Greenhouse Gas Emissions from Duke University Employee Commuters: The Cost-Effectiveness of Reductions

by

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Abstract

Duke University is seeking to decrease greenhouse gas emissions from its employee commuters. I build a linear optimization model to predict Duke University and Medical Center employee commute mode share. Combining these results with a forecast of Duke employee growth, I calculate the impact on employee commuter greenhouse gas emissions of 1) existing Duke carpooling and bus subsidies, 2) a $10 per month increase in employee parking costs and 3) a $20 per month increase in employee parking costs. The cost-effectiveness of these measures in 2015 to Duke University is $309.96 per mtCO2e for existing policy, -$248.87 per mtCO2e for a $10 per month increase in parking costs and -$516.21 per mtCO2e for a $20 per month increase in parking costs. Including costs to commuters, the cost-effectiveness of these policies to society as a whole is $57.41, $84.18, and $399.82 per mtCO2e. From the perspective of Duke University, excluding costs to employee commuters, the existing policy scenario is the least cost-effective strategy for achieving greenhouse gas emissions reductions from employee commuters. The parking cost increases are the least cost-effective when costs to employee commuters are included. From this combined perspective, the existing policy scenario is the most cost-effective policy.

1. Introduction

Duke University, by signing the American College and University Presidents Climate Commitment in 2007, has committed to reducing its greenhouse gas (GHG) emissions to zero. Despite not having yet chosen a target date, Duke has inventoried its GHGs from transportation, on campus steam production and purchased electricity. The Campus Sustainability Committee is currently assessing the costs and effects of policy options for GHG reductions in these sectors. Transportation GHGs equaled 134,685 metric tons of carbon dioxide equivalent (mtCO2e) in 2007 and are approximately 30% of Duke's total GHG emissions. These emissions result from employee commuters, employee air travel and the university bus fleet. Duke does not count GHGs from student commuters toward its footprint. The goal of this study is to estimate and compare the costs and effects of Duke University policy options to reduce transportation GHG emissions from employee commuting.

Employee commuter GHG emissions account for 64% of Duke transportation GHGs and for 19% of total Duke GHGs. The amount of GHG emissions from employee commuters depends on both the number of employees and on how they travel to work, or their commute mode. Commuters can drive alone, carpool, take local and regional buses to work, walk or bike to work. Duke employee commuter GHG policies are designed to decrease the percentage of commuters driving alone since this commute mode generates the highest GHG emissions per trip (DU GHG Emissions Inventory, 2008).

Duke uses biannual surveys of its employees, compiled by the Triangle Transit Authority, to estimate commute mode share. In 2003, the survey estimates that 85.6% of employees drove alone to work, 7.9% carpooled, 2.5% took regional or local buses and 2.85% walked or biked (TTA, 2004). In 2004, Duke University Parking Services initiated a program to promote carpooling by employee commuters. Employees in commuting to work in groups of 3 or more are given discounts on premium parking permits. In 2007, 77.5% of employee commuters drove alone to work, 10% carpooled, 3.2% took the bus and 5.4% walked or biked (TTA, 2008).

One policy approach for Duke University to decrease GHG emissions from employee commuters is to change the relative prices of options to commute. Duke can reduce polluting behavior by increasing the cost of one good or service relative to the price of another preferred substitute. In 2004, Duke decreased the price to park for carpoolers to increase this mode share relative to driving alone. An additional example of a pricing policy is increasing parking costs. In theory, if Duke increases the cost of driving to work alone, the percentage of employees that drive to work alone will decrease and the percentages of workers that carpool and take public buses to commute will increase.

Understanding how pricing policies affect an individual's commute mode choice is fundamental to estimating the potential effects of Duke commuter pricing policies. Transportation systems can be economically modeled to analyze individual choice under different pricing scenarios. For example, road congestion is a negative externality, or a cost imposed on a driver by another without the first's consent. Several studies (Arnott et al., 1991; Anderson and de Palma, 2004) examine the effect of road charges (tolls) on reducing road congestion externalities. Cities, like London and Singapore, have adopted this pricing policy to reduce the number of vehicles on the road and congestion externalities.

Duke University has recently introduced one additional policy to further reduce commuting GHGs. Starting in August 2008, Duke employees can purchase discounted regional and city bus passes through payroll deduction. Duke is considering one additional pricing policy: raising the price of employee parking permits to discourage this commute mode option relative to alternatives. Duke has not formally evaluated the costs of its existing or additional employee commuting policies relative their GHG reductions. Neither has Duke University compared these commuting policies to alternatives in transportation, in other university activities or outside the university (e.g., GHG offsets).

This study has 3 objectives: (1) to generate a baseline scenario for Duke commuter GHG emissions from 2008 to 2020, (2) to estimate the effect on GHG emissions from three policy scenarios; and (3) to compare the costs to the effects of Duke GHG emissions by measuring cost-effectiveness ($ per metric ton carbon dioxide equivalent).[1] In the baseline scenario, Duke has not implemented its existing commuter policies. I calculate the baseline in this manner to compare the effect of existing policy to business-as-usual. I then model 3 policy scenarios. The first policy scenario includes existing commuter pricing policies. In the second scenario, I predict the effect of a $10 per month increase in employee parking permits. I model a $20 per month parking price increase in the last policy scenario.

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[1] As a metric for greenhouse gas emissions, I use metric ton carbon dioxide equivalent (mTCO2e). This unit accounts for the greater global warming effect of methane (CH4) and dinitrogen oxide (CH4) emissions compared to carbon dioxide (CO2).

2. Methods

I estimate the cost-effectiveness of GHG emissions reductions from Duke employee commuters under four scenarios. Conventionally, baseline scenarios reflect current business-as-usual conditions, but Duke University considers its existing commuter policy as actions taken to count under its baseline (pers. comm. Catotti, 2008).

- In the Duke employee commuter Baseline Scenario, Duke has not implemented its carpool or its bus commute incentives policy.
- In the Existing Policy Scenario, Duke continues its existing commuter policies. Duke has reduced the prices of Durham Area Transit Authority (DATA) 30-day bus pass from $36 to $12 and Triangle Transit Authority (TTA) 30-day bus passes from $64 to $24. Carpoolers pay $48 per year compared to $404.20, the annual cost of an average parking permit.[2]
- For the second policy scenario (Parking Policy Scenario 1), Duke increases the annual cost of the average parking permit by $10 per month per person from $33.68 to $43.68 per month per permit.
- The third policy scenario (Parking Policy Scenario 2) predicts the effect on employee commuter mode share from a $20 per month per person increase in the price to park (From $33.68 to $53.68 per month per permit). Both parking scenarios are additional to the existing scenario so the existing commuter policies are still in effect.

