

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

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**1 ABSTRACT**

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

21  
22 **Keywords:** Location Selection, Transit Bus, Operations, Emissions, MOVES, GPS, GIS  
23

## 1 INTRODUCTION

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

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

28 In this study, three strategies for minimizing emissions during deadheading are proposed,  
29 including: optimal re-assigning buses to existing bus yards, relocating one or more current bus  
30 yards, and constructing a new bus yard. These strategies are analyzed for implementation in the  
31 current MARTA local transit system. 90 candidate yard locations were identified and the  
32 optimal location was determined for the objective of minimizing deadhead mileage. In the new  
33 yard configuration, deadhead routes were generated by using ArcGIS Network Analyst. In  
34 order to evaluate these three strategies, potential reductions in fuel consumption and emissions  
35 were quantified using MOVES-Matrix, a multidimensional emission rate matrix obtained from  
36 tens of thousands of MOVES runs (6). Second-by-second speed and position data were  
37 collected from the MARTA bus fleet, the principal rapid-transit system in the Atlanta

1 metropolitan area by using a GPS device to map their daily trips. Deadhead operations are then  
2 extracted from these operations, and assigned with emission rates from MOVES runs. Besides  
3 the effects of emissions, additional costs for relocating or constructing a bus yard are  
4 investigated in order to comprehensively evaluate the proposed strategies.

