

Reducing Emissions through Transportation Mode Switching

Bus Rapid Transit in Cape Town, South Africa

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This study examines the air pollution effects of a proposed bus rapid transit (BRT) system in Cape Town, South Africa. The BRT system would allocate a pair of traffic lanes for exclusive use by buses. A logit model is used to predict changes in travelers' choices among the trains, buses, minibuses, and automobiles along the BRT corridor. The response of public transportation operators to changes in passenger demand is simulated. Finally, emissions of greenhouse gases and local pollutants are predicted for different combinations of system design and operational characteristics. With the anticipated policy intervention, emissions of carbon dioxide and local pollutants decrease 5 to 7 percent relative to the status quo. Emissions levels are found to be more responsive to congestion effects of the BRT system than to the improvement in bus service. Increases in travel time resulting from the intervention, including congestion-caused delays for minibus and car users, exceed time savings for bus riders.

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1 introduction

Concern about climate change has led to increasing interest in approaches to sustainable urban development. Especially in rapidly developing countries, urban and transportation planning decisions can have a profound effect on the magnitude of future environmental problems. The present study evaluates the ability of a specific intervention, the introduction of a bus rapid transit (BRT) system, to alter the status quo trend of rising transportation sector pollution in Cape Town, South Africa. The analysis assesses “mode switching” as a means of reducing emissions from transportation vehicles. That is, if the BRT system attracts passengers from other modes, emissions may fall if the passengers leave vehicles with higher levels of pollution per passenger trip.

Section 2 introduces the challenge of meeting rising urban travel demand in less developed countries while reducing greenhouse gases emissions and describes existing means of transportation in Cape Town. Section 3 covers the methodology employed to estimate the emissions effects of the BRT system. Sections 4, 5, and 6 report econometric, emissions, and economic results, respectively. Finally, Section 7 offers conclusions and recommendations for future research.

2 background

Carbon dioxide and other greenhouse gas emissions from transportation have global consequences. Anthropogenic increases in greenhouse gas concentrations threaten to disrupt agricultural and ecological systems by altering temperatures, rainfall patterns, and other aspects of the climate (IPCC 2001). Some negative consequences of climate change may affect poorer tropical and subtropical countries disproportionately (IPCC 2001: 9, 12), worsening global inequality. Less developed countries are also vulnerable because they have limited resources to adapt to climate change.

Energy consumption in transportation, currently 28 percent of global energy use, is rising faster than in any other sector (Fulton et al. 2002:17; Sperling 2002: 2). Transportation was responsible for 23 percent of global carbon dioxide emissions in 1997 (Sperling 2002:21). In South Africa, transportation activities produce one-fifth of the country's greenhouse gas emissions (Prozzi et al. 2002:20).

Less developed countries (LDCs) will account for most of the growth in transportation sector greenhouse gas emissions over the coming decades, in large part because of rising automobile ownership and use (Fulton et al. 2002:20). Although higher incomes often coincide with greater numbers of trips taken in private vehicles, this relationship is not fixed (Sperling 2002:10). Through policy and investment decisions that constrain private vehicle ownership and use while providing attractive alternatives, cities can influence patterns of urban development in a way that reduces greenhouse gas emissions.

Given the pressing social issues they face, LDCs have limited resources to commit to efforts to reduce greenhouse gas emissions. Wealthy countries have made some funding available for LDC transportation projects through international donor agencies such as the Global Environment Facility (GEF). Projects sponsored by the GEF initially focused on improving vehicle efficiencies and promoting fuel cell demon-

stration technology, but some of the organization's more recent efforts recognize that significant, near-term transportation emissions reductions will require a more comprehensive approach (Hook and Wright 2003:7). Projects in Santiago, Chile and Lima, Peru seek to promote public and non-motorized transportation through infrastructure improvements and land-use planning (GEF 2004). Shifting the balance away from private automobile use is expected to reduce emissions in these cities. In general, cities with greater fractions of trips by public transportation tend to produce lower transportation sector greenhouse gas emissions (Newman and Kenworthy 1999:120).

A key intervention consists of improving the performance of buses. In cities around the world, traffic congestion slows bus speeds, making buses increasingly unappealing to current and potential riders. "Bus rapid transit" has emerged as an array of technologies that can reduce bus travel times and otherwise provide a more convenient service. BRT systems feature various combinations of the following characteristics:

- Dedicated lanes, free of other road traffic
- Station stops
- Level boarding, sometimes through multiple doors
- Prepaid boarding
- Traffic signal priority at intersections
- Arrival time displays at stations

Taken together, these design approaches give BRT some of the "feel" of a rail system, but at a significantly lower cost. BRT construction costs range from \$1 to 10 million per kilometer (km), compared to \$10 to 30 million per km for light rail and \$15 to \$180 million per km for subways. The use of existing road infrastructure allows for rapid implementation, in contrast to the lengthy planning and construction periods required for rail systems. Bogotá, Colombia, implemented a 41 km BRT system in 2 years (CAF and Transmilenio 2004:7). In Jakarta, Indonesia, the design and construction of a 12.9 km BRT line lasted only 8 months (Fjellstrom 2003:2). By reallocating road space from private to public vehicles, BRT can improve the relative appeal of public transportation, potentially setting the stage for a transition to a less pollution-intensive transportation system.

2.1 Urban context in South Africa

Greenhouse gas emissions from South Africa's transportation sector are particularly high as a result of decades of racially motivated urban policy. The National Party, after coming into power in 1948, instituted a series of regulations to ensure the complete segregation of South Africa's racial groups. An early piece of apartheid legislation, the 1950 Group Areas Act, compelled local authorities to create separate commercial and residential areas for blacks, whites, Indians, and persons of mixed racial descent (Tomlinson 1990:35). Planners located black townships in the urban periphery, well away from white residential neighborhoods, forcing township residents to make long daily trips to work. In Cape Town, townships lie an average of 19 kilometers from the central business district (Prozzi et al. 2002:3). The effect of increasing physical separation between work and home locations is exemplified by the disappearance of South Africa's bicycling industry and culture (White 1999). Overall, the long travel distances resulting from apartheid spatial policies caused transportation energy use and greenhouse gas emissions to rise above levels in more compact cities (Naude et al. 2000:16).

Initially, the national government subsidized long-distance bus and train services to ensure the supply of black labor despite the long commute distances (ibid). Transportation subsidies became increasingly unsustainable in the 1980s as government priorities shifted to social services and internal security (Prozzi et al. 2002:7). Private minibuses were allowed to expand their service in order to relieve the government of some of the financial burden of public transportation. Still, subsidies remain high, covering 56 percent of rail operating costs and 60 percent of bus operating costs in Cape Town (Behrens and Wilkinson 2003:161).

2.2 Transportation in Cape Town

Consistent with trends elsewhere in the developing world, Cape Town faces increasing levels of private automobile ownership and use. Growth in the city's automobile stock, approximately 45 percent from 1990 to 2000, exceeds the growth rate of the population and is expected to continue at a rapid pace (CCT 2004b:107; Behrens 2002:8). A market segmentation

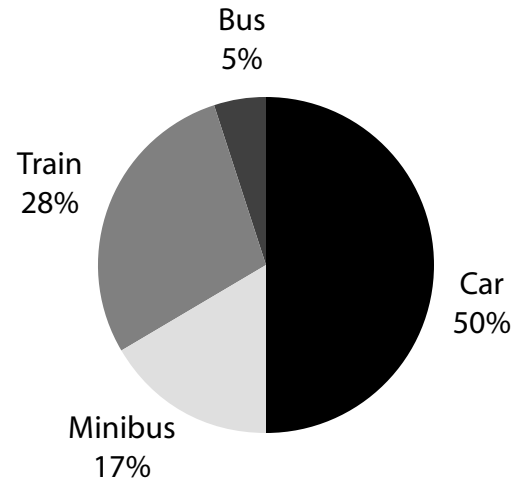


Figure 1 | Modal shares of all passenger trips in Cape Town

study conducted by the South African Department of Transport predicted that the number "stubborn" travelers, those only willing to travel by automobile, would increase 88 percent by 2020 (Cameron and Kingma 2002:1). The number of "selective" travelers, open to using public transport but financially able to use cars, would rise by 30 percent over the same time period (ibid). "Selective" travelers currently make up 19 percent of the urban population, and "stubborn" travelers, 14 percent (Cameron and Kingma 2002: 2). Rising affluence, a dispersion of home and work locations, and the poor quality of public transportation are all contributing to the rising use of private vehicles. The additional cars contribute to congestion, slowing public and private vehicles alike. In addition, increased automobile use exacerbates unhealthy levels of air pollution in Cape Town.