To calculate GHG emissions and cost-effectiveness in the baseline scenario and in the three policy scenarios, I combine six methods. First, I forecast the number of Duke employees from

[2] Subsidized bus fare and carpool parking permits prices from Duke University Parking and Transportation Services.

2008 to 2020. Next, I calculate the mode share of Duke employees under the four scenarios by building a model of commute cost per trip by employee wage rate and commute distance. To estimate GHG emissions reductions from mode shares and employee number, I input mode shares and employee number into a GHG emissions equation. I determine costs to commuters from the commute mode model. I build cash flows for each policy to estimate costs to Duke University. Lastly, I calculate cost-effectiveness in 2015 from the Duke University and social welfare perspectives by comparing costs to GHG emissions reductions. I use 2015 as snap-shot view of cost-effectiveness.

2.1. *Forecasting Duke Commuter Growth*

The number of Duke employees is one major factor in greenhouse gas emissions from employee commuters. To forecast employee commuter number into the future, I apply different time-series forecasting models to historical employee data over the period 1990 to 2002. I examine linear trend, random walk, random walk with drift, moving average and Brown's exponential smoothing model for predicting total employees from 2003 to 2020. Regression is another possible method for forecasting time-series data, but I do not have access to potential independent variable data. In choosing the forecast model, I hold out 5 periods for validation. Holding out observed data from 2002-2007 allows me to compare forecasted values with real values for a measure of how well the model predicts the data. [3]

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[3] The most accurate forecasting model will have the lowest standard error statistics measured by the root mean squared error, mean absolute error and mean absolute percentage error (Hayter, 2002)

2.2. Cost Minimization Commute Mode Model

There are several methods to estimate the costs and effects of pricing policies on commute mode choice and commuter greenhouse gas emissions. One is to model a transportation system by developing equations for the costs of commuting.[4] Economic analysis can be used to predict mode share by calculating the equilibrium point in the system. This equilibrium corresponds to a state with minimized costs or where marginal costs are equal to marginal benefits. Commuter costs vary across individuals because commuters differ in their value of time and their distance from work. Parry and Small (2007) estimate optimal subsidies for public bus fares by developing cost equations for commuters and public transportation. Houde et al (2007) model the Washington, D.C. transportation system. These models are built with assumptions specific to commuter preferences and location and they estimate the effects of charges and subsidies on commuter mode choice. I derive cost equations for Duke employee commuters based on these models.

A related way to frame the modeling of employee commuters is to portray commuter mode decisions as a probability model. The sum of the probabilities of commuters driving to work, carpooling to work, and taking a public bus to work is equal to one. Washbrook et al (2006) develop a methodology to estimate these probabilities and how they change when costs are changed relative to one another. For a $0.64 per day increase in parking, for example, commuters that drive alone to work decrease from 83% to 80%. This model is specific to Vancouver because its coefficients are from a survey of two Vancouver communities. Although it is not

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[4] Costs to drive a car equal the sum of monetary and non-monetary costs. Monetary costs include parking, fuel, vehicle maintenance, bus fare and road tolls. Non-monetary costs are waiting and in-vehicle traveling time. Carpooling reduces the monetary costs of driving because they are shared. Bus commuting eliminates monetary costs except bus fare, but non-monetary costs are higher because waiting time increases.

appropriate to translate the model results to Duke University, these results are theoretically consistent with potential Duke commute policies.

To estimate Duke employee mode share and employee commuter costs under the four scenarios, I build a linear commute mode cost minimization model. The model simulates the decision of employee commuters to drive alone, carpool or take the bus to work. This individual commute mode decision (K) is based on costs per trip per commuter given the commuter's distance from work (D), wage rate (R) and several other input variables and parameters specific to the scenario and the commute mode. I define parameters (Table 1) as those variables that are constant to all commute modes, commuter types and scenarios. In contrast, input variables (Table 2) are values that are specific to certain commute modes, commuter types and scenarios.

In the model, individual commuters are grouped into commuter types ($Commuter_{DR}$) based on D and R. I assume seven D categories and three R categories. The 2008 TTA survey estimates the percentage of Duke commuters by commute distance (Appendix A) and I use this distribution. For wage rates, I obtained wage rate data for Duke employees from Duke Human Resources. I derive wage rate percentiles and divide all employees into three categories. The low, medium and high wage rate groups correspond to the 25th, 50th and 75th percentiles of Duke wage rates.[5] In the absence of joint distributions for D and R input variables, I make the important assumption that at each commute distance, there are an equal number of employees from each of the three wage rates. In the model, the percentage of commuters at distance category is divided equally into the three wage rate categories. At the expense of some accuracy, this division of D and R

[5] Duke wage rates are confidential and I cannot publish them in this report.

simplifies the model calculations. In the model commuter types choose a least-cost mode and the model assigns to that mode the percentage of total commuters in that commuter type.

The model calculates commute cost per trip per commuter for each scenario (I) based on the input variables (D and R), the decision variable (K) and several parameters and input variables. Commute cost per trip is equal to the sum of monetary (M) and non-monetary (NM) commute cost per trip per commuter.

(6) $\text{Commuter Cost Per Trip per Commuter}_{DRKI}$ (\$ per trip per person) = $M_{DKI} + NM_{DRK}$

M is the sum of parking cost per trip (P), variable driving cost per trip (V), fixed driving cost per trip (F) and bus fare cost per trip (B). In the model, M changes according to the different parking price changes, and subsidies to carpooling and bus commuting. NM is the sum of driving time cost per trip (T) and waiting time cost per trip (W). This commute cost changes with commute mode but does not change in each scenario.

(7) M_{DKI} (\$ per trip) = $P_{KI} + V_{DK} + F_K + B_{KI}$

(8) NM_{DRK} (\$ per trip) = $T_{DRK} + W_{DRK}$

Parking cost per trip is specific to each mode and scenario. For K = bus, P is equal to zero for all scenarios. Under the Baseline Scenario for K = driving alone and K = carpooling, P is equal to the cost of employee parking permits per year plus the parking increase per year divided by average trips per year divided by the average carpoolers per group. For driving alone, average carpoolers per group is equal to one. In the policy scenarios, $P_{carpool}$ is equal to the subsidized parking cost for carpoolers divided by the average trips per year. Parking increase per year is equal to zero for these scenarios. I estimate average carpoolers per group in the calibration section, below.

(9) P_{KI} = (Parking Permit Cost per $Year_K$ + Parking Increase per $Year_{KI}$)* 1/Trips per Year * 1/Average Carpoolers per $Group_K$

Variable Driving cost depends on D and K but do not change with R or the scenario. When K = bus, V is equal to zero. For driving alone and carpooling, V is the sum of fuel, tire, maintenance, and depreciation costs (AAA, 2008) per mile times D divided by the average carpoolers per group. The model assumes that carpool groups divide variable costs as they take turns using their personal vehicles to drive to work. Again, average carpoolers per group is equal to one for driving alone.

