Emissions Benefits from Reducing Local Transit Service Deadheading: An Atlanta Case Study

Hanyan Li, Graduate Research Assistant*
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/662-8184
Email: hli378@gatech.edu

Haobing Liu, Graduate Research Assistant
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/426-1678
Email: haobing.liu@gatech.edu

Xiaodan Xu, Graduate Research Assistant
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/502-0794
Email: xxu312@gatech.edu

Yanzhi "Ann" Xu, Ph.D.
Research Engineer II
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/723-0543
Email: yanzhi.xu@ce.gatech.edu

Michael O. Rodgers, Ph.D.
Principal Research Scientist and Adjunct Professor
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/385-0569
Email: michael.rodgers@ce.gatech.edu

Randall L. Guensler, Ph.D.
Professor
School of Civil and Environmental Engineering, Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332
TEL: 404/894-0405
Email: randall.guensler@ce.gatech.edu

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*Corresponding author

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ABSTRACT

Transit agencies are always seeking opportunities to conserve fuel (which typically provides simultaneous emissions reductions). According to the 2010 national bus transportation statistics for the United States, deadhead trips cover 13.3% of a total of 2.4 billion transit bus miles. Therefore, reducing deadheading tends to be a promising alternative to achieve reduction of fuel consumption and emissions. In order to minimize fuel consumption and emissions related to deadheading, this study proposes three strategies including optimal assignment of buses to existing bus yards, relocating a bus yard to a better location, and constructing a new bus yard. The Metropolitan Atlanta Rapid Transit Authority (MARTA) is taken as an example for analysis these three scenarios and the effectiveness of each strategy is evaluated in terms of fuel saving, emissions reduction, and cost impacts. Bus assignment and yard selection are conducted through GIS-based network analysis. Potential improvements on fuels and emissions are quantified through MOVES-Matrix, a high-performance emission simulation platform built based on MOVES model, with real-world operations data applied. Cost impacts relate to transit facility and operating costs. The results show that relocating the current yard is the “winning” strategy in perspective of emissions in the long run; however, re-assigning buses achieves 6% reduction in fuel consumption and does not require additional expenditures. The paper showcases the strategies for reducing deadheading in the planning process for transit agencies, and the analysis herein, conducted for the Atlanta region, can be easily applied to other agencies across the nation.

Keywords: Location Selection, Transit Bus, Operations, Emissions, MOVES, GPS, GIS

INTRODUCTION

Transit agencies are always seeking opportunities to reduce fuel consumption, which typically provides both cost savings and simultaneous emissions reductions. When optimizing a bus route network, many transit agencies aim to achieve the highest ridership and to maximize revenue service operations. However, non-revenue bus travel, or deadhead, is seldom taken into account. Deadhead covers a non-negligible portion of the entire operations, for example, deadhead covers 12.02% of the total local transit mileage for the Metropolitan Atlanta Rapid Transit Authority (MARTA), *(1)*. Hence, reducing deadheading tends to be a promising alternative to achieve reductions of fuel consumption and emissions.

There are two common types of deadhead: 1) buses travel to or from the maintenance facility (yard) and a terminus stop where revenue service begins or ends (start/ending stop), and 2) buses travel between the end of service on one route to the beginning of another. This research aims at presenting strategies to minimize the former type of deadhead operations. Before stepping into the proposed strategies, previous studies related to deadhead minimization are reviewed. Some studies determine the optimal garage number, locations, and corresponding bus allocations with the objective function of minimizing total garage-related costs. Waters et al. used discrete space models to achieve minimal costs, which considered the garage cost, modeled as a function of the number of buses stored, as well as breakdowns and accidents *(2)*. Willoughby used a mixed integer programming models and considered five candidate garages including investment costs for initial investment *(3)*. Some other studies focus on achieving minimal deadhead mileage. Prakash et al. determined the non-dominated schedules for traveling from yards to starting points of routes, the number of buses, and spare capacity, with two objectives *(4)*. One is to minimize the cumulative deadhead distance, and the other is to maximize deadhead distance by individual buses. Nasibov et al. proposed four models with different restrictions (garage capacity and operator distinction) in order to better support operational and strategical decisions *(5)*. CO_2 emission reduction was also analyzed for each model.

In this study, three strategies for minimizing emissions during deadheading are proposed, including: optimal re-assigning buses to existing bus yards, relocating one or more current bus yards, and constructing a new bus yard. These strategies are analyzed for implementation in the current MARTA local transit system. 90 candidate yard locations were identified and the optimal location was determined for the objective of minimizing deadhead mileage. In the new yard configuration, deadhead routes were generated by using ArcGIS Network Analyst. In order to evaluate these three strategies, potential reductions in fuel consumption and emissions were quantified using MOVES-Matrix, a multidimensional emission rate matrix obtained from tens of thousands of MOVES runs *(6)*. Second-by-second speed and position data were collected from the MARTA bus fleet, the principal rapid-transit system in the Atlanta metropolitan area by using a GPS device to map their daily trips. Deadhead operations are then extracted from these operations, and assigned with emission rates from MOVES runs. Besides the effects of emissions, additional costs for relocating or constructing a bus yard are investigated in order to comprehensively evaluate the proposed strategies.

In this paper we will discuss data preparation, including GPS operating data and deadhead operations then describe the methods used for generating emission rate and yard selection. We will then present the results of evaluation in terms of emissions and costs, followed by a brief discussion of impacts and future research.