Public transportation ridership stands at about half of all trips in the city (CCT 2002:8). The three modes of public transportation—buses, minibus taxis, and trains—have bad reputations, especially among residents in higher income brackets. The electrified train system is known for high rates of robbery, assault, and even murder (CCT 2004b:113), and the trains have a poor on-time record. Minibuses generally maintain fixed routes, but service is unscheduled and unreliable, vehicle interiors are often cramped, and erratic driving results in frequent traffic accidents. Buses offer more regular schedules and the better personal safety for riders, but slow speeds make them the

least popular form of public transportation.

Little coordination occurs among the three public transportation modes, leading to duplication of service. The City of Cape Town has no budgetary or legal control over the train operator Metrorail, which operates as a subsidiary of a corporation owned by the national government (Holtzhausen 2003). Over the past decade, the minibuses industry has undergone a rapid, unplanned expansion, its ridership as a fraction of all trips by public transportation rising threefold. Opportunistic minibus operators sought out Cape Town's most lucrative routes, to the detriment of bus and rail ridership. Most of the new minibus passengers switched from buses, leading to intense competition between the two road-based modes (CCT 2002:27). The high frequency of service on some routes during the morning and evening peak periods served as a key selling point for minibuses. In 2000, the conflict between buses and minibuses erupted in the form of a "taxi war," resulting in deaths and injuries among drivers and passengers.

Buses and minibuses both continue to serve long distance routes, with the result that many vehicles have unused capacity. Bus passengers fill only around 43 percent of capacity even during peak periods (CCT 2004b:111). Bus loads remain low in part because the City requires the operator, Golden Arrow Bus Services, to provide service to communities that otherwise would lack transportation options. The smaller-sized minibuses would be more appropriately scaled to this task, but the City has more control over Golden Arrow, a public-private partnership, than over the private minibus companies.

2.3 Air quality in Cape Town

The shift from public transportation to private vehicle use in Cape Town contributes to rising motor vehicle emissions of local pollutants, including particulate matter and nitrous oxides. Particulate matter (PM) contributes to lung cancer, heart attacks, asthma, and strokes. Ground-level ozone, formed by reactions of nitrogen oxides (NO_x) and organic compounds in the presence of sunlight, exacerbates respiratory ailments, including asthma. Besides their health effects, "brown haze" episodes, accentuated by a temperature inversion layer during the winter, are considered to be detrimental to Cape Town's growing tourism industry

(Wicking-Baird et al. 1997).

Diesel and gasoline vehicles contribute 42 and 25 percent, respectively, of particulate matter emissions in Cape Town (ibid:iv). Diesel vehicles account for nearly half of visibility impairment, and gasoline vehicles, 17 percent (ibid:v). While testing has indicated that atmospheric NO_x concentrations in Cape Town are in decline, ozone and PM levels are increasing or remaining roughly steady (CCT 2004b:11). The City's *State of Environment* report expresses concern that PM concentrations are especially high in the densely populated, lower-income area of Khayelitsha (ibid). PM concentrations, in Khayelitsha and elsewhere, exceed the United Kingdom's health guidelines (ibid:14). Wicking-Baird et al. (1997:60) expect PM pollution levels to rise at a rate of 4 percent per year because fuel consumption is increasing and the motor vehicle fleet in Cape Town is aging.

South Africa has not set national ambient air quality or mobile source emissions standards. Most vehicles in the country still lack catalytic converters (Prozzi 2002:18). Motor vehicle pollution control is limited to efforts at the local level. The City of Cape Town has established a program to identify smoking diesel vehicles (CCT 2004a). Since 2000, the City has stopped offending vehicles at roadside checkpoints, recorded the light transmittance of exhaust, and required owners to have their vehicles serviced. The program does not address pollution from gasoline vehicles.

2.4 Bus rapid transit in Cape Town

To address its worsening congestion and pollution problems, the City of Cape Town has proposed a 30 km BRT line along the "Klipfontein Corridor," a series of 4- and 6-lane arterials stretching from the central business district to outlying suburbs and former townships. City officials began the planning process in early 2003 and plan to have the system operational by 2005. The BRT system is part of a USD 70 million project to rejuvenate portions of the city that had been marginalized during the years of apartheid (Gophe 2004).

Presently buses, minibuses, and private automobiles all use the roads that comprise the Corridor. Along some portions of the Corridor, the city has painted an additional lane stripe to indicate that only

buses and minibuses may use the leftmost lane. Without enforcement from traffic officers, the lane designation has failed to increase bus and minibus speeds. Private car drivers use the public transportation lane without hesitation and sometimes even park in the lane, forcing through-traffic to enter the remaining general lanes (Manojlovic 2003; personal observations). Even if enforced, the lane designation would have a limited effect on public transportation travel times. Cars may still enter the lane to make left turns, and buses would be subject to the erratic stopping patterns of minibuses. The proposed BRT system would appropriate two lanes, either on the sides of the road or at the median, making use of a physical barrier to separate buses from other traffic.

To the extent that travelers view the BRT system as an improvement over the existing bus mode, they may be inclined to switch to BRT from their current modes. This switching could have emissions benefits to the extent that the BRT system transports riders more efficiently, in terms of pollution, than do the alternate modes. For instance, introduction of the BRT system could reduce emissions of greenhouse gases if it drew passengers from cars, such that the fall in emissions resulting from the decrease in car travel more than compensated for the rise in emissions from the increase in bus travel. The next section describes the methodology used to predict the overall emissions effect.

3 analytical approach

Researchers have followed a variety of methods in analyses of the emissions effects of new public transportation systems, depending on the scope, data sources, time horizon, and goals of the study. The following discussion attempts to give a sense of the approaches that are relevant to this study.

Romilly (1999) investigates changes in social costs from pollution if car users switch to buses in urban settings in the United Kingdom. A spreadsheet model calculates the cost differential between scenarios: in one scenario, 160 passengers travel with automobiles, and in other, the riders travel by bus. In each case, the load factor—the number of passengers in each vehicle—and distance traveled are assumed to equal the corresponding national averages for the U.K. Since external costs for buses sometimes exceed those for cars for his assumed load factors, Romilly performs sensitivity analysis to determine what bus loads would be sufficient for the bus and car costs to be equal.

Prozzi et al. (2002), in a discussion of greenhouse gas emissions from transportation in South Africa as a whole, offer a pair of emissions scenarios for 2020. The study seeks to gauge the extent to which the country could alter its emissions trajectory by way of governmental policy interventions. To generate the alternative emissions scenarios, the researchers assumed two sets of changes in vehicle loads, modal splits, trip lengths, and other variables, relative to the base year of 2000. These assumptions simulate plausible responses to governmental efforts to make public transportation more efficient and convenient, among other things. The accuracy of the emissions projections depends on the researchers' understanding of the relationship between governmental regulation and the behavior of travelers.