(10) V_{DK} = (D * (Fuel Cost Per $Mile_K$ + Tire Cost per $Mile_K$ + Maintenance Cost per $Mile_K$ + Depreciation Cost per $Mile_K$)) / Average Carpoolers per $Group_K$

Fixed driving cost includes insurance, license, registration, taxes, and finance (AAA, 2008). Carpoolers do not share fixed costs and fixed costs equal zero for bus commuters.

(11) F_K = Insurance $Cost_K$ + License $Cost_K$ + Registration $Cost_K$ + Tax_K + Finance $Cost_K$ / Average Trips per Year

Bus cost depends on the scenario. Duke does not subsidize bus cost in the Baseline Scenario and it subsidizes bus cost by the same amount in the three policy scenarios. The costs for bus fares are listed earlier in this section. For driving alone and carpooling, bus costs are equal to zero.

(12) B_{KI} = Average Bus Pass Cost per $Year_{KI}$ / Average Trips per Year

I derive the cost of travel time from Parry and Small (2007). In that model of urban commute, the value of travel time is equal to 0.5 times R for peak travel and 0.375 times R for off-peak travel. I assume that commuters are traveling to work only during peak periods. In my model, VOT is the factor multiplied by R. For the cost of travel time, I multiply the value of time by D and by the inverse of the average commute speed for Durham, NC (US Census Bureau, 2007).

(13) $T_{DR} = 1/S * D * VOT * R$

Parry and Small (2007) estimate that the value of waiting time is 60% higher than the value of travel time. In the model, I estimate the average wait time for each mode and I estimate a factor for the value of wait time (VOW_K). I am unable to directly calculate the added wait time for commuting by bus or carpooling, thus I assume any commute time longer than the time it takes to drive alone is wait time. I call this additional time the Wait Factor (L_K). L_K is equal to zero for driving alone. For bus and carpool, L_K is equal to the average Durham commute times for bus and carpool commute divided by the average Durham commute time for driving alone minus one.[6] $L_{carpool}$ is equal to 0.48 and L_{bus} is equal to 0.99. In the calibration section, I discuss VOW_K and how I change its value to increase the accuracy the model.

(14) $W_{DRK} = T_{DR} * VOW_K * L_K$

After calculating the cost per trip for $Commuter_{DRK}$, the model chooses the minimum cost commute mode for $Commuter_{DR}$. The model then assigns the percentage of commuters in that R and D category to the minimum cost commute mode for that commuter type. Again, commuters at each distance category (Appendix A) are divided equally into the three wage categories (Duke HR, 2008). Summing these mode share percentages across all $Commuter_{DR}$ returns the percentage of the total commuters in each commute mode. To estimate annual commuter costs, I sum the individual costs by mode and multiply by the mode shares and the total number of commuters.

[6] Average commute times by mode from the US Census Bureau, 2007 American Community Survey.

One commute mode that the model does not estimate is driving alone but not parking at Duke. Duke Parking services does not keep track of these data but it is likely that some Duke employees will choose not to park in Duke parking lots. Thus, the model under-estimates the percentage of employees driving alone to work and may over-estimate reductions in GHG from parking policies.

2.3. Model Calibration

The final step in building the model is to check its results with observed mode shares in 2005 and 2007. With initial parameter estimates described above, the model over-estimates the effect of increased subsidies for bus and carpool commuting in 2007. The model results for the Existing Policy Scenario mode share over-estimate the number of carpoolers and bus riders compared to the observed 2007 mode share. To increase the accuracy of the model, there are several candidate parameters and input variables I can adjust. I had estimated these values from existing literature because they are difficult to measure specifically for Duke employee commuters. These values are VOW_k, the average number of carpoolers per group and VOT.

To calibrate the model results to observed mode shares, I increase $VOW_{carpool}$ and VOW_{bus} and I set average number of carpoolers per group to 2.3. These are the two model values, from the three I have identified, that change the cost the commute modes relative to each other. Increasing average carpoolers per group decreases the cost to carpool relative to the cost to drive alone. I also increase VOW from 0.6 to $VOW_{carpool}$ = 1.135 and VOW_{bus} = 4.2. These values are high relative to Parry and Small (2007). The high VOW_K may be due to L_K being an underestimate in the W_{DRK} equation. L_K is an average for Durham and may not accurately reflect the waiting times for Duke commuters from outside of Durham. I choose to change VOW_K and not L_K because I have the less confidence in the original VOW_K parameter values. In the Parry and Small (2007) model, 0.6 describes the value of waiting time for commuters in large metropolitan cities like Washington, D.C., Los Angeles and London.

Table 1: Summary of model parameters after calibration.

Parameter	Value	Source
S	31.2 MPH	US Census Bureau, 2007
Average Faculty Trips per Year	475	2008 Duke GHG Inventory
VOT	0.5	Parry and Small, 2007
Average Carpoolers per Group	2.3	Calibration

Table 2: Summary of model input variables after calibration.

Input Variable	Value	Source
D	1, 3.5, 8, 13, 18, 23, 72.5 miles	TTA, 2008
R	Proprietary	Duke Human Resources
Parking Permit Cost per $\text{Year}_{\text{driving alone}}$	$404.2	Duke Parking Services
Parking Permit Cost per $\text{Year}_{\text{carpool, baseline}}$	$404.2	Duke Parking Services
Parking Permit Cost per $\text{Year}_{\text{carpool, policy (all)}}$	$48	Duke Parking Services
Parking Permit Cost per Year_{bus}	$0	Duke Parking Services
Parking Increase per $\text{Year}_{\text{driving alone, baseline and existing}}$	$0	Estimate
Parking Increase per $\text{Year}_{\text{driving alone, parking 1 policy}}$	$10	Estimate
Parking Increase per $\text{Year}_{\text{driving alone, parking 2 policy}}$	$20	Estimate
Parking Increase per $\text{Year}_{\text{carpool}}$	$0	Estimate
Parking Increase per Year_{bus}	$0	Estimate
2007 Fuel $\text{Cost}_{\text{driving alone and carpool}}$	$0.1167 per mile	AAA, 20008
2007 Maintenance $\text{Cost}_{\text{driving alone and carpool}}$	$0.0457 per mile	AAA, 20008
2007 Tire $\text{Cost}_{\text{driving alone and carpool}}$	$0.0072 per mile	AAA, 20008
2007 $\text{Depreciation}_{\text{driving alone and carpool}}$	$0.22 per mile	AAA, 20008
2007 Fixed $\text{Cost}_{\text{driving alone and carpool}}$	$2255 per year	AAA, 20008
Average Bus Cost per $\text{Year}_{\text{driving alone}}$	$0	Estimate
Average Bus Cost per $\text{Year}_{\text{carpool}}$	$0	Estimate
Average Bus Cost per $\text{Year}_{\text{bus, baseline}}$	$608.33	TTA and DATA
Average Bus Cost per $\text{Year}_{\text{bus, policy (all)}}$	$219.00	TTA and DATA
$\text{VOW}_{\text{driving alone}}$	0	Calculated
$\text{VOW}_{\text{carpool}}$	1.35	Calibration
VOW_{bus}	4.2	Calibration
$\text{L}_{\text{driving alone}}$	0	Calculated

Input Variable	Value	Source
$L_{carpool}$	0.48	US Census Bureau, 2007
L_{bus}	0.99	US Census Bureau, 2007

2.4. GHG Emissions Calculator

I extract the formula for calculating employee commuter GHG emissions from the 2008 Duke GHG Emissions Inventory. This method takes as inputs the number of employees and mode share. The output is annual GHG emissions in mTCO2e per year.