DATA PREPARATION

Deadhead Operations

Currently, three bus yards (Laredo, Perry, and Hamilton) are housing local transit buses from MARTA. Deadhead operations (i.e., non-revenue service to and from the starting and ending stops respectively) are pre-determined during the service planning period and will not be changed unless major changes of service or traffic occur. Because the operating cycle is a week, weekly frequency (March 2015) of deadhead trips from bus yards to the start/ending stops of each bus route were collected and used as a weighting variable for optimizing deadhead mileage as described in the following section.

GPS Operations Data

Second-by-second transit operations data were collected by installing GPS devices on regular transit buses from MARTA. 7,183 hours of operating data were collected on local transit fleet for 381 days between June 28th, 2004 and Oct 24th, 2005. The GPS unit collected data automatically and the data were processed and converted to a useable format (csv) off-line.

METHODOLOGY

Emission Rate Generation

GPS traces for bus operations were pre-processed before being incorporated into the emissions analysis using the procedures shown in the Figure 1 below. Subsequently, emission rates were determined using MOVES-Matrix for both the baseline and alternative scenarios.

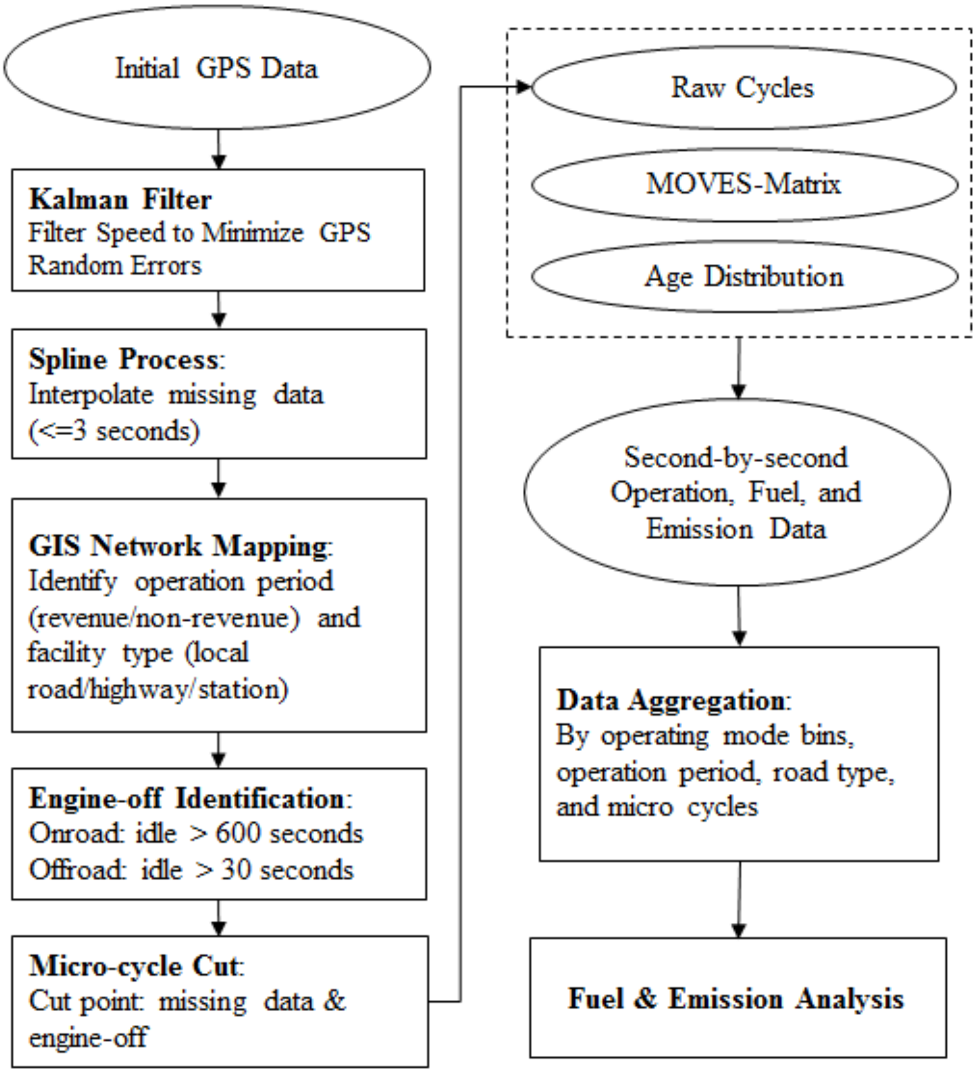

Figure 1. Data Processing Diagram

Data Pre-processing

The quality of the GPS data strongly depends on the GPS signal condition, represented by the number of satellites and positional dilution of precision (PDOP) values. Although GPS receivers employ proprietary filtering algorithms to compensate for data beyond known variances by correcting the data through embedded software, it is still necessary to further smooth the data because proprietary filtering algorithms cannot filter all outliers that manifest themselves as random errors in the GPS output data stream. A modified discrete Kalman filter algorithm has proven effective in controlling GPS random errors *(7)* and was used to correct the GPS speed. This approach uses a Kalman Gain Matrix based on the GPS quality criteria. In this method, if the number of satellites is below 4 or the PDOP is above 8, the quality of the individual speed measurement is determined to be poor and will be revised based on the speed of the previous second. Missing GPS traces due to obstruction and signal interference are interpolated through cubic spline algorithm in order to generate consecutive speed profiles for emission modeling. A missing segment is splined if its duration is no longer than 3 seconds, and bracketed with six good GPS points (i.e..three seconds before and three seconds after the segment but no earlier or later than 10 seconds) otherwise the segment is identified as missing.