Studies that consider the emissions effects of shorter-term modifications of transportation systems can attempt to model changes in travel demand with

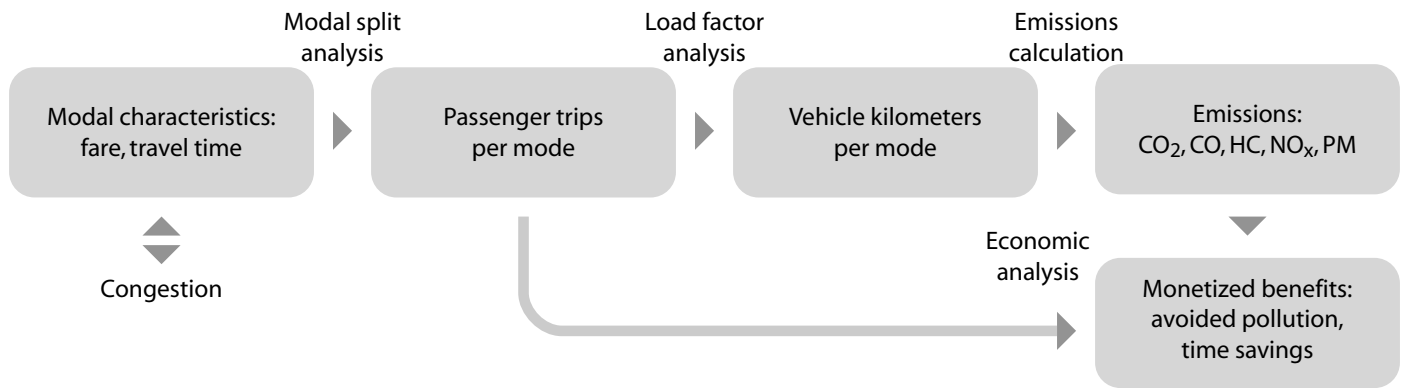
more precision. Some analyses make use of transportation modeling software, which follows a four-step simulation process, consisting of trip generation, trip distribution, mode choice, and trip assignment. "Trip generation" models use demographic information, including household income and vehicle ownership, and employment data to predict the number of trips originating and arriving in each zone that a modeler has created for a city. The "trip distribution" component then allocates a certain number of these trips to each origin-destination pair in the city. For each trip defined by the first two steps, the "modal choice" model uses information on characteristics of the trips and of the travelers' preferences to predict modal shares for each origin-destination pair. Finally, the "trip assignment" component predicts the routes taken by travelers so as to optimize the levels of congestion through the city's road network.

The city of Bogotá, Colombia, has applied for funding through the Clean Development Mechanism to extend its BRT system, based on predicted reductions in greenhouse gas emissions. Bogotá's emissions estimation procedure (CAF and Transmilenio 2004) relies on the results of transportation modeling software to predict the future "modal split," the distribution of travelers among the available transportation modes, for corridors relevant to the BRT system. Compared to the country-level predictions in Prozzi et al. (2002), the policy intervention is defined at a finer level of detail in the modeling software, and the software uses revealed preference data to make a more rigorous prediction about the future behavior of individual travelers. Then, the modal split proportions are used to calculate the number of trips by each mode, and these figures are multiplied by average trip lengths and emissions rates.

3.1 From trips to emissions

The present study begins with the third step, "modal choice," from the transportation modeling software process described above. The outcomes of the first two steps, the total number of trips and the origins and destinations of those trips, are assumed to remain the same under all policy intervention scenarios. Changes in modal choice, in the third step, are expected to

Figure 2 | Modeling process



constitute the primary mechanism by which the BRT system reduces emissions.

Figure 2 summarizes the modeling approach in the present study. Demand for travel by different transportation modes influences the amount of vehicle travel by each mode, which in turn determines emissions. To predict how characteristics of the bus rapid transit system will influence individuals' choices among the different modes, a discrete choice model is used to gauge travelers' responsiveness to changes in travel time. The next steps involve reallocating trips among the modes, estimating the number of vehicles needed to satisfy this demand, and calculating amount of pollution produced by these vehicles. In sum, the impact of the bus rapid transit (BRT) system on emissions depends on the demand behavior of riders as well as the supply decisions of public transit operators.

3.2 Scope of the analysis

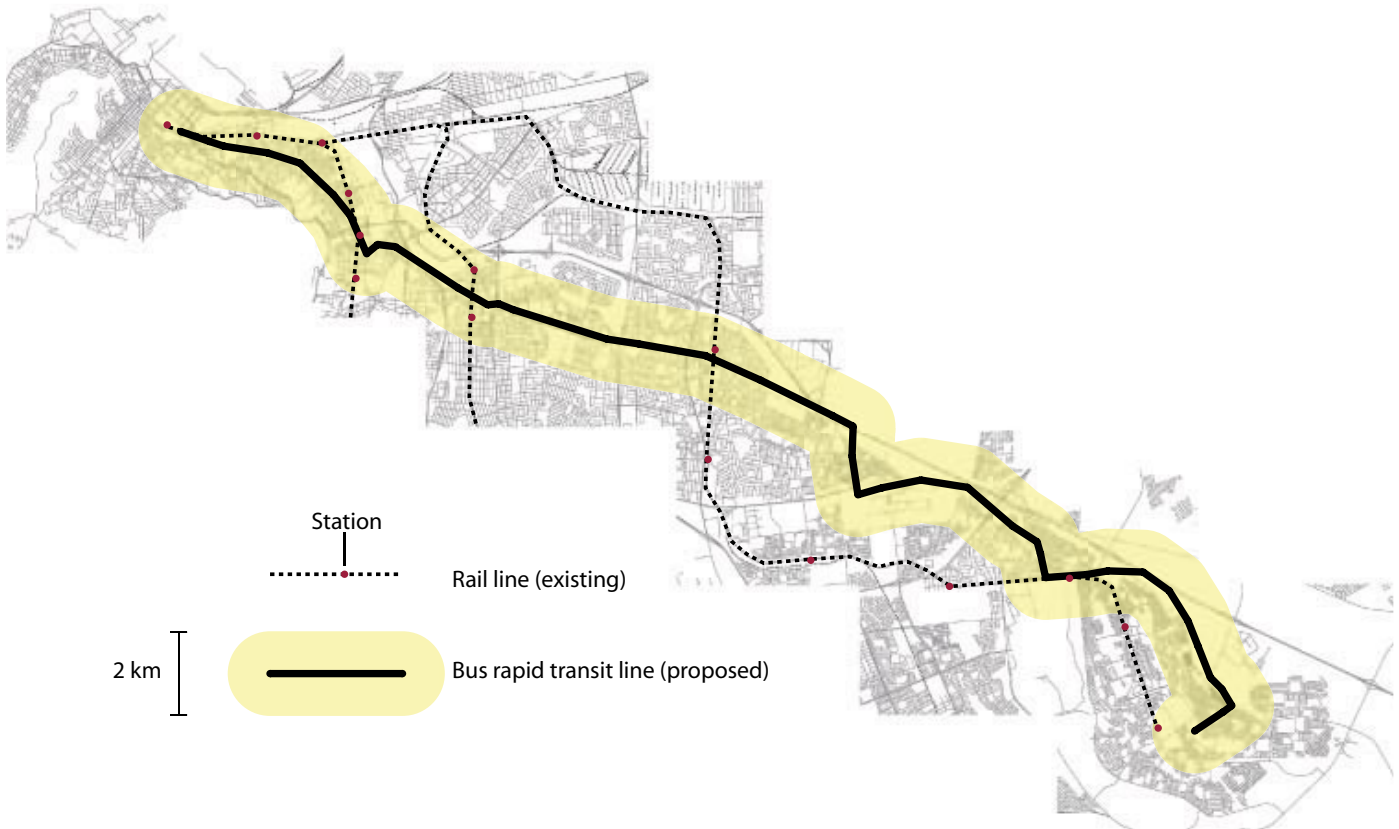
The BRT system will impact the Cape Town metropolitan area as a whole, but the most significant effects will be felt along the Klipfontein Corridor. In particular, most passengers riding the new system will be those who live or work in proximity to the BRT line. Thus, the present analysis considers only trips between origins and destinations that lie within approximately 1 km on either side of the BRT route, indicated in Figure 3. The theoretical BRT system alignment used in this study represents the preferred choice of the city and provincial transportation planners who attended an

Integrated Planning Group Meeting on 31 July 2003.