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

## 9 **DATA PREPARATION**

### 10 **Deadhead Operations**

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

### 18 **GPS Operations Data**

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

## 23 **METHODOLOGY**

### 24 **Emission Rate Generation**

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

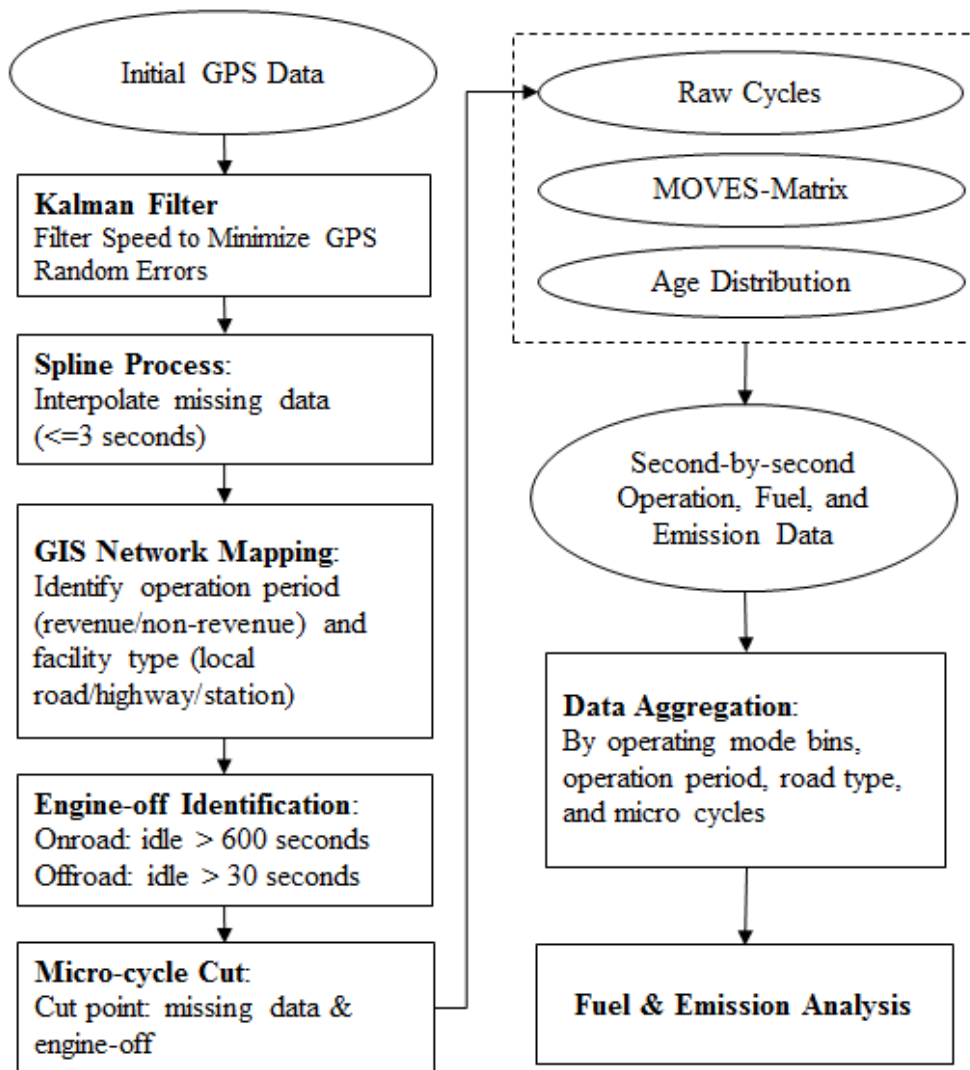


Figure 1. Data Processing Diagram

1

2

3 *Data Pre-processing*

4 The quality of the GPS data strongly depends on the GPS signal condition, represented by the  
 5 number of satellites and positional dilution of precision (PDOP) values. Although GPS receivers  
 6 employ proprietary filtering algorithms to compensate for data beyond known variances by  
 7 correcting the data through embedded software, it is still necessary to further smooth the data  
 8 because proprietary filtering algorithms cannot filter all outliers that manifest themselves as  
 9 random errors in the GPS output data stream. A modified discrete Kalman filter algorithm has  
 10 proven effective in controlling GPS random errors (7) and was used to correct the GPS speed.  
 11 This approach uses a Kalman Gain Matrix based on the GPS quality criteria. In this method, if  
 12 the number of satellites is below 4 or the PDOP is above 8, the quality of the individual speed  
 13 measurement is determined to be poor and will be revised based on the speed of the previous  
 14 second. Missing GPS traces due to obstruction and signal interference are interpolated through

1 cubic spline algorithm in order to generate consecutive speed profiles for emission modeling. A  
 2 missing segment is splined if its duration is no longer than 3 seconds, and bracketed with six  
 3 good GPS points (i.e. three seconds before and three seconds after the segment but no earlier or  
 4 later than 10 seconds) otherwise the segment is identified as missing.

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

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

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

20 After all the above steps, raw GPS traces are cut based on missing data and engine-off  
 21 status to generate micro-cycles, which are further filtered through thresholds of average speed  
 22 (1mph) and duration (1minute). In the available data, 9,004 cycles are obtained from local  
 23 transit. These micro-cycles extracted from GPS data provide second-by-second operations  
 24 (operating mode).

### 25 *STP Calculation and Operating Mode Bin Assignment*

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

$$STP = (A/M) \times v + (B/M) \times v^2 + (C/M) \times v^3 + (a + g \times \sin \theta) \times v \quad (1)$$

30 Where:

31 *A*: road load coefficients in units of (kiloWatt second)/(meter)

32 *B*: road load coefficients in units of (kilowatt second<sup>2</sup>)/(meter<sup>2</sup>)

33 *C*: road load coefficients in units of (kiloWatt second<sup>3</sup>)/(meter<sup>3</sup>)

34 *M*: mass for the source type in metric tons

35 *v*: vehicle speed in meters/second

1  $a$ : vehicle acceleration in meters/second<sup>2</sup>

2  $\sin \theta$ : the (fractional) road grade

3  $g$ : acceleration due to gravity (9.8 meter/ second<sup>2</sup>)

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

### 9 *Second-by-Second Emission Rates Assignment*

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

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

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

- 1 • Age Distribution: current MARTA vehicle inventory (11)
- 2 • 23 Links: each link is applied with 100% fraction of one operating mode bin, time scaled to 1
- 3 hour operation using link length and link average speed