(1) Total Employee Commuter GHG Emissions = Personal Vehicle GHG + Bus Commuter GHG

(2) Personal Vehicle GHG = Personal Vehicle Distance * Personal Vehicle Efficiency * CO2e Gasoline Factor

(3) Personal Vehicle Distance = Commuter Trips per Year * Average Miles per Trip * ((Total Employee Commuters * Percentage Driving Alone) + (Total Employee Commuters * Percentage Carpooling / Average Number of Carpoolers per group))

(4) Bus Commuter GHG = Bus Commuter Distance * Bus Efficiency * CO2e Diesel Factor

(5) Bus Commuter Distance = Commuter Trips per Year * Average Miles per Trip * Number Commuters * Percentage Bus Commuters

In all calculations, I assume zero change in trips per year, average commute distance and emissions factors over time. Over the short-term, it is unlikely that driving costs will cause a change in employee distance from work. Over the long-term it is feasible that employees will live closer to campus if commuting costs increase. It is beyond the scope of my study to estimate this long-term effect of Duke policies. Similarly, I do not estimate changes in vehicle efficiencies and fuel mixes that will decrease emissions factors. This omission may overstate the GHG emission from the policy scenarios, but the baseline scenario should be overstated by the same amount so the incremental effect of the policy scenarios is accurate. Lastly, I assume the average carpoolers per group are equal to the values calculated in the calibration.

Table 3: Summary GHG calculator parameters.

Parameter	Value	Source
Personal Vehicle Fuel Efficiency	22.10 miles per gallon	2008 Duke GHG Inventory
CO2e Emissions Gasoline Factor	0.008935 metric ton CO2e per gallon	2008 Duke GHG Inventory
Average Miles per Trip	15.05 miles	2008 Duke GHG Inventory
Bus Efficiency	39.67 miles per gallon	2008 Duke GHG Inventory
CO2e Emissions Diesel Factor	0.00999 metric ton CO2e per gallon	2008 Duke GHG Inventory

2.5. Duke Cash Flows

I calculate Duke cash flows for the 4 scenarios from 2008 to 2020. As mode shares change, Duke's parking revenue changes and the university must account for parking and bus subsidies. As commuters switch from driving alone to carpooling and bus commuting, Duke benefits from avoided parking space construction cost. I assume all new construction is for outside spaces to avoid over-estimating avoided costs. Duke parking spaces cost $200 per space for construction and $100 per space for maintenance. In the policy scenarios, the Duke cash flow must account for carpooling software that the university is using to facilitate carpool groupings for its employees (Appendix B).

2.6. Cost-Effectiveness Analysis

To compare the costs and effects of Duke commuter GHG emissions reductions, I conduct a cost-effectiveness analysis. Cost-effectiveness is a measure of cost per level of effect (Levin and McEwan, 2001). In the context of Duke employee commuter GHG emission mitigation, the most cost effective option will have the lowest cost per reduction in metric ton carbon dioxide equivalent ($ per mTCO2e). I choose to measure the cost and effect of the scenarios in 2015. This 'snap-shot' view of cost-effectiveness in one year is equivalent to the annuitized value the emissions reductions over all years because the GHG emission reductions from the model and GHG calculator are constant over time.

To compare GHG reductions between scenarios, I determine the incremental GHG reductions for each scenario. For incremental costs for each scenario, I divide costs into three categories: cost to Duke University, cost to commuters, and the sum, or the social cost. I calculate Duke costs from the Duke cash flows and commuter costs from the commute mode model. Social cost is the sum of Duke University and commuter cost.

3. Results

3.1. Employee Commuter Forecast

From 1990 to 2007, Duke commuters grew from 25,729 to 34,342. Duke staff numbered 24,094 in 1990 and 31,131 in 2007. In the same period, faculty increased from 1,635 to 3,211. In 2007, staff was 90.7% of commuters and faculty were 9.3 percent of commuters. I compare 5 time-series models for estimating total number of employees into the future: (1) random walk model, (2) random walk with drift model, (3) linear trend model, (4) moving average model and (5) brown's linear exponential smoothing model.

To predict the number of employees, I first compare estimation period and validation period error statistics from each model (Table 4). The linear trend model, brown's linear exponential smoothing model and random walk with drift model (Figure 1) have the lowest RMSE, MAE and MAPE for the estimation period. The linear trend model has the highest forecast estimates and it over-estimates the validation period. The Brown's linear exponential smoothing predicts a decrease in employee number. This decreasing trend is heavily influenced by the most recent data points. The random walk with drift model forecasts increasing employee number but over-estimates total employees in 2005 and under-estimates them in 2006.

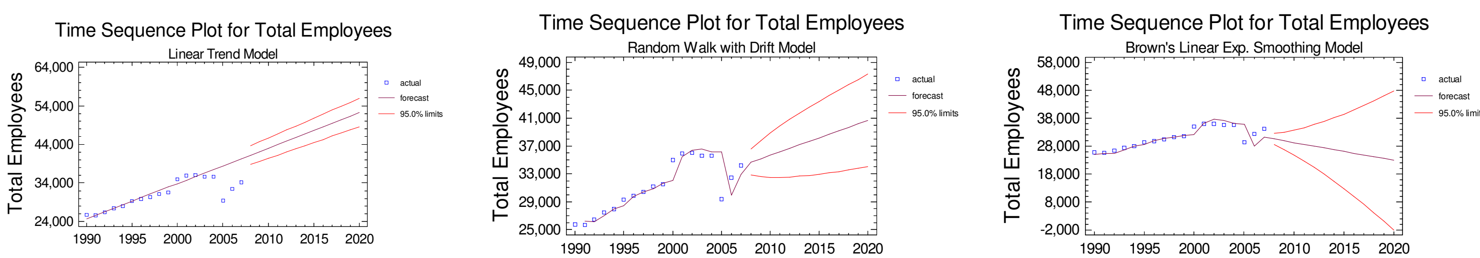

Figure 1: Time sequence plots for linear trend, random walk with drift and brown's linear exponential smoothing of employee number.