An individual taking a trip with public transportation that begins and ends within the 2 km-wide Corridor will have the option of completing the entire trip by BRT, since the trip will begin and end a reasonable walking distance away from the BRT line—10 minutes' worth or less. Extending the study area beyond 1 km from the BRT route would introduce significant uncertainty. If travelers who begin their trips outside the 2 km band wanted to travel by BRT, they would likely make their way to the Corridor with a different transportation mode and then transfer to the BRT system. Analysis of the propensity to add a transfer to one's journey is beyond the scope of this study. Furthermore, the future degree of integration between the BRT line and these "external" routes remains highly uncertain from a regulatory standpoint. The current structure of the public transportation system discourages transfers among the public transportation modes. Trains, buses, and minibuses use independent fare structures and ticketing systems, and train stations interface only partially with the road transportation network. Only 7 percent of public transport users interviewed for this study were taking trips that involved intermodal transfers. In excluding consideration of routes outside the 2 km interval, this study makes the conservative assumption that barriers to transfers will limit the bulk of mode switching to trips that most closely follow the route of the BRT system.

This study considers the 38 minibus and 39 bus lines that have both origins and destinations that are accessible from within the 2 km Corridor. Some persons who wish to travel within the Corridor may

Figure 3 | Bus rapid transit corridor



board vehicles with origins or destinations outside of the Corridor. However, based on the assumption that buses and minibuses principally provide line haul services between their origins and destinations, such trips should occur infrequently.

As indicated in Figure 3, the rail network has stations within the Corridor, but the tracks do not always run parallel to the proposed BRT line. The present study considers trips along 5 train lines between pairs of stations accessible from within the Corridor, as indicated by red dots in Figure 3. Some stations do not themselves lie within the 2 km Corridor, but are assumed to be within walking distance of the Corridor.

Information on the origins and destinations of car travelers is unavailable. This study assumes that the fraction of aggregate automobile traffic on Corridor roads that represents trips within the Corridor equals the corresponding fraction of minibus trips on Corridor roads. The automobile traffic volumes are derived from vehicle counts conducted by the City of Cape Town in 2002.

3.3 The modeling process in detail

The following discussion applies the modeling steps outlined in Figure 2 to the 2 km-wide Corridor study area delineated in Figure 3.

3.3.1 Modal split analysis

The first step in the modeling process predicts how characteristics of the bus system will influence the distribution of riders among the different transportation modes. An individual's decision to take one form of transportation rather than another depends on a variety of factors, including the relative cost, travel time, convenience, and safety of the alternatives. Some variables—cost and time—lend themselves to straightforward quantification, and this study relies on them in its discussion of the potential for mode switching. Transportation planners consider cost and travel time to be the fundamental determinants of modal choice, a pattern borne out by a roadside survey in Cape Town. Of 44 travelers, 82 percent reported

Table 1 | Frequency of responses to the question, “Why do you choose mode X over the alternatives?”

Mode used	Response					
	Price	In-vehicle travel time	Wait time	Walk time	Personal safety	Comfort
Train	3	2		1		
Bus	8		1	2	8	1
Minibus	3	9	1	1	1	1
Bicycle	1				1	

cost or travel time as the primary reason for choosing one mode over another (see Table 1).

Econometric model

Multinomial logit, a standard disaggregate model used in transportation planning, can help predict the effect of a change in a characteristic of a mode on the probability that an individual selects the mode. The utility, U_{ni} , of mode i for person n depends on known variables, such as cost and travel time, as well as factors unobserved by the researcher:

$$U_{ni} = V_{ni} + \varepsilon_{ni} \tag{1}$$

where V_{ni} is the observed “representative utility” of mode i for person n and ε_{ni} represents unobserved factors (Train 2003:38). For a choice among three alternatives, the model defines the probability of choosing mode x for person n as

$$P_{ni} = \frac{e^{V_{ni}}}{e^{V_{ni}} + e^{V_{nj}} + e^{V_{nk}}} \tag{2}$$

V_{ni} is a linear function of the trip characteristics that the traveler would face when using mode i :

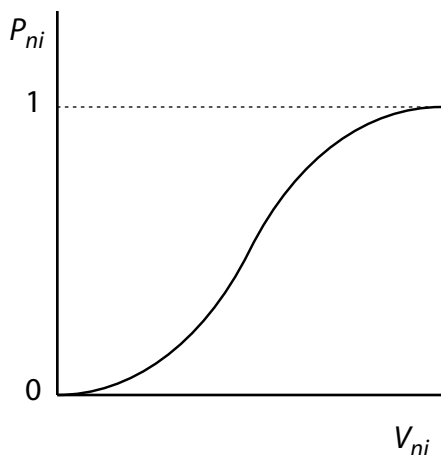
$$V_{ni} = \alpha(c_{ni} / w) + \beta t_{ni} + k \tag{3}$$

where c_{ni} is the cost and t_{ni} is the travel time faced by person n on mode i , and w is person n 's wage.

In the logit formula, P_{ni} varies with the representative utility of mode i as shown in Figure 4 (Train 2003: 42). If P_{ni} is particularly low or high, changes in mode i 's characteristics—and thus the utility that riders derive—result in small changes in P_{ni} . In the middle of the probability range, P_{ni} changes more easily. The behavior of P_{ni} with respect to V_{ni} reflects the intuition that if two options are similar, a slight change in their relative characteristics will have a large effect on the outcome of the decision between them. Conversely, if one option is strongly preferred to another, a slight change in the characteristics will have a smaller impact on the decision.

Statistical software packages use a “maximum likelihood” procedure to determine values of the coefficients, α , β , and so on, that allow the probabilities predicted by the formula P_{ni} to reflect the choices actually observed by the researcher. The estimates of logit coefficients in this study are generated by a program written in Gauss by Professor Kenneth Train (1999) at the University of California, Berkeley.

Figure 4 | Relationship in the logit model between the representative utility of mode i and probability of selecting mode i



Potential weaknesses of the logit model

The logit model offers a mathematical approximation that cannot capture the full complexity of decision-making processes. Drawbacks include the following:

- The logit equations assume that changes in the characteristics of the existing bus mode can

represent the new bus rapid transit system adequately. Depending on design decisions of the city, though, the BRT system in reality may function more as an entirely new mode. If the transportation authorities buy new buses rather than reallocating the existing fleet, the BRT system may attract riders simply because of the cleanliness, comfort, or generally “modern” feel of the new vehicles.

- When a change in the characteristics of a particular mode increases the level of utility experienced by the riders, the logit formula predicts a rise in P . To compensate for this increase in P , the remaining probabilities decrease by the same proportion. That is, the ratio between the two remaining probabilities remains the same. This assumption may not coincide with actual travel behavior patterns along the Corridor if patrons of a particular mode have a greater propensity to change modes than do riders of another mode. For instance, the BRT system could draw more people from minibuses than from trains if the similar operational attributes of the two road-based modes rendered them good substitutes of one another.
- The model assumes a widespread willingness to switch from one mode to another. However, some travel surveys in South Africa, including those described in Lombard and Hugo (2002) and Van Zyl et al. (2001), have revealed that many users do not perceive any alternatives to their current modes. In some cases, riders do not have alternatives because they are captive to the cheapest public transportation mode. The assumption of this study’s logit model that all individuals enjoy a choice between three public transportation modes may overestimate mode switching potential.