4 It is easy to assign emission rate to each second from the matrix table of bus emission  
 5 rate, based on operating mode bin of each second. For example, in 2015, the CO emission rate  
 6 for a new CNG transit bus is 0.064 g/sec (230.569 g/hr) when operating between 9 and 12  
 7 kW/tonne. This process is more efficient than directly running MOVES since it avoids  
 8 duplicated calculations while producing identical results. Five criteria pollutant emissions (HC,  
 9 CO, NO<sub>x</sub>, PM<sub>10</sub> and PM<sub>2.5</sub>), CO<sub>2</sub>, and fuel consumption rate were estimated using this approach.

## 10 Operation and Emission Aggregation

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

15  
 16 Table 1. Fuel and Emission Rate (Pollutant: grams/mi/veh, Fuel: KJ/mi/veh)

Fuel Type	Road Type	CO	NO <sub>x</sub>	PM <sub>2.5</sub>	CO <sub>2</sub>	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

## 17 Yard Selection

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

### 21 *Current Practice*

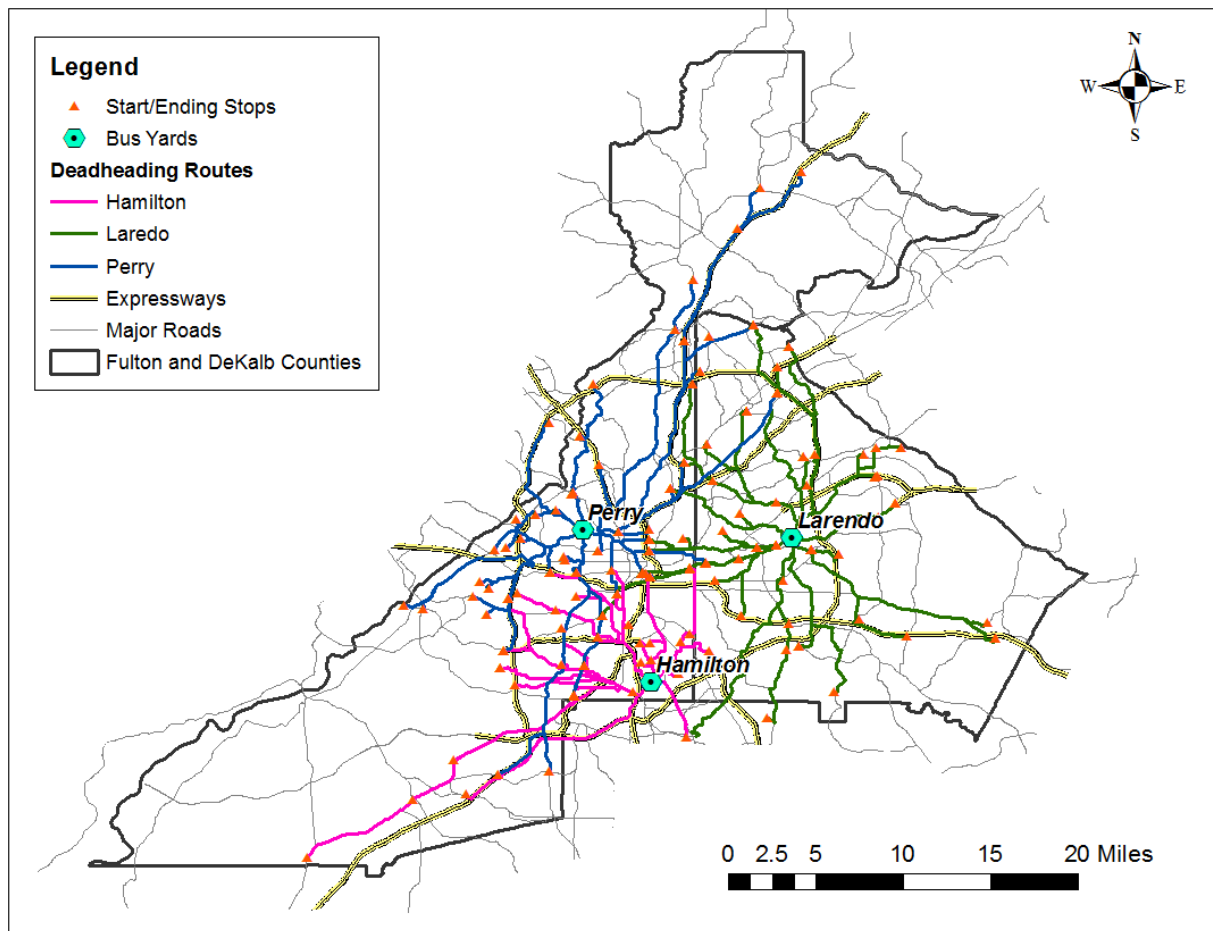
22 As for deadhead routing, MARTA aims to minimize the traveling time and traveling distance,  
 23 but the deadheading routes are not strictly determined. Therefore, shortest-path algorithm is  
 24 implemented in ArcGIS Network Analyst to generate the deadheading routes of buses from the  
 25 start/ending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



