily demand patterns for different facility types. Not only may the demand patterns vary, but service rates may also be affected. In addition to facility type, facility layout may influence modeling strategies.

The researchers made many assumptions in the course of this research; future research and additional data collection can begin to examine these. Understanding changes in arrival and service rates throughout the day at different facility types is a critical issue. With additional data collection, the interarrival and interservice time for each rate may be examined individually to verify that they have a negative exponential distribution. The values estimated through the modeling effort may be verified in the field. There should also be a verification of travel times and behaviors within the queue.

Finally, when considering business impacts, the queuing systems for the facilities' interiors must be investigated to determine if degradation in customer service occurs. The interior queuing systems are even more likely than drive-thrus to vary by facility type. Characterizing and quantifying these impacts remains a critical barrier to implementation that requires attention.

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