To determine the operating period (revenue and deadhead) and facility type (restricted and unrestricted roadways) for each second of the operating data GIS network mapping was conducted. In this procedure, geospatial analysis is used to match the collected GPS traces with regular transit routes. The matching portions of the traces are identified as revenue service, and the other portions as deadhead activity. Next, the GPS traces are matched to existing expressway locations using a 72-feet buffer from the centerlines on each direction to minimize errors *(1)*.

Evaluation of idling versus engine stops is more difficult to determine using only location data traces. Drivers are likely to turn off the engine or switch to extended idle if they need to stop the bus for a long time for fuel savings or other reasons. To separate these conditions for purposes of analysis, the study defines an “idling threshold” for local transit is 1mph. A series of speeds below these thresholds is considered to be an idling condition. In the following two circumstances, the status of the operations is treated as engine-off, and any related fuel consumption or emissions will be excluded in the analysis:

a) On-road: when the length of continuous idling speed is longer than 10 minutes
b) Off-road: when the length of continuous idling speed is longer than 30 seconds.

After all the above steps, raw GPS traces are cut based on missing data and engine-off status to generate micro-cycles, which are further filtered through thresholds of average speed (1mph) and duration (1minute). In the available data, 9,004 cycles are obtained from local transit. These micro-cycles extracted from GPS data provide second-by-second operations (operating mode).

STP Calculation and Operating Mode Bin Assignment

In this research, emissions are estimated from emissions factors derived from U.S. EPA’s MOVES model *(8)*. For each second, Scaled Tractive Power (STP) and operating mode bin as defined in MOVES are calculated to link bus activity and emission inventory *(9)*. The second-by-second STP equation is:

$$STP = \left({}^{A}\!/_{M}\right)\times v + \left({}^{B}\!/_{M}\right)\times v^2 + \left({}^{C}\!/_{M}\right)\times v^3 + (a + g\times \sin\theta)\times v \qquad (1)$$

Where:

A: road load coefficients in units of (kiloWatt second)/(meter)
B: road load coefficients in units of (kilowatt second^2)/(meter^2)
C: road load coefficients in units of (kiloWatt second^3)/(meter^3)
M: mass for the source type in metric tons
v: vehicle speed in meters/second

a: vehicle acceleration in meters/second^2
$\sin\theta$: the (fractional) road grade
g: acceleration due to gravity (9.8 meter/ second^2)

MARTA buses correspond to transit bus (source use type ID=42) in MOVES model, so A, B, C, and M are determined from MOVES as 1.03968, 0, 0.00358702, 16.556 and 17.1 from the MOVES database *sourceUseTypePhysics (10).* Second-by-second operating mode bin is generated by using STP, speed, and acceleration value. For simplicity, the gradient is assumed to be flat ($\sin\theta=0$). In future research, specific grade(s) will be included.

Second-by-Second Emission Rates Assignment

Emissions are estimated based on MOVES second-by-second emission rates for actual vehicle speed traces to provide the fundamental data used for further aggregation. As the sample size becomes larger, it becomes increasingly impractical to run MOVES directly and thus emissions estimates are based on using MOVES-Matrix.

MOVES-Matrix is built based on a huge amount of MOVES runs *(6)*. MOVES runs are iterated across all variables that affect output emission rates, and each iteration yields an emission rate applicable to all kinds of air pollutant in uniform source type, uniform model year (age group), specific operation (average speed & road type, or on-road VSP/STP operating mode bin) with a given calendar year and applicable regional regulatory parameters (fuels properties, I/M) under specific temperature and humidity conditions. After all these runs, users are able to call for MOVES-Matrix emission rates from other operations and obtain the exact same emission outputs as MOVES model without having to launch MOVES or transfer outputs into the analyses. Basically, users determine the subset of operations by calendar year, fuel month and meteorology, and then use MOVES-Matrix to find the applicable emission rate. Users can then assemble fleet emissions rates uses these emissions factors weighted by on-road activity for each operational condition. In this research, in order to compare different strategies, we obtained rates from MOVES-Matrix with the settings listed below:

- Calendar Year: 2015
- Region: Fulton County, Atlanta
- Month: January
- Date and Time: weekday, 7:00-8:00AM
- Meteorology (default value determined by time and region from MOVES):
    - Temperature: 30 F
    - Humidity: 75%
- Fuel: default winter fuel supply and fuel share from MOVES
- I/M Strategy: default 2015 I/M strategy from MOVES
- Source Type: transit bus (source type ID = 42)

- Age Distribution: current MARTA vehicle inventory *(11)*
- 23 Links: each link is applied with 100% fraction of one operating mode bin, time scaled to 1 hour operation using link length and link average speed

It is easy to assign emission rate to each second from the matrix table of bus emission rate, based on operating mode bin of each second. For example, in 2015, the CO emission rate for a new CNG transit bus is 0.064 g/sec (230.569 g/hr) when operating between 9 and 12 kW/tonne. This process is more efficient than directly running MOVES since it avoids duplicated calculations while producing identical results. Five criteria pollutant emissions (HC, CO, NO_x, PM_{10} and $PM_{2.5}$), CO_2, and fuel consumption rate were estimated using this approach.

Operation and Emission Aggregation

From second-by-second data, we can aggregate operations and emissions by road type and by operation period (revenue/deadhead). Then emission rates in grams/mile/vehicle were aggregated by summing second-by-second emissions and divided by distance under different scenarios in terms of operating mode, fuel type, and age distribution.