$$D_i = \sum_{j=1}^n D_j \tag{1}$$

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

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

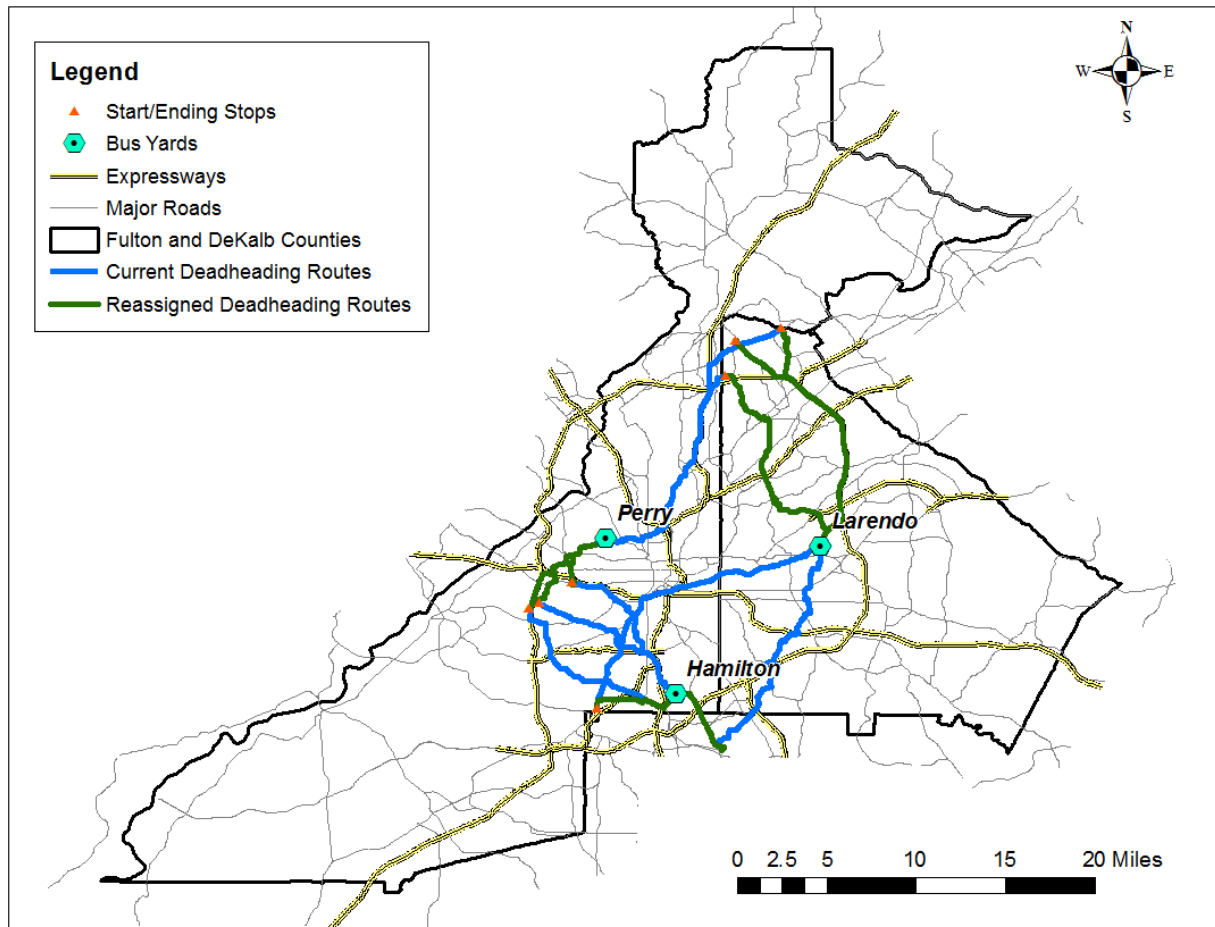


6  
 7 **Figure 2. Current Deadheading Routes**

8 *Yard Re-Assignment*

9 As mentioned above, the current bus assignment may not obtain the minimum total deadhead  
 10 distance; therefore, each bus route is re-allocated to one among the three yards to achieve the  
 11 minimum. In this case, for each bus route, deadhead routes are generated for each bus route and  
 12 compare with the current assignment. The results show that the 12 bus routes should be assigned

1 to a different yard, aggregated in [Table 2](#). The figure below shows an example of reassigning  
 2 three bus routes, and the weekly deadheading distance of these three routes is reduced from  
 3 464.28 to 329.4 mile.



4  
 5 Figure 3. Example of Reassigned Deadheading Routes

#### 6 *Existing Yard Relocation*

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

- 10 (1) Identify yard candidates. Yard candidates indicate the future locations of the relocated bus  
 11 yards, mostly on major streets. According to the zoning code, bus yards should be placed in  
 12 industrial zones. Therefore, 90 candidates are identified on the intersections of major streets  
 13 within the industrial zones. In fact, yards cannot be constructed in the intersections; in this  