Table 4: Employee number forecast models - Estimation and validation period error statistics.

Estimation Period Model	**RMSE**	**MAE**	**MAPE**
Linear Trend	815.705	578.485	1.85
Random Walk	1220.74	874.833	2.79
Random Walk with Drift	981.80	554.451	1.74
Moving Average	2150.71	1951.37	6.08
Brown's Linear Exponential Smoothing	1058.88	699.755	2.24
Validation Period Model			
Linear Trend	3.42	4983.64	15.58
Random Walk	1.02	2276.2	7.33
Random Walk with Drift	1.08	2375.72	7.63
Moving Average	8.89	1877.33	6.12
Brown's Linear Exponential Smoothing	1.46	3213.48	10.09

After narrowing the options for the final forecasting model to linear trend, brown's linear exponential smoothing and random walk, I compare two diagnostics plots: the residual plot and the residual autocorrelations plot. An accurate forecasting model will have statistically independent, homoscedastic residuals and no significant residual autocorrelations. All three models violate the assumption that residuals are homoscedastic (Figure 2) and both the random walk with drift model and Brown's linear exponential smoothing have no significant residual autocorrelations (Figure 3). Based on analysis of error statistics and diagnostic plots for five time-series forecasting models, I choose to predict total employees from 2008 to 2020 using a random walk with drift model (Table 5).

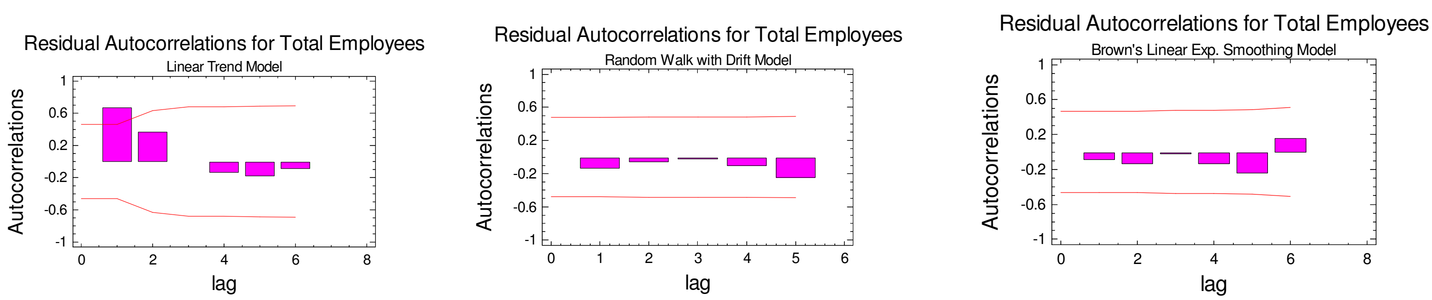

Figure 2: Residual autocorrelation plots for linear trend, random walk with drift and brown's linear exponential smoothing of employee number.

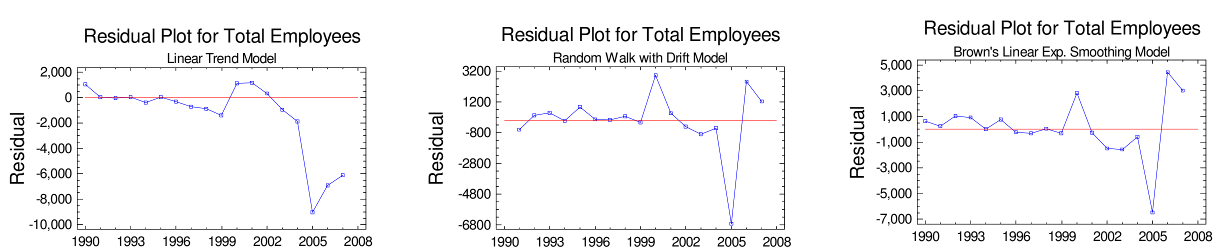

Figure 3: Residual plots for linear trend, random walk with drift and brown's linear exponential smoothing of employee number.

Table 5: Total employee forecast with random walk with drift model.

Year	Forecast Employee
2008	34685.6
2009	35183.2
2010	35680.8
2011	36178.4
2012	36675.9
2013	37173.5
2014	37671.1
2015	38168.7
2016	38666.3
2017	39163.9
2018	39661.5
2019	40159.1
2020	40656.6

3.2.1. Employee commute mode model

Given prices of parking and bus passes, the employee commute mode model returns the percentage of Duke staff and faculty choosing to drive alone, carpool or take the bus to and from work. I model four scenarios with this model: 1) the Baseline Scenario – Duke has no programs to promote carpooling or bus commuting, 2) Existing Policy Scenario – Duke lowers the parking cost for carpools of three or more employees and subsidizes bus commuting, 3) Parking Policy Scenario 1 – Duke raises the average price to park by $10 per month in addition to existing policy and 4) Parking Policy Scenario 2 – Duke raises the average price to park by $20 per month in addition to existing policy.

For the Baseline Scenario, the employee commute mode model predicts 88.60% of Duke University employee commuters drive alone, 7.65% carpool and 3.75% use the bus to commute. Under the Existing Policy Scenario, 80.95%, 15.30% and 3.75% of employee commuters drive alone, carpool and take the bus. The commute mode model predicts that 65.63%, 30.62% and 3.75% of Duke employee commuters will drive alone, carpool and take the bus with a $10 per month increase in parking cost. With a $20 per month increase in parking costs, 60.38% of employee commuters drive alone, 35.87% carpool and 3.75% use public buses (Table 6). Tables 7-10 present the percentage of Duke employee commuters by mode and by wage rate for each scenario.

Table 6: Duke employee commute mode model aggregated percentage results by scenario.

	Drive alone	Carpool	Bus
Baseline scenario	88.6%	7.65%	3.75%
Existing policy scenario	81.0%	15.3%	3.75%
Parking 1 policy scenario	65.6%	30.6%	3.75%
Parking 2 policy scenario	60.4%	35.9%	3.75%

Table 7: Baseline scenario - Duke employee commute mode model percentage results by mode and by wage rate.

Low Wage	Percentage
Driving alone	24.4%
Carpool	7.7%
Bus	1.3%
Medium Wage	
Drive alone	32.1%
Carpool	0.0%
Bus	1.3%
High Wage	
Driving alone	32.1%
Carpool	0.0%
Bus	1.3%

Table 8: Existing policy scenario - Duke employee commute mode model percentage results by mode and by wage rate.