Data sources

The logit estimation for the present study makes use of a subset ($n = 132$) of data collected by Lombard and Hugo (2002). The researchers surveyed commuters in two districts of Cape Town: Nyanga/Guguletu and Mitchell’s Plain. Nyanga and Guguletu lie directly on the proposed BRT Corridor, and Mitchell’s Plain is demographically representative of some areas along the Corridor. A computerized survey program first asked

each respondent to enter the fare, travel time, and other characteristics of the mode that he or she generally uses to travel to work. Next, the program inquired as to whether the respondent could travel to work by any other mode. In the event that respondents perceived an alternative, the researchers requested details similar to those for the chosen mode. The logit estimation excludes responses without an alternative (11 percent of the sample). The sample included train, minibus, and bus users. Since the survey requested information for only a single alternative mode, the present study relies on the three pairs of two-way comparisons—train and bus, bus and minibus, and minibus and train—to conduct a trinomial logit estimation.

According to Willumsen (2004), current best practice in transportation modeling involves using software to compute trip characteristics for each mode between specified starting and ending points. The only information that the researcher must collect from the sample population is endpoint locations and modal choices. In the case of the Lombard and Hugo (2002) data, the responses represent participants’ impressions of trip characteristics, which may not coincide with the true characteristics. The survey method did incorporate some redundancy in order to elicit accurate responses. For example, the program checked the reported total travel time against the reported trip start and end times. Still, the data involve a degree of subjectivity. Inaccurate trip characteristic reporting became more frequent when the survey asked about trip characteristics for alternate modes since many respondents did not seem particularly familiar with the alternative options (Lombard and Hugo 2002).

Switching from cars

Much of the planning for the BRT system in Cape Town focuses on improving public transportation for existing users, with the goal of preventing further erosion of public transportation ridership. Luis Willumsen (2003), transportation planning consultant to the City of Cape Town, predicts that the BRT system will draw few current automobile users. Thus, part of this analysis limits mode switching to the public transportation modes.

Nonetheless, many lower income car owners in the city use their private vehicles selectively, and an attractive BRT option could further reduce the amount

that they travel in cars. On Fridays, for instance, congestion on Cape Town’s streets increases as commuters who normally travel with public transportation switch to automobiles to avoid having their weekly paychecks stolen during the trip home. BRT systems elsewhere in the world have successfully attracted riders from automobiles. In Vancouver, 20 percent of new riders had used cars previously (Levinson et al. 2003:6). Approximately 10 percent of the riders of Bogotá’s BRT system had traveled in automobiles (CAF and Transmilenio 2004:38).

3.3.2 Load factor analysis

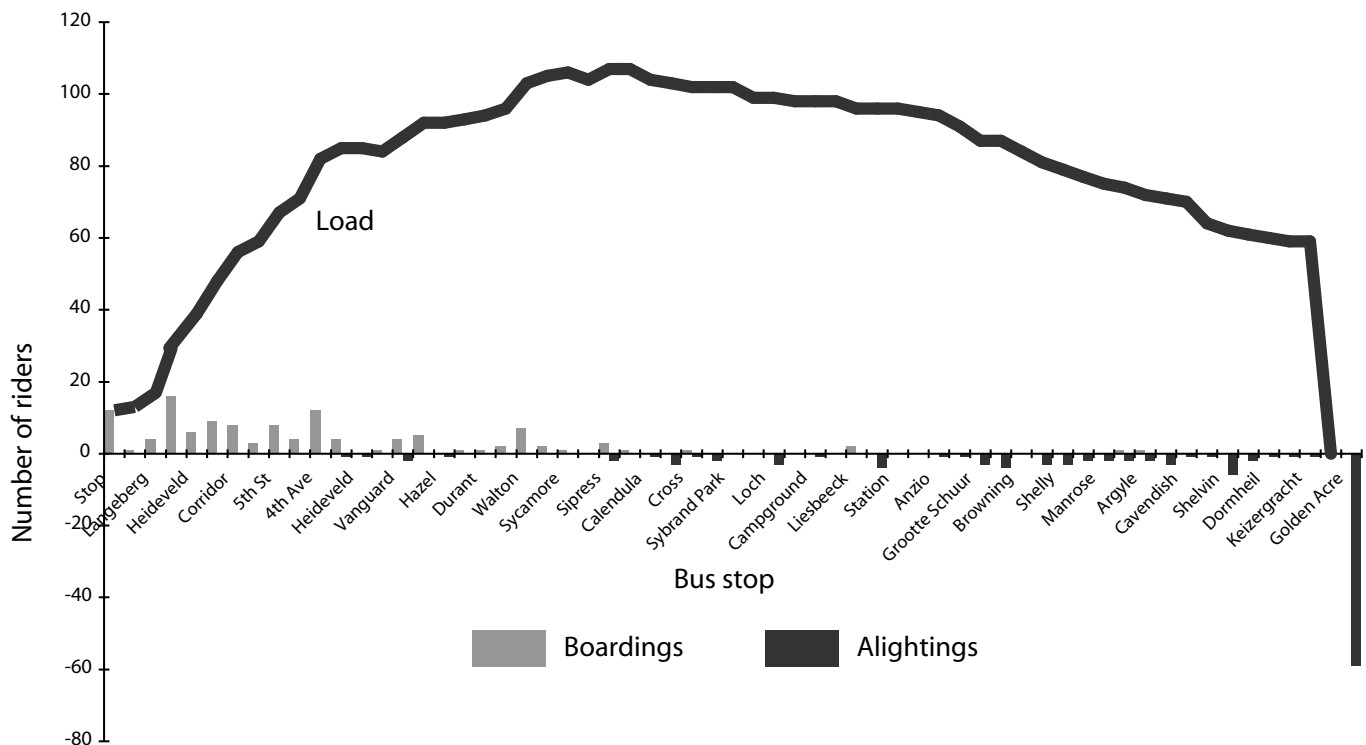
In the modal split analysis, the logit equation predicts changes in the aggregate modal split for trips along the Klipfontein Corridor. The modal split can be applied to the total number of trips taken to determine how many trips are taken on each mode. Then, the load factor analysis involves predicting the number of vehicles that will be used to carry the projected volumes of riders. (See Figure 2.)

Data sources

For estimates of status quo vehicle-km traveled by the different modes, the present study relies on data compiled by the City of Cape Town’s Directorate of Transport, Roads and Stormwater. National law mandates that each municipality regularly publish a Current Public Transport Record (CPTR) that catalogs average daily vehicle operating patterns and ridership levels. The Cape Town CPTR distinguishes between morning peak, midday, and evening peak time periods. The latest update reflects traffic levels in 2000 and 2001. The CPTR offers data for the three public transportation modes as follows:

- **Trains.** The CPTR includes the number of trains and volume of passengers traveling between each pair of adjacent stations as well as the number of boardings and alightings at each station. Information on the number of tickets sold in October 2002 between every pair of stations in the Cape Town rail network supplements the CPTR data, which do not distinguish among different origin and destination pairs. Only a portion of total train traffic along each rail segment represents

Figure 5 | Typical bus ridership pattern



travel between Corridor locations. The ratio of Corridor traffic to total traffic is assumed to equal the ratio of ticket sales for Corridor trips to total ticket sales.

- Minibuses. The CPTR assumes that in most cases minibuses provide a “line-haul” service.” That is, a group of passengers boards at the origin of a particular line and travels the entire distance to the destination. Thus, the CPTR provides a single figure for the ridership for each route.
- Buses. For each stop along a line, the CPTR lists the volume of passengers on the vehicle, the number of boardings, and the number of alightings. Given the difficulty of calculating the average number of passengers per unit of distance, this study takes the maximum passenger volume over the course of each trip to represent the number of passengers that traveled the route. The maximum usually offers a decent approximation of average ridership because buses in Cape Town tend to provide line haul service, similar to minibuses. Figure 5 shows a typical bus ridership pattern. Most passengers board before the bus travels far from its origin, and most get off at the end of the line. Relatively few riders board or alight from the bus mid-route. This assumption is conservative because it results in the underestimation of the potential for emissions reductions through increases in load factors.