 14 case, the distance of traveling from intersection to the actual location is ignored.
- 15 (2) Generate Origin-Destination (OD) Cost Matrix between all bus start/ending stops (origins)  
 16 and yard candidates (destinations) based on the established road network. This is  
 17 implemented in ArcGIS network analyst by using a multiple-origin, multiple-destination

1 algorithm based on Dijkstra's algorithm, designed to solve the single-source, shortest-path  
 2 problem on a weighted graph.  
 3 (3) Calculate the total deadhead distance under the condition of relocating one bus yard ( $y_3$ ) to  
 4 one of the 90 yard candidates ( $j$ ), shown in Equation (3). Then prioritize the total deadhead  
 5 distance for each condition.

$$D_j = \sum_{i=1}^{96} (5f_{1,i} + f_{2,i} + f_{3,i}) * \min(D_{i,j}, D_{i,y_1}, D_{i,y_2}) \tag{3}$$

$$j = 1, 2, \dots, 90, \quad y_1, y_2, y_3 \in \{Laredo, Perry, Hamilton\}, y_1 \neq y_2 \neq y_3$$

6 Select the relocated yard. Relocating Hamilton, Perry, and Laredo yard will achieve  
 7 10.35%, 9.19%, and 6.79% of the total deadheading mileage at most. Therefore, Hamilton yard  
 8 is chosen to be relocated. Bus routes are assigned to Perry, Laredo and the new yard, and then  
 9 the new deadhead routes are generated as shown in [Figure 4](#), and the deadhead mileages are  
 10 summarized in [Table 2](#).