Low Wage	Percentage
Driving alone	24.4%
Carpool	7.7%
Bus	1.3%
Medium Wage	
Drive alone	24.4%
Carpool	7.7%
Bus	1.3%
High Wage	
Driving alone	32.1%
Carpool	0.0%
Bus	1.3%

Table 9: Parking 1 policy scenario ($10 per year increase) - Duke employee commute mode model percentage results by mode and by wage rate.

Low Wage	Percentage
Driving alone	16.8%
Carpool	15.3%
Bus	1.3%
Medium Wage	
Drive alone	24.4%
Carpool	7.7%
Bus	1.3%
High Wage	
Driving alone	24.4%
Carpool	7.7%
Bus	1.3%

Table 10: Parking 2 policy scenario ($30 per year increase) - Duke employee commute mode model percentage results by mode and by wage rate.

Low Wage	Percentage
Driving alone	11.5%
Carpool	20.6%
Bus	1.3%
Medium Wage	
Drive alone	24.4%
Carpool	7.7%
Bus	1.3%
High Wage	
Driving alone	24.4%
Carpool	7.7%
Bus	1.3%

3.2.2 Duke Employee Commute Costs

The Duke employee commute mode model calculates costs per trip by commute mode for each scenario. Combining these data with the forecast of Duke total employees, I calculate the costs to Duke employee commuters by mode for each scenario in 2015. For the Baseline Scenario, the commute costs to Duke employees equal $455.9 million. Under the Existing Policy Scenario, commute costs equal $454.7 million. Commuter costs equal $457.9 million and $460.9 million, under the Parking Policy Scenarios 1 and 2. (Table 11).

Table 11: Duke employee commute model results – 2015 commuter costs by scenario ($ per year).

	Annual Cost	Incremental Annual Cost	Incremental Annual Cost per Employee
Baseline	$455,922,091	-	-
Existing Policy	$454,717,513	-$1,204,578	-$31.56
Parking Policy 1 ($10 per year increase)	$457,898,084	$3,180,571	$83.33
Parking Policy 2 ($20 per year increase)	$460,896,545	$2,998,461	$78.56

3.3. Duke Employee Commute GHG emissions

I combine the employee forecast results and the mode shares from the commute mode model to calculate GHG emissions under each scenario. In the Baseline Scenario, GHG emissions from Duke employee commuters increase from 94,493 mTCO2e per year in 2008 to 110,759 mTCO2e per year in 2020. For the same period of time, GHGs increase from 90,158 to 105,679 mTCO2e per year under the Existing Policy Scenario. With a $10 per month increase in parking cost, GHG emissions start at 81,480 in 2008 and reach 95,506 mTCO2e per year by 2020. A $20 per month increase in parking cost leads to GHGs from 78,505 to 92,020 mTCO2e (Table 12 and Figure 7).

Table 12: Annual Duke University and Medical Center employee commuter GHG emissions (mTCO2e per year).

	Baseline	Existing Policy Scenario	$10 Parking Increase Scenario	$30 Parking Increase Scenario
2008	94,493	90,158	81,480	78,505
2009	95,848	91,452	82,649	79,632
2010	97,204	92,745	83,818	80,758
2011	98,560	94,039	84,987	81,884
2012	99,915	95,332	86,155	83,010
2013	101,270	96,625	87,324	84,136
2014	102,626	97,918	88,493	85,262
2015	103,982	99,212	89,662	86,389
2016	105,337	100,505	90,831	87,515
2017	106,693	101,799	92,000	88,641
2018	108,048	103,092	93,169	89,767
2019	109,404	104,386	94,338	90,894
2020	110,759	105,679	95,506	92,020

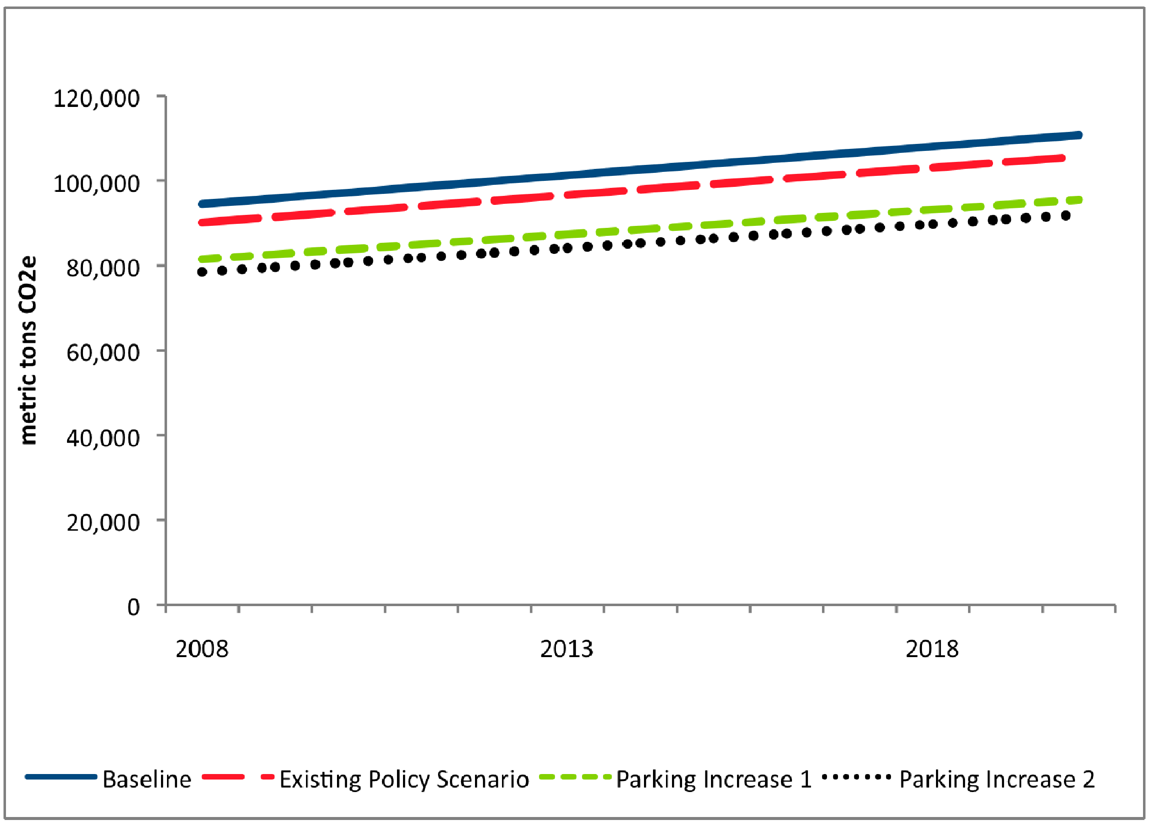

Figure 4: Projected Duke University and Medical Center employee commuter GHG emissions (2008-2020). Combined results from employee forecast and Duke employee commute model.