Data on automobile travel are limited to roadside vehicle counts conducted by the City of Cape Town, separate from the CPTR.

Passenger volumes under the alternative scenarios

The mode switching analysis considers the changes in travel time and fare that would be experienced by someone making a representative Corridor trip, from the Nyanga/Guguletu area to the central business district. All travelers along the Corridor are assumed to benefit from time savings proportional to those experienced by the Nyanga/Guguletu subset, so this subset’s change in modal choice is applied to all Corridor travelers.

Modal shifts occur among the pools of all trips taken on each mode. Besides failing to account for the differences in modal characteristics experienced by riders in different parts of the Corridor, such aggrega-

tion leads to inaccuracy to the extent that the modes have different trip length distributions. The inaccuracy results in a conservative estimate of emissions effects because buses have the highest average trip lengths.

For the logit formula, the change in P_{ni} , the probability of choosing mode i , due to a change in parameter z of the same mode is defined as

$$\frac{\partial P_{ni}}{\partial z_{ni}} = \beta_i P_{ni} (1 - P_{ni}) \quad (4)$$

(Train 2003:62). If z changes for mode j , the effect on the probability of choosing mode i is defined as

$$\frac{\partial P_{ni}}{\partial z_{nj}} = -\beta_i P_{ni} P_{nj} \quad (5)$$

(ibid). The following formula combines (4) and (5) and approximates the change in P_{ni} in response to a small marginal change in z for the three modes:

$$\Delta P_{ni} = \beta_i P_{ni} \left(\frac{(1 - P_{ni})(\Delta z)_i - P_{nj}(\Delta z)_j - P_{mi}(\Delta z)_i}{P_{ni}(\Delta z)_i - P_{ni}(\Delta z)_i} \right) \quad (6)$$

Δz could equal, among other things, the reduction in bus travel time as a result of dedicated bus lanes. Extrapolation of the coefficients β_z to apply to automobiles allows for consideration of four modes in the modal split model:

$$\Delta P_{ni} = \beta_i P_{ni} \left(\frac{(1 - P_{ni})(\Delta z)_i - P_{nj}(\Delta z)_j - P_{mi}(\Delta z)_i}{P_{ni}(\Delta z)_i - P_{ni}(\Delta z)_i} \right) \quad (7)$$

With the new probability, a new number of trips can be calculated for each mode. For example,

$$B_x = (P_{ni} + \Delta P_{ni})(T_0 + B_0 + M_0). \quad (8)$$

where B_x is the number of bus trips in scenario x , and T_0 , B_0 , and M_0 are the numbers of train, bus, and mini-bus trips under the status quo scenario.

Traffic volumes under alternative scenarios

Operators of the different modes are expected to react differently to changes in passenger demand:

- Three of the rail lines are operating near or over capacity, but the operator cannot supply additional trains due to limitations of the signaling system. For these lines, the number of trains is assumed to remain constant. For the remaining two lines, which see lower passenger loads, the number of trains rises or falls in proportion to

changes in the number of riders.

- Cape Town’s buses have an average seated capacity of 67 and standing room for 25 persons. The CPTR and other city publications (such as CCT 2002) count the sum of standing and sitting room to be the capacity of a bus. However, given potential for growth on a particular route, the operator tends to add a new vehicle when the load exceeds the seated capacity (Krause 2004). Thus, to the extent that the BRT system results in higher bus ridership, existing buses are allowed to fill to the seated capacity. Until all buses on a particular line have reached a load of 67 passengers, the number of vehicles remains constant. As soon as a line’s new volumes exceed present capacity, new buses are added as needed to maintain a load factor of 67 passengers per vehicle.
- In the minibus industry, supply decisions are market-driven, so drivers are expected to leave routes with falling ridership in search of more profitable opportunities. Therefore, the number of vehicles rises or falls in proportion to changes in the number of riders. That is, the number of vehicles is multiplied by the same scalar that is used to adjust the number of riders. The load factor for each route remains the same.
- As with minibuses, the load factor for cars is assumed to stay constant at 2 persons per vehicle. The number of vehicles is directly proportional to the number of riders.

Passenger and vehicle volumes are calculated for each individual train, bus, and minibus route. Separate calculations are maintained for the morning, midday, and evening periods in order to account for changes in load factors at different times of the day.

Table 2 | Emissions factors: greenhouse gases (kg / km)

	<i>Basic (CO₂ only)</i>	<i>LEM (CO₂ and equivalents)</i>
Train	1.62	0.14
Bus	1.19	6.09
Minibus	0.33	0.89
Car	0.26	0.55

3.3.3 Emissions calculation

The present study estimates emissions levels on a per-kilometer basis. The first set of emissions factors, labeled “Basic,” assumes direct conversions (Environment Canada 2003; Eskom 2003; Mkhabela 2003) between volume of fuel or quantity of electricity consumed and the mass of carbon dioxide released. Fuel consumption factors for private automobiles and minibuses come from Schutte (1996:2-2), who provides parameters for the South African context. The fuel consumption factor for buses constitutes a weighted average of the efficiencies of five different types of buses that comprise the fleet of Golden Arrow Bus Services (GABS), Cape Town’s bus operator. Electricity consumption of trains is assumed to equal the average for U.S. heavy rail systems (APTA 2003). The level of greenhouse gas emissions from electricity production reflects the mix of nuclear, coal, and hydroelectric sources that serve Cape Town, as estimated by the South African electricity provider Eskom.

The second set of emissions factors, “LEM,” is from the Lifecycle Emissions Model, developed by Mark Delucchi (2003) at the University of California, Davis. Whereas the Basic factors consider only end-use emissions, the LEM estimates take into account the additional upstream pollution generated in the process of producing the fuels. In addition, the LEM

Table 3 | Emissions factors: local pollutants (g / km)

	<i>Basic</i>				<i>LEM</i>			
	CO	HC	NO _x	PM	CO	HC	NO _x	PM
Bus	12.5	2.7	16.0	14.4	12.6	3.3	18.9	3.1
Minibus	22.5	1.8	2.7	2.0	17.7	1.9	0.9	0.1
Car	17.5	1.4	2.1	1.5	17.7	1.9	0.9	0.1

Table 4 | European emissions standards for buses
(g / km)

	CO	HC	NO _x	PM
Euro II (1998)	2.0	0.5	10.0	0.5

calculates emissions of non-CO₂ greenhouse gases and reports these emissions in CO₂-equivalent values. These additional emissions are especially significant in South Africa (Delucchi 2004). Dr. Delucchi had previously customized the LEM for use in South Africa. For this study, the customized model was run to predict emissions per vehicle-km in the year 2005. The "Basic" and "LEM" emissions factors are listed in Tables 2 and 3.

The emissions calculations do not take into account variation due to speed, the frequency of stops, or other specific vehicle operating characteristics. Following the calculation of the number of vehicle-km traveled, the amount of pollution produced by the vehicles is determined. For the Basic emissions factors,

$$[\text{emissions}] = \left[\frac{\text{kg pollutant}}{\text{L fuel}} \right] \left[\frac{\text{L fuel}}{\text{km}} \right] [\text{vehicle - km}] \quad (9)$$

For the LEM emissions factors,

$$[\text{emissions}] = \left[\frac{\text{kg pollutant}}{\text{km}} \right] [\text{vehicle - km}] \quad (10)$$

For sensitivity analysis, current emissions of local pollutants from the GABS bus fleet are compared to emissions levels in the event that the City buys new buses. The "Euro" emissions standards, adopted by the European Union, are used to represent these potential emissions from new vehicles. Euro II standards, listed in Table 4, applied to new vehicles sold in Europe beginning in 1998 (Fulton et al. 2002:47).