Table 1. Fuel and Emission Rate (Pollutant: grams/mi/veh, Fuel: KJ/mi/veh)

Fuel Type	Road Type	CO	NOx	$PM_{2.5}$	CO_2	Fuel
Diesel	Unrestricted	3.03	7.98	0.52	1,031	14,003
	Restricted	1.7	4.6	0.23	666	9,042
CNG	Unrestricted	7.46	5.41	0.02	1,010	17,112
	Restricted	4.72	3.84	0.04	615	10,418

Yard Selection

Based on section above, the emissions generated during current weekly deadheading operations can be derived with proposed methodology. In this section, the three strategies are implemented with new assignments of buses to yards generated.

Current Practice

As for deadhead routing, MARTA aims to minimize the traveling time and traveling distance, but the deadheading routes are not strictly determined. Therefore, shortest-path algorithm is implemented in ArcGIS Network Analyst to generate the deadheading routes of buses from the start/ending stops to the assigned yard, shown below. Then the deadhead distance for each bus route (D_i) is caculated by summing up all the distances of pulling into and out of the assigned yard (D_j), represented equation (1), where n is the number of pulling activities. The total weekly deadheading distance of the entire MARTA transit bus system is calculated through equation (2), where$f_{1,i}$, $f_{2,i}$, $f_{3,i}$ are the route frequency of a weekday, Saturday, and Sunday, respectively.

$$D_i = \sum_{j=1}^{n} D_j \quad (1)$$

$$D = \sum_{i=1}^{96} (5f_{1,i} + f_{2,i} + f_{3,i}) D_i \quad (2)$$

After generating the deadheading routes, the portions of deadhead operationgs on restricted roadways are identified through network mapping in order to further evaluate the emissions and fuel consumption, shown in Table 2. It can be seen that some buses are not assigned to the closest yard and some deadheading distances are too long. This proves the need to reconsider the assignment of buses to depots in order to minimize the total deadhead distance.

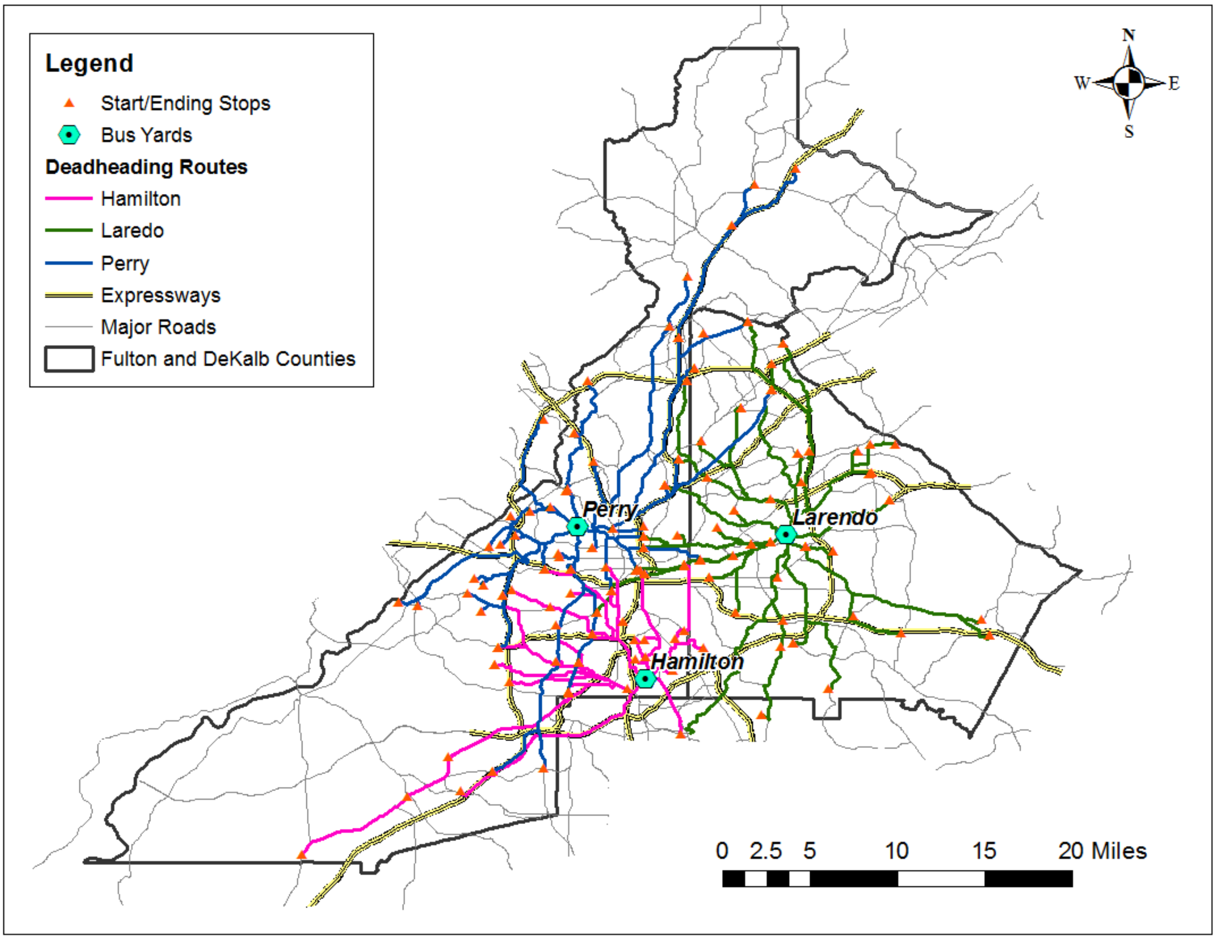

Figure 2. Current Deadheading Routes

Yard Re-Assignment

As mentioned above, the current bus assignment may not obtain the minimum total deadhead distance; therefore, each bus route is re-allocated to one among the three yards to achieve the minimum. In this case, for each bus route, deadhead routes are generated for each bus route and compare with the current assignment. The results show that the 12 bus routes should be assigned to a different yard, aggregated in Table 2. The figure below shows an example of reassigning three bus routes, and the weekly deadheading distance of these three routes is reduced from 464.28 to 329.4 mile.