In 2015, incremental GHG emission reductions equal 4,769.73 mTCO2e per year in the Existing Policy Scenario. GHG emissions decrease by 9,549.84 mTCO2e per year in the Parking Policy

Scenario 1 relative to the Existing Policy Scenario. With a $20 per month parking cost increase, incremental employee commuter GHG emissions are 3,273.34 mTCO2e (Table 13).

Table 13: Incremental GHG emissions reductions by scenario.

	2015 GHG reductions (mTCO2e per year)
Existing Policy Scenario	4,769.72
Parking 1 Policy Scenario ($10 per year increase)	9,549.84
Parking 2 Policy Scenario ($30 per year increase)	3,273.34

3.4. Duke Cash Flows

Duke must account for the cost of its commuter policies relative to each other (Appendix B). I construct cash flows for Duke University that include cash-ins of parking revenue from commuters driving alone and avoided costs from parking space construction and maintenance. Cash-outs include the cost of carpooling organizing software and subsidies to bus riders and carpoolers. In 2015, the Baseline Scenario annual net cash flow equals $14.18 million. In this year, the Existing Policy scenario net cash flows equals $12.70 million, the Parking Policy 1 Scenario net cash flow is $15.08 million and the Parking Policy 2 Scenario net cash flow is $16.77 million (Table 14). Table 14 also calculates the incremental cost of each commuting policy scenario.

Table 14: 2015 Duke net parking cash flow and incremental annual costs.

	Net Cash Flow	Incremental Annual Cost
Baseline	14,182,051	-
Existing Policy	12,703,650	1,478,400
Parking Policy 1 ($10 per year increase)	15,080,277	-2,376,627
Parking Policy 2 ($20 per year increase)	16,769,995	-1,689,718

3.5. Duke Employee Commute Policy Cost-effectiveness Analysis

First, I list the distribution of all the possible costs and benefits to Duke University and to Duke employee commuters from Duke commute policies (Table 15).

Table 15: Breakdown of costs from Duke parking increases and subsidies by stakeholder group.

Costs	Duke University	Duke Employee Commuters	Total Social
Parking Permits	- Parking Cost	+ Parking Cost	0
Parking Subsidy	+ Parking Subsidy	- Parking Subsidy	0
Carpooling Software	+ Software Cost		+ Software Cost
Variable Cost Savings		- Variable Cost	- Variable Cost
Avoided Parking Space Construction and Maintenance	- Avoided Parking Space Cost		- Avoided Parking Space Cost
Bus Fare		+ Duke Bus Fare Cost	+ Duke Bus Fare Cost
Bus Fare Subsidy	- Bus Subsidy	+ Bus Subsidy	0
Driving Time		+ Driving Time Cost	+ Driving Time Cost
Waiting Cost		+ Waiting Cost	+ Waiting Cost

Combining the incremental commuter costs from Table 11 and the incremental Duke costs from Table 14, I estimate the incremental social annual costs from the Duke employee commuter policy scenarios (Table 16). I divide the annual incremental Duke, Duke employee commuter and total social costs by the incremental GHG emissions reductions for measures of cost-effectiveness by scenario (Table 17).

Table 16: 2015 total social annual costs and incremental annual costs by scenario.

	2015 Social Annual Cost	Incremental Annual Cost
Baseline	$441,740,040	-
Existing Policy Scenario	$442,013,863	$273,823
Parking Policy Scenario 1	$442,817,807	$803,944
Parking Policy Scenario 2	$444,126,551	$1,308,743

Table 17: Cost-effectiveness in 2015 by scenario ($ per mTCO2e).

	Duke University	Duke Employee Commuter	Total Social
Existing Policy Scenario	$309.96	-$252.55	$57.41
Parking Policy 1 Scenario	-$248.87	$333.05	$84.18
Parking Policy 2 Scenario	-$516.21	$916.03	$399.82

4. Discussion

The most cost effective measure, taking all costs into account, is the Existing Policy Scenario at $57.41 per mTCO2e. In 2015, it will reduce Duke GHG emissions from employee commuters by 4,769 mTCO2e per, a 4.6% reduction compared to the Baseline Scenario. Costs are negative to commuters because fuel savings and subsidies exceed added time costs from more carpooling and bussing. Excluding costs to employee commuters, the Existing Policy Scenario is the least cost-effective measure. Duke carpooling and bus subsidies cost Duke $309.96 per mTCO2e. These subsidies exceed avoided parking space construction and maintenance costs. The net social cost-effectiveness of the Existing Policy Scenario is less than the Duke cost-effectiveness because the costs to Duke employee commuters are negative.

Despite less commuters driving alone under Parking Policy Scenario 1 (a $10 per month increase in parking cost to driving alone), this scenario is less cost-effective than the Existing Policy Scenario. The distribution of costs is also different as costs to Duke are negative and costs to commuters are positive. Duke costs are negative from avoided parking space costs and increased parking revenue from commuters both driving alone and carpooling. The university subsidizes the increased carpoolers but this cash-out is offset by increased parking revenue. Commuters pay these higher parking charges which, with added waiting cost, exceed fuel savings. Thus, this $10 per month increase is a cost-effective GHG emission reduction for Duke, but it costs employee commuters $333.05 per mTCO2e.

Parking Policy Scenario 2 (a $20 per year increase in parking cost to commuters driving alone) is the least cost effective measure from the social welfare perspective. Similar to Parking Policy Scenario 1, Duke costs are negative but commuter costs are positive by a higher magnitude. Duke does not compensate commuters for higher waiting costs and parking costs. From the Duke perspective, this scenario is the most cost-effective but commuters pay $78.56 per commuter.

In all cases, bus commuting mode share is constant at 3.75% of Duke commuters. At all wage rates, the only situation where this mode is the minimum cost commuting option is at a distance of 1 mile. In the model, the quantity of waiting time is equal to 1.99 times the quantity of travel time for driving alone. The value of this waiting time for bus travel is equal to 4.2 times the value of travel time when driving alone. These high waiting values make taking the bus unattractive to commuters at all distances except 1 mile. From the model results, I conclude that the bus subsidy to Duke employee commuters does not compensate the commuter for this mode's the high waiting cost. The bus commuter mode share does not increase with higher parking costs to commuters driving alone because there is no additional bus subsidy in the parking policy scenarios.

When both Duke and commuter costs are taken into account, the most cost-effective policy is the existing policy. The loss in Duke's parking revenue and increased commuter wait time costs are greater than the commuter fuel savings and Duke avoided parking space costs. Taking only Duke costs and benefits into account, the most cost effective policy is the $20 per month parking cost increase (Parking Policy Scenario 2). From a social cost perspective, the $20 per month parking cost increase is the least cost-effective.