4 econometric results

The Lombard and Hugo (2002) data were used to estimate several alternate logit model specifications, three of which are presented in the following discussion. The specifications take a linear form, as presented in Section 3.3.1:

$$V_{mi} = \alpha(c_{mi}/w) + \beta t_{mi} + k \quad (3)$$

In developed countries, many studies of the value of time have demonstrated that travelers value the components of a trip by public transportation at different rates. For instance, an individual might find time spent waiting for a bus to be more onerous than time spent riding in the bus. To estimate the differences in valuation among the time segments, t_{mi} in Equation 3 is replaced by three variables—walk, wait, and in-vehicle travel time—each with a unique coefficient. Logit estimation for the separate time components with the Lombard and Hugo (2002) data produces an insignificant coefficient for in-vehicle travel time, indicated under Model 1, in Table 5. The coefficient, furthermore, has the wrong sign, implying that an increase in travel time for a particular mode will result in higher patronage of the mode. (The fare variable is divided by wage because doing so reduces the degree to which the variable reflects the correlation between income and modal choice.)

Some transportation researchers in South Africa

have found that individuals do not differentiate between trip components as much as has been observed in other settings. Van Zyl et al. (2001) explain that in focus group interviews in the South African city of Durban, respondents expressed a similar value for access, wait, and in-vehicle times and gave precedence to overall travel times. In Cape Town, Van Zyl and Hugo (2002) generally found total time to be significant for train, bus, and minibus riders, but the time component variables were rarely significant.

Thus, Model 2 combines the trip segments into a single travel time. The result is a time coefficient with the correct sign, but the coefficient is still insignificant. Since Models 1 and 2 both yield insignificant results, the Lombard and Hugo (2002) data do not allow for an evaluation of the hypothesis that South Africans place comparable values on walk, wait, and in-vehicle times.

Model 3 obtains a significant coefficient for total travel time by combining additional information with the Lombard and Hugo (2002) data. The logit estimation procedure constrains the time coefficient to 2.77 times the fare/wage coefficient, the ratio found by Van Zyl and Hugo (2002) in a stated preference study in Cape Town. The ratio means that respondents valued travel time at 2.77 times their wage rates. The corresponding ratio in Model 2 is 2.59, so the constraint imposes a moderate adjustment.

Table 5 | Logit model coefficients

Variable	Model 1		Model 2		Model 3	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Fare / wage (Rands per min.)	- 0.0072	3.14	- 0.0064	2.88	- 0.0064	3.14
In-vehicle time (min.)	0.0332	1.24				
Walk time (min.)	- 0.0700	2.19				
Wait time (min.)	- 0.0222	0.76				
Total time (min.)			- 0.0166	1.10	- 0.0176*	3.14
Constant: train	0.2528	0.46	0.7044	1.45	0.7265	2.08
Constant: bus	1.0383	1.97	1.9582	4.43	1.9803	6.13

* Constrained to 2.77 times the fare/wage coefficient

5 simulation results

This chapter compares current emissions from Klipfontein Corridor transportation vehicles to emissions under scenarios that incorporate BRT. The Central Case intervention represents the likely characteristics of the BRT system. Parameters in the sensitivity analyses depart from those in the Central Case in to test the importance of Central Case assumptions about the design of the BRT system and the system’s effects on other modes of transportation.

5.1 Status quo emissions

Carbon dioxide emissions from Corridor vehicles currently total approximately 90 tons per weekday, dominated by the contributions of cars and minibuses, as shown in Figure 6. While cars account for only 17 percent of status quo passenger-kilometers on the Corridor, they produce 70 percent of the carbon dioxide pollution. Trains, by contrast, account for 62

percent of passenger-kilometers but only 5 percent of total emissions.

Figure 7 displays status quo emissions rates per passenger-km for Corridor trips. Compared to minibuses, buses operate with lower load factors, thus accounting for the higher emissions rate.

5.2 Policy intervention—Central Case

Parameters

In this scenario, buses continue to travel along their current routes, which sometimes begin on neighborhood streets before joining the arterial roads that will contain BRT infrastructure. To the extent that the buses travel on the BRT roads—74 percent of trip distances, on average—they can travel in the dedicated lanes and make use of intersection signal priority technology. Thus, changes in travel time apply only to these enhanced portions of each route.

The BRT system is expected to reduce travel times by removing buses from congested road conditions and by giving buses signal priority at intersections. Average bus speeds are assumed to rise from approximately 15 km/h presently to 24 km/h in the dedicated lanes, based on the performance of BRT systems else-

Figure 6 | Status quo emissions

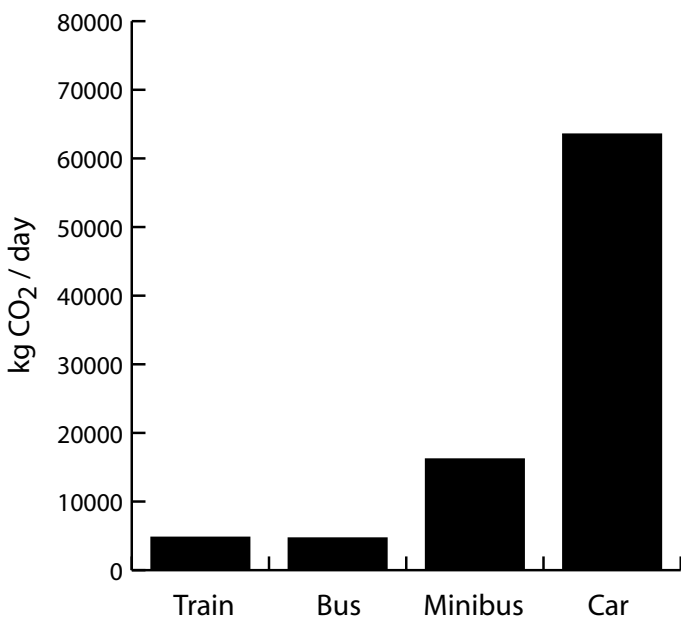


Figure 7 | Status quo emissions rates

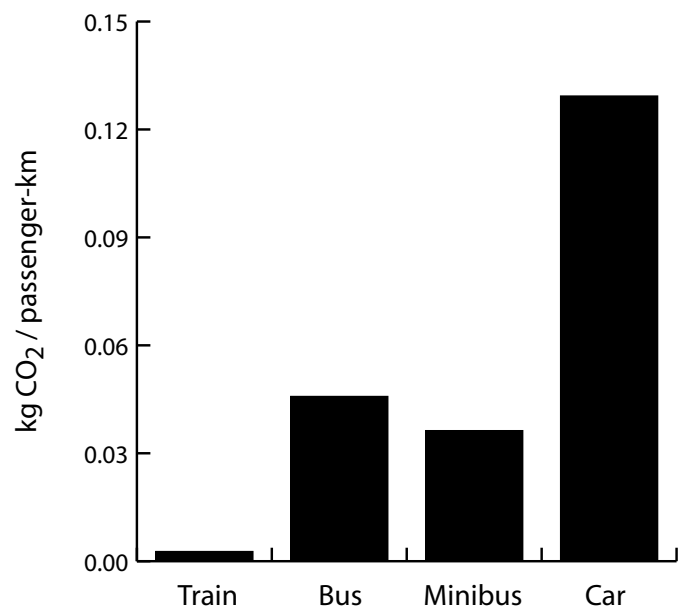


Table 6 | Nyanga/Guguletu–downtown, Central Case

	Distance	Speed (km/h)		In-vehicle time (min.)	
		Status quo	Proposed	Status quo	Proposed
Train	22.6	40	40	34	34
Bus	17.4	15	24	68	50
Minibus	17.4	39	33	27	32
Car	17.4	39	33	27	32

where in the world (Levinson et al. 2003:11) as well as expert advice (Willumsen 2004). Extrapolation of the speed increase to 74 percent of the distance between Nyanga/Guguletu and downtown yields a time savings of 18 minutes.