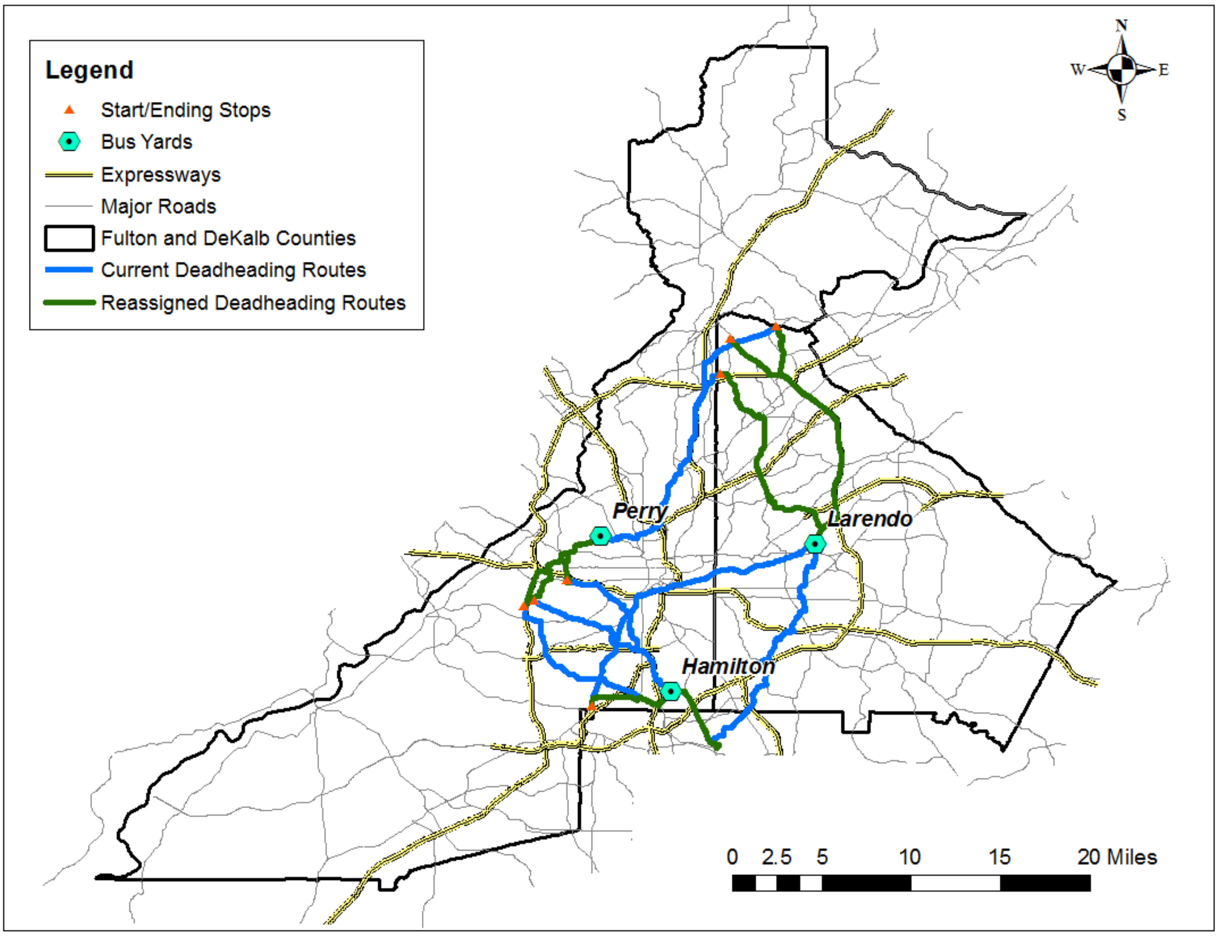

Figure 3. Example of Reassigned Deadheading Routes

Existing Yard Relocation

Relocation strategy is to discard one of the current three yards and select a new yard from the 90 yard candidates. The current bus revenue service is assumed to be the same in the new yard configuration. Major steps are listed below.

(1) Identify yard candidates. Yard candidates indicate the future locations of the relocated bus yards, mostly on major streets. According to the zoning code, bus yards should be placed in industrial zones. Therefore, 90 candidates are identified on the intersections of major streets within the industrial zones. In fact, yards cannot be constructed in the intersections; in this case, the distance of traveling from intersection to the actual location is ignored.

(2) Generate Origin-Destination (OD) Cost Matrix between all bus start/ending stops (origins) and yard candidates (destinations) based on the established road network. This is implemented in ArcGIS network analyst by using a multiple-origin, multiple-destination

algorithm based on Dijkstra's algorithm, designed to solve the single-source, shortest-path problem on a weighted graph.