In this model, subsidies for carpooling and penalties to commuters driving alone affect commuters at low wage rates and small distances from Duke more than other commuter types. For the high and medium wage rate commuters, the only change in commute mode is 7.7% of commuters switching from driving alone to carpooling in the Existing Policy Scenario. All of the scenarios affect the mode share of employee commuters in the lowest wage rate. In all but one of the scenarios, mode share changes come from commuters living less than 8 miles from Duke. In the Parking Policy 2 Scenario, commuters living at the 13 mile D and low R group commute change from driving alone to carpooling. Duke may wish to consider additional policies to decrease the percentage of commuters driving alone who live greater than 8 miles from Duke and who earn greater than the 25th percentile wage rate.

When I compare the commute mode model results of the Existing Policy Scenario to the observed 2007 mode share data, it is evident that the model over-estimates both the percentage of commuters driving alone and the percentage of commuters carpooling. The TTA survey reports 77.5% of commuters driving alone and 10% of commuters carpooling and the model returns 80.95% driving alone and 15.3% carpooling. I explain this inaccuracy because the model does not account for commute modes other than the driving alone, carpooling and bussing. This leaves out the 9.3% of commuters that the TTA survey reports chose to walk or bike to work in 2007. This leads to a slight overestimate of emissions reductions in each scenario.

Studies of parking charges on parking demand have not traditionally focused on the cost-effectiveness of emissions reductions but rather on the effect of increased parking costs on commuters driving alone. Wilson and Shoup (1990) estimate the parking price elasticity of demand for solo driving to be between -0.1- and -0.68. Washbrook et al. (2006) estimate elasticities of commuter driving alone from parking charges to be between -0.23 and -0.41. In my model, the parking price elasticity of demand is equal to between -0.51 (Parking Policy Scenario 1) and -0.22 (Parking Policy Scenario 2). My results are consistent with the Wilson and Shoup (1990) results but they are outside of the range estimated in Washbrook et al. (2006).

Duke University should compare the cost-effectiveness of GHG emissions reductions from employee commuters to the cost-effectiveness of other measures within Duke transportation activities, from other Duke emitting activities and outside Duke's footprint (GHG offsets). For example, a recent study by the Nicholas Institute for Environmental Policy Solutions (Polk and Potes, 2008) examined the potential supply and cost-effectiveness of GHG offsets in North

Carolina that they are available with cost-effectiveness as low as $5 per mtCO2e. The university should carry out this type of cost-effectiveness analysis for all potential GHG emission reduction measures.

5. Limitations and Potential Improvements

The main limitations in this study are in the commute mode model and the distributions of data for Duke commuter wage rates and distance. The resolution of the commute mode model is dependent on available data and I must artificially assume that commuters at each distance are equally divided by wage rate. In reality, the percentage of commuters in each wage rate living at a given distance will differ. This affects the accuracy of the model and also restricts output to discrete intervals.

Secondly, the model does not account for the number of commuters that walk or ride their bicycle to work. The TTA survey estimates that as many as 5.4% of employee commuters regularly take this commute mode with zero GHG emissions relative to the other modes. Commuters are most likely to choose this mode if they live closer to work. In not estimating commuters walking or biking, I over-estimate GHG emissions for each scenario.

Lastly, it is likely that a percentage of commuters will choose to drive alone and not park at Duke as parking costs increase in the two parking policy scenarios. Anecdotally, parking options outside of those provided by Duke University are few, but the model should account for this mode choice to be completely accurate. The parking policy scenarios likely under-estimate GHG emissions as a result of this omission.

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Appendix A: 2008 TTA Survey Results

The Triangle Transit Authority (TTA) conducts biannual surveys of employers in its service area. They asked commute behavior questions to 3,349 Duke University and 2,273 Duke Hospital employees. The survey asked the employee for current mode of transportation, travel time, travel distance (Table 1) and "attitudes towards environmentally friendly commute modes" (Tables 2 and 3). From these responses, we gauge the potential effect of Duke employee commuter GHG reduction policies.

Table 1: 2003 TTA Duke University and Duke Hospital times to work, distances to work and mode choice (TTA, 2004).

Employee travel to work by mode	Duke University	Drive alone: 82.3% Carpool: 8.6% Vanpool: 0.1% Motorcycle/Moped: 0.4% Take the Bus: 2.9% Bicycle: 2.6% Walk or run: 4.3% Telecommute: 0.9%
	Duke Hospital	Drive alone: 89.1% Carpool: 7.2% Vanpool: 0.4% Motorcycle/Moped: 0.2% Take the Bus: 2.1% Bicycle: 0.0% Walk or run: 0.8% Telecommute: 0.1%

Table 2: 2005 TTA Duke University and Duke Hospital times to work, distances to work and mode choice (TTA, 2006).

How many miles do you live from your worksite?	Duke University	<2: 2% 2-5: 25.2% 6-10: 22.4% 11-15: 26.3% 16-20: 8.3% 21-25: 8.4% >25: 13.4%
	Duke Hospital	<2: 0.8% 2-5: 14.0% 6-10: 24.5% 11-15: 16.1% 16-20: 10.1% 21-25: 10.6% >25: 23.9%
Employee travel to work by mode	Duke University	Drive alone: 86.3% Carpool: 8.7% Vanpool: 0.2%

		Motorcycle/Moped: 0.3% Take the Bus: 1.3% Bicycle: 1.5% Walk or run: 0.8% Telecommute: 0.2% Other: 0.8%
	Duke Hospital	Drive alone: 91.2% Carpool: 6.1% Vanpool: 0.0% Motorcycle/Moped: 0.6% Take the Bus: 0.7% Bicycle: 0.2% Walk or run: 0.1% Telecommute: 0.1% Other: 1.1%

Table 3: 2007 TTA Duke University and Duke Hospital times to work, distances to work and mode choice (TTA, 2008).

How many miles do you live from your worksite?	Duke University	<2: 6% 2-5: 30.2% 6-10: 22.4% 11-15: 14.1% 16-20: 8.1% 21-25: 6.6% >25: 12.7%
	Duke Hospital	<2: 1.5% 2-5: 15.7% 6-10: 23.6% 11-15: 17.4% 16-20: 11.6% 21-25: 8.8% >25: 21.3%
Employee travel to work by mode	Duke University	Drive alone: 72.4% Carpool: 10.9% Vanpool: 0.2% Motorcycle/Moped: 0.8% Take the Bus: 3.9% Bicycle: 5.1% Walk or run: 4.3% Telecommute: 0.4% Other: 2.0%
	Duke Hospital	Drive alone: 82.6% Carpool: 9.1% Vanpool: 0.3% Motorcycle/Moped: 0.4% Take the Bus: 2.5% Bicycle: 0.6% Walk or run: 0.8% Telecommute: 0.1% Other: 3.7%