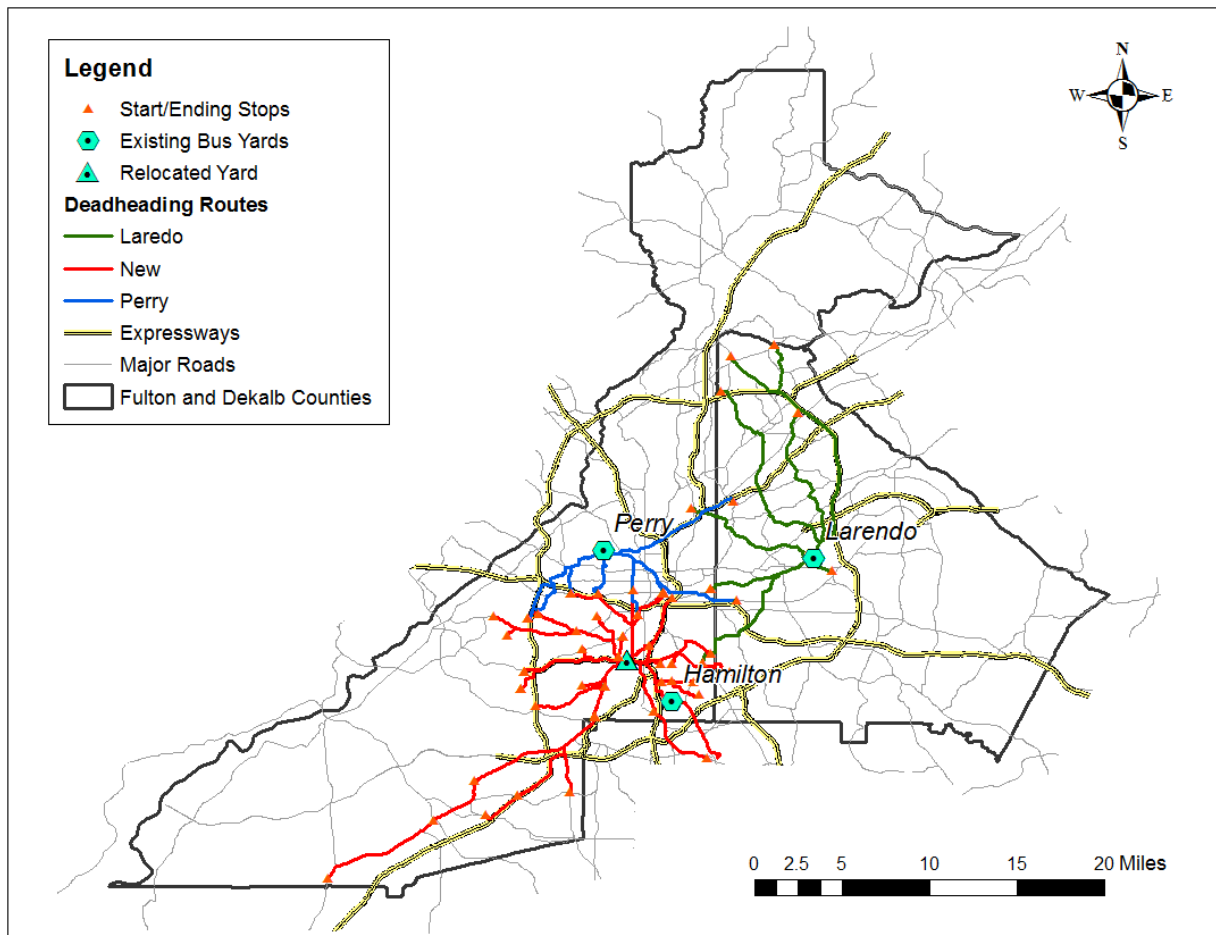


Figure 4. New Deadheading Routes of Relocated Yard Case

11  
 12  
 13

1 *New Yard Construction*

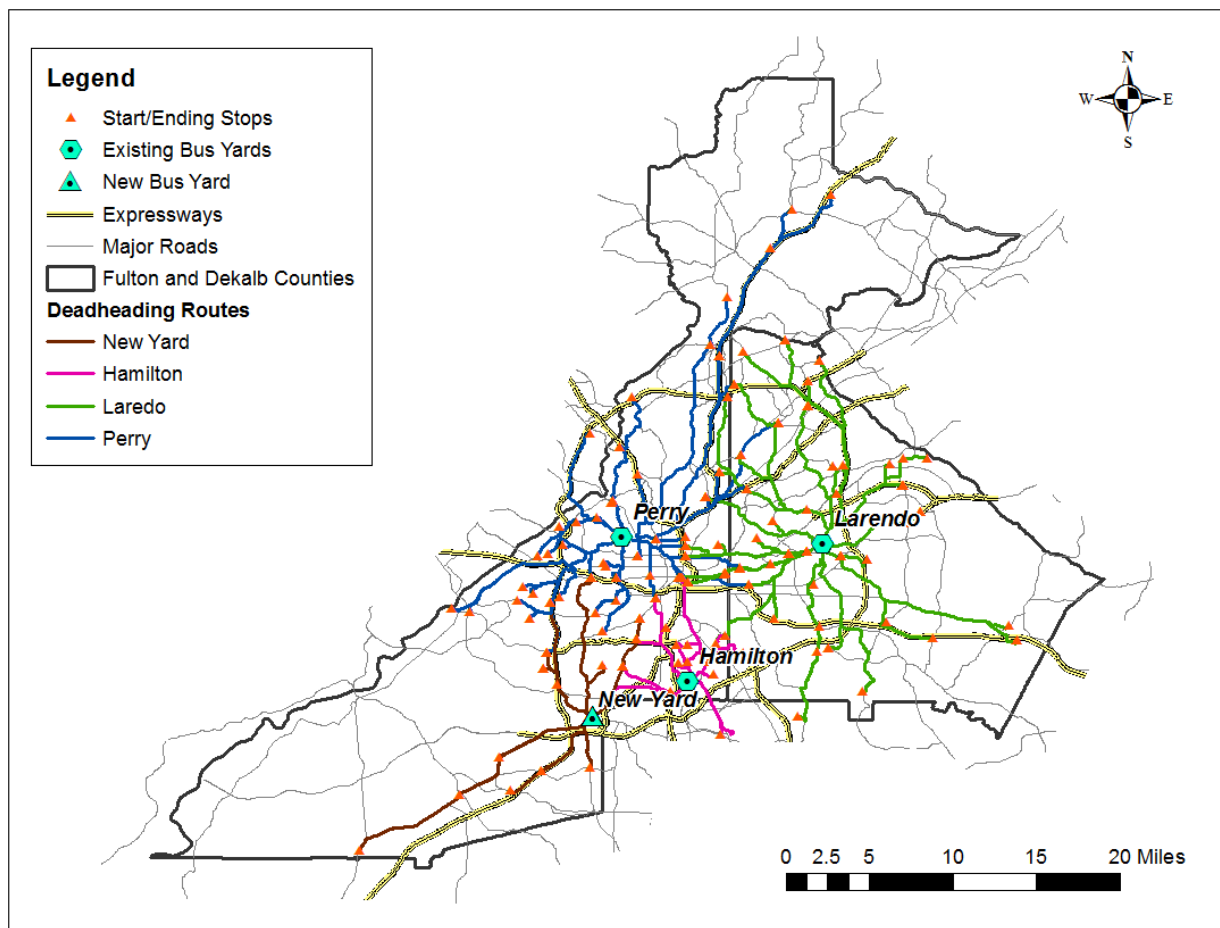
2 New yard construction strategy refers to construct one new yard while maintaining the current  
 3 three yards. The current bus revenue service is assumed to be the same in the new yard  
 4 configuration. Main steps are listed below.