(3) Calculate the total deadhead distance under the condition of relocating one bus yard ($y3$) to one of the 90 yard candidates (j), shown in Equation (3). Then prioritize the total deadhead distance for each condition.

$$D_j = \sum_{i=1}^{96} \left(5f_{1,i} + f_{2,i} + f_{3,i}\right) * \min\left(D_{i,j}, D_{i,y1}, D_{i,y2}\right) \qquad (3)$$

$$j = 1,2,\ldots,90, \qquad y1, y2, y3 \in \{Laredo, Perry, Hamilton\}, y1 \neq y2 \neq y3$$

Select the relocated yard. Relocating Hamilton, Perry, and Laredo yard will achieve 10.35%, 9.19%, and 6.79% of the total deadheading mileage at most. Therefore, Hamilton yard is chosen to be relocated. Bus routes are assigned to Perry, Laredo and the new yard, and then the new deadhead routes are generated as shown in Figure 4, and the deadhead mileages are summarized in Table 2.

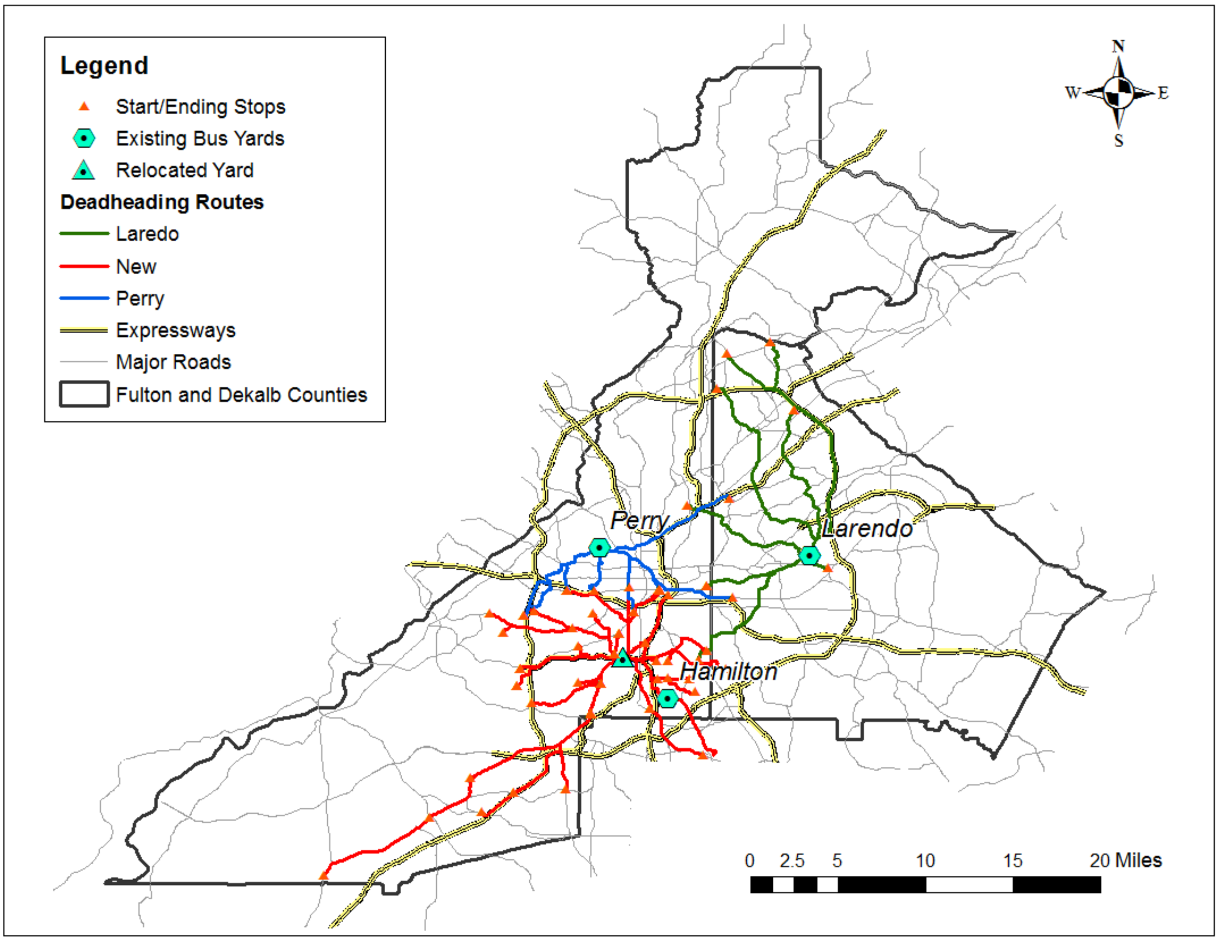

Figure 4. New Deadheading Routes of Relocated Yard Case

New Yard Construction

New yard construction strategy refers to construct one new yard while maintaining the current three yards. The current bus revenue service is assumed to be the same in the new yard configuration. Main steps are listed below.

(1) Identify yard candidates and generate Origin-Destination (OD) Cost Matrix, the same as the relocation case.

(2) Calculate the total deadhead distance under the condition of construct a new bus yard (j), shown in Equation (4). Then prioritize the total deadhead distance for each yard candidate.

$$D_j = \sum_{i=1}^{96} \left(5f_{1,i} + f_{2,i} + f_{3,i}\right) * \min\left(D_{i,j}, D_{i,y1}, D_{i,y2}, D_{i,y3}\right) \tag{4}$$

$$j = 1,2,\dots,90, \qquad y1, y2, y3 \in \{Laredo, Perry, Hamilton\}, y1 \neq y2 \neq y3$$

Select the new yard. The yard which achieves the minimum total deadhead distance is chosen and the results are summarized in Table 2.