The allocation of lanes for exclusive use by buses probably will result in increasing congestion elsewhere in the Corridor. Willumsen (2004) predicts that this feedback mechanism may increase minibus and car travel times by 7 minutes for the entire BRT Corridor. Five of the 7 minutes of delay are assumed to occur between Nyanga/Guguletu and downtown. Table 6 summarizes the expected travel time changes for the Central Case.

Note that passengers switching to buses experience increases in travel times. For these individuals, switching constitutes an improvement in terms of other factors, such as price.

Results

The changes in travel times under the Central Case result in a small change in modal shares, as indicated in Table 7. Buses gain ridership under the central BRT scenario because of the decrease in travel time. Cars and minibuses lose ridership. Since minibuses and

Table 7 | Mode switching, Central Case

	Modal share (%)	
	Status quo	Policy intervention—Central Case
Train	49.3	50.4
Bus	5.5	7.4
Minibus	23.0	21.5
Car	22.2	20.7

cars characteristics worsen relative to trains, trains attract some of the former minibus and car riders.

Emissions of carbon dioxide and all local pollutants decrease 5 to 7 percent relative to the status quo in the Central Case.

5.3 Sensitivity

Table 9 summarizes the results of the sensitivity analyses described in this section.

Doubling of time coefficient

For this scenario, the coefficient, β , on travel time in Equation (3) is assumed to be twice the magnitude of the coefficient in Model 3, -0.0176 , which was calculated using the Lombard and Hugo (2002) data set. The doubled coefficient is within the range of magnitudes calculated in other studies (i.e., Ortúzar 2000: 368; Train 2003:76). The large change in emissions reductions—a near doubling—illustrates the crucial role of the logit estimation in the overall modeling process. The doubling of the time coefficients results in less than a doubling in emissions reductions be-

Table 8 | Emissions, Central Case

	Emissions (kg)		
	Status quo	Policy intervention—Central Case	Change (%)
CO ₂	90,491	85,369	- 5.7
CO	5,583	5,221	- 6.5
HC	458	429	- 6.3
NO _x	717	677	- 5.6
PM	539	510	- 5.4

Table 9 | Emissions: sensitivity analysis

Policy intervention	Change relative to status quo (%)				
	CO ₂	CO	HC	NO _x	PM
Central Case	- 5.7	- 6.5	- 6.3	- 5.6	- 5.4
Doubling of time coefficient	- 11.2	- 13.0	- 12.6	- 11.0	- 10.6
No congestion (car, minibus)	- 1.4	- 1.7	- 1.6	- 1.2	- 1.1
Doubling of congestion (car, minibus)	- 10.0	- 11.3	- 11.0	- 9.9	- 9.6
Single BRT line	- 5.4	- 7.0	- 6.6	- 4.8	- 4.3
No switching from cars	- 1.5	- 1.8	- 1.8	- 1.3	- 1.2
Minibuses remain on Corridor	- 5.0	- 5.8	- 5.6	- 4.9	- 4.7

cause of changing load factors on the buses. Initially, riders switching to buses occupy empty seats in buses already in operation. As those buses fill, further switching necessitates the provision of additional buses, with their associated emissions.

Congestion feedback

Emissions levels are also highly responsive to changes in travel times for cars and minibuses. Comparing the scenario without congestion delays for cars and minibuses to the Central Case indicates that the congestion effect leads to a larger percentage-point reduction in emissions than does the improvement in bus service alone: emissions fall 1.4 percent without congestion, compared to 5.7 percent with congestion. That is, some passengers switched to buses as a result of the 18-minute reduction in bus travel time, but a greater number of passengers switched to buses as a result of the 5-minute increase in minibus and car travel times.

The decomposition of modal switching behavior in the congestion sensitivity test demonstrates that changes in the characteristics of the three modes are associated with different degrees of responsiveness. These differences reflect the behavior of the underlying modal choice model, which predicts a higher level of responsiveness if probabilities are high. (See Figure 4.) Since bus modal share is low initially, improvements in bus service result in minimal changes in bus modal share. The increase in minibus travel time, on the other hand, results in a more dramatic change in minibus ridership. The overall emissions reductions reflect the “push” effect of a drop in the quality of

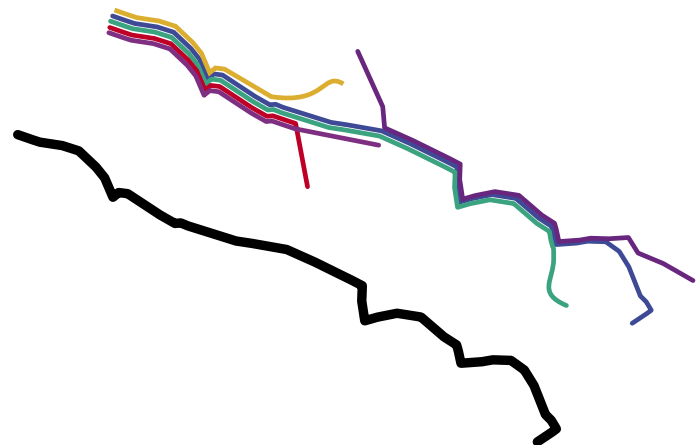
minibus service more than the “pull” effect of the bus improvements.

Single BRT line

This scenario replaces the existing bus routes with a single route that operates solely in the dedicated lanes. All buses travel the entire distance of the Corridor, reflecting the desire of some City officials to provide a higher level of service to communities that suffered the most during the decades of apartheid. Figure 8 compares the Central Case system design with the single line.

The number of buses traveling along the single service line is set to satisfy the peak demand during the morning, midday, and evening periods, wherever it occurs along the Corridor. While some riders may

Figure 8 | Central Case (top) and single BRT line (bottom) (approximate)



experience an increase in walking times, this change should be offset by a decrease in wait times, since riders will have more vehicles from which to choose. Applying the changes that affected 74 percent of the Corridor under the Central Case to the entire Corridor decreases travel times by 7 additional minutes, for a total bus travel time savings of 25 minutes.

If bus lines were restructured into the single line without any improvements in travel times, daily emissions would fall 836 kg because a smaller number of buses would be needed. Given expected changes in travel times and consequent increases in bus ridership, the restructured line results in slightly higher CO₂ emissions than in the Central Case. The improved travel time allows the single BRT line system to attract 34 percent more riders to buses than does the Central Case, contributing to emissions reductions. However, the buses used to accommodate the additional riders must travel the entire length of the Corridor under this scenario, whereas in the Central Case they only serve the specific routes where extra capacity is needed. The extra distance traveled partly offsets the emissions reductions achieved through mode switching.

No switching from cars

To gauge the importance of the uncertainty regarding the propensity of automobile users to switch to the public transportation modes, this scenario assumes that no travelers switch to or from cars. The logit equation is used to model switching only among the three public transportation modes.

Since private automobiles produce most of the Corridor’s carbon dioxide emissions, emissions reductions from mode switching are considerably smaller when the volume of private vehicle traffic is assumed to remain constant.

Minibuses linger

This scenario relaxes the assumption that minibuses leave the Corridor in proportion to the change in passenger demand. Instead, only half of the vehicles expected to stop operating under the Central Case actually do so. The City of Cape Town hopes to engage the minibus industry by giving minibus operators the opportunity to participate in the new transit author-

ity that will operate the BRT line. However, Bogotá, despite following a similar plan upon introducing its BRT system, fell short of its goal to reduce the number of transit vehicles along Corridors affected by the new system (CAF and Transmilenio (2004:34).

Since switching from cars accounts for a large portion of the emissions reductions, as explained in the “no switching from cars” section, the increase in minibus emissions under this scenario has only a slight impact on the overall size of emissions reductions.

5.4 Sensitivity to emissions factors