- 5 (1) Identify yard candidates and generate Origin-Destination (OD) Cost Matrix, the same as the  
 6 relocation case.  
 7 (2) Calculate the total deadhead distance under the condition of construct a new bus yard (*j*),  
 8 shown in Equation (4). Then prioritize the total deadhead distance for each yard candidate.

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

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

9  
 10 Select the new yard. The yard which achieves the minimum total deadhead distance is  
 11 chosen and the results are summarized in [Table 2](#).



12  
 13 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%

## 6 STRATEGY EVALUATION

### 7 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).

$$E_{i,j} = \frac{\sum_r \sum_d \sum_t \text{Rate}_{r,j} M_{r,i} N_t}{\sum_t N_t} \quad (5)$$

$$\text{Reduction}_{i,j} = \frac{E_{i,j} - E_{base,j}}{E_{base,j}} * 100\% \quad (6)$$

13 Where,

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

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

16  $\text{Reduction}_{i,j}$ : reduction percentage of pollutant  $j$  under strategy  $i$ ;

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

18  $j$ : criteria pollutant and GHGs index, i.e., CO, NOx, PM<sub>2.5</sub>, CO<sub>2</sub>;

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

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

21  $N_t$ : fleet size fuel type  $t$ ;

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

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

9

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

Strategy	CO	NOx	PM <sub>2.5</sub>	CO <sub>2</sub>	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%

11

12 To get a better sense of the effectiveness of these strategies, reassigning buses within the  
 13 three existing yards, relocating an existing yard, and constructing a new bus yard, will achieve  
 14 the annual reductions of CO<sub>2</sub> of 134,430, 267,415, and 265,133kg, respectively. This proves  
 15 that more reasonable assignment of buses to depots is promised to reduce fuel consumptions and  
 16 emissions.

## 17 Cost Analysis

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

28 Even though the costs for constructing a CNG yard vary significantly for different local  
 29 settings, some studies have been conducted to estimate the facility costs. In 2001, WMATA  
 30 commissioned a new \$4 million CNG refueling station (incorporating three compressors) to  
 31 serve a fleet of 164 CNG buses at the depot in Bladensburg, Maryland. In addition, the annual

1 electricity costs for running the compressors is approximately \$360,000, and modifying the  
2 maintenance facility to accommodate CNG buses requires \$11.6 million (12). A recent contract  
3 announced by the Orange County Transportation Authority costs \$3.6 million for designing,  
4 building, and operating a new CNG refueling station to serve 63 CNG buses and provide  
5 500,000 DGE annually (13). In TCRP Report 132, CNG facility costs are modeled as a base  
6 cost of \$1,000,000 plus \$15,000 per CNG bus (14). Operating a CNG yard costs more than a  
7 traditional diesel yard because of the additional costs of electricity for the compressors,  
8 estimated as roughly equal to 6% of CNG infrastructure costs per year. In the default setting of  
9 FuelCost2, additional facility operational costs for CNG is estimated as \$0.05 per mile assuming  
10 the average annual mileage is 37,000 per bus. Lowell indicates that the cost of CNG fuel station  
11 construction is \$25,800 per bus, according to a cost calculator developed by Marathon Technical  
12 Services and used by the National Renewable Energy Laboratory (15). The U.S. Department of  
13 Energy indicates that the estimated total cost including costs of engineering, equipment and  
14 installation of a private fleet station is \$550,000 - \$850,000; the included installation costs are  
15 estimated at 65% of equipment costs (16). The wide price ranges presented are consequent of  
16 the variance of equipment available, the fleet size, etc. More detailed information is required in  
17 order to get an estimate for a specific project.

## 18 **CONCLUSIONS**

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

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

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