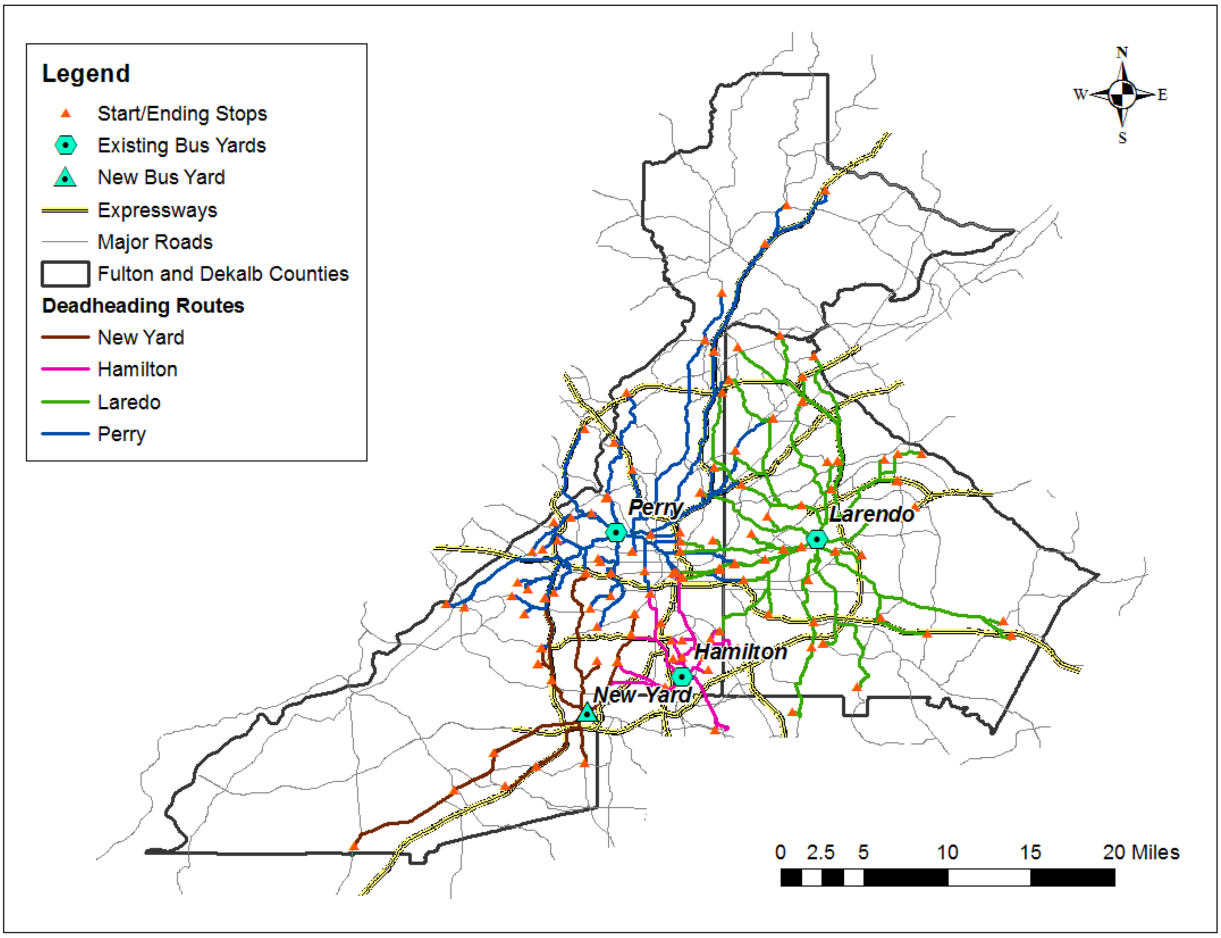

Figure 5. Deadheading Routes of New Yard Case

The table below shows the weekly deadhead mileage for the current practice and proposed three strategies. As mentioned above, the cycle of local transit is a week, and thus weekly deadhead mileage can represent regular deadhead operations.

Table 2. Weekly Deadhead

Strategy	Total		Restricted Facility		Unrestricted Facility	
	Mileage	Percentage	Mileage	Percentage	Mileage	Percentage
Current (Base)	47,378.4	N/A	8,445.4	N/A	38,933.0	N/A
Yard Re-Assignment	44,783.3	-5.48%	8,310.5	-1.60%	36,472.9	-6.32%
Existing Yard Relocation	42,473.4	-10.35%	8,853.7	4.84%	33,619.6	-13.65%
New Yard Construction	41,907.4	-11.55%	7,250.2	-14.15%	34,657.2	-10.98%

STRATEGY EVALUATION

Emissions Analysis

In order to evaluate the effectiveness of the fuel saving strategies, annual emissions and fuel consumption are estimated by Equation (5). Current deadhead operations is set as the base case, and emission reduction for each strategy is obtained by Equation (6). Vehicle inventory and annual mileage are obtained from National Transit Database *(11)*.

$$\boldsymbol{E_{i,j} = \frac{\sum_r \sum_d \sum_t Rate_{r,j} M_{r,i} N_t}{\sum_t N_t}} \tag{5}$$

$$\boldsymbol{Reduction_{i,j} = \frac{E_{i,j} - E_{base,j}}{E_{base,j}} * 100\%} \tag{6}$$

Where,

$E_{i,j}$: weekly emissions of pollutant j under strategy i;

$E_{base,j}$: weekly emissions of pollutant j under the base case;

$Reduction_{i,j}$: reduction percentage of pollutant j under strategy i;

i: strategy index, under different settings of deadhead mileage;(

j: criteria pollutant and GHGs index, i.e., CO, NOx, $PM_{2.5}$, CO_2;

r: road type index, i.e., restricted or unrestricted roadways;

t: fuel type index, i.e., CNG or diesel;

N_t: fleet size fuel type t;

$Rate_{r,d,j}$: emission rate of pollutant j, on road type r;
$M_{r,d,i}$: weekly deadhead mileage on road type r, under strategy i.

The evaluation the results are shown in Table 3. Even though the weekly deadhead distance of constructing a new bus is lower than relocating the existing yard, it does not achieve the most significant reduction of emissions. This is because the portion of restricted mileage for the relocating strategy is increased by 4.84% whereas it is decreased by 14.15%, and the emission rates on restricted facility is much lower than those on unrestricted facility.

Table 3. Annual Emission Reduction (Pollutant: Kg, Fuel: KJ)

Strategy	CO	NOx	$PM_{2.5}$	CO_2	Fuel
Current Practice Base	14,095	14,296	386	2,334,269	50,131,415,280
Yard Re-Assignment	-5.76%	-5.73%	-5.80%	-5.76%	-5.75%
Existing Yard Relocation	-11.45%	-11.34%	-11.61%	-11.46%	-11.44%
New Yard Construction	-11.36%	-11.38%	-11.33%	-11.36%	-11.36%

To get a better sense of the effectiveness of these strategies, reassigning buses within the three existing yards, relocating an existing yard, and constructing a new bus yard, will achieve the annual reductions of CO_2 of 134,430, 267,415, and 265,133kg, respectively. This proves that more reasonable assignment of buses to depots is promised to reduce fuel consumptions and emissions.

Cost Analysis

In order to evaluate the feasibility of the three proposed strategies, this chapter analyzes the extra facility and maintenance costs of relocating and constructing a new bus yard as compared with the current situation. The strategy of re-assigning buses to the closest yards is assumed not to cause any extra costs. This is because no significant changes of the number of buses assigned to each bus yard or extra bus runs occur. In fact, reducing deadhead will cause the reduction of operating time, and thus contribute to the savings of employment. In this study, such saving is not analyzed. The costs of relocating and constructing a new bus yard are analyzed for CNG garage only, because MARTA is leaning towards to only purchase CNG buses in the future. The most important costs associated with developing a CNG bus facility are those related to land, engineering drawings, station design, equipment, and installation.

Even though the costs for constructing a CNG yard vary significantly for different local settings, some studies have been conducted to estimate the facility costs. In 2001, WMATA commissioned a new $4 million CNG refueling station (incorporating three compressors) to serve a fleet of 164 CNG buses at the depot in Bladensburg, Maryland. In addition, the annual electricity costs for running the compressors is approximately $360,000, and modifying the maintenance facility to accommodate CNG buses requires $11.6 million *(12)*. A recent contract announced by the Orange County Transportation Authority costs $3.6 million for designing, building, and operating a new CNG refueling station to serve 63 CNG buses and provide 500,000 DGE annually *(13)*. In TCRP Report 132, CNG facility costs are modeled as a base cost of $1,000,000 plus $15,000 per CNG bus *(14)*. Operating a CNG yard costs more than a traditional diesel yard because of the additional costs of electricity for the compressors, estimated as roughly equal to 6% of CNG infrastructure costs per year. In the default setting of FuelCost2, additional facility operational costs for CNG is estimated as $0.05 per mile assuming the average annual mileage is 37,000 per bus. Lowell indicates that the cost of CNG fuel station construction is $25,800 per bus, according to a cost calculator developed by Marathon Technical Services and used by the National Renewable Energy Laboratory *(15)*. The U.S. Department of Energy indicates that the estimated total cost including costs of engineering, equipment and installation of a private fleet station is $550,000 - $850,000; the included installation costs are estimated at 65% of equipment costs *(16)*. The wide price ranges presented are consequent of the variance of equipment available, the fleet size, etc. More detailed information is required in order to get an estimate for a specific project.

CONCLUSIONS

Optimal yard locations with the minimal total weekly deadhead mileage are selected for three evaluated strategies. Re-assigning buses, relocating one existing bus yard, and constructing a new bus yard reduce the deadheading mileage by 5.48%, 10.35%, and 11.55%. The results show that relocating Hamilton yard and constructing a new yard provide more significant improvements (reduction of 11%) as compared with re-assigning buses to existing yards (reduction of 6%) in terms of saving fuel and reducing emissions. This is because the new yard is closer to more starting/ending stops. Moreover, lowest weekly total deadheading mileage achieved by constructing a new bus yard does not result in the lowest weekly emissions, because the portion on restricted facility is reduced.

Even though the three strategies contribute to significant fuel saving and emissions reduction associated with deadhead, studies on costs of constructing a new yard show that initial costs of developing the facility and further additional operating costs are not negligible. Whether or not it is more cost-effective to relocate/construct a new facility requires life-cycle analysis on costs and emissions. If not considering new facility development, re-assigning buses to the yard that can reduce deadhead is a promising strategy. This may require some time or training to familiarize the operators with the routes, but the costs of this is trivial as compared with the other two strategies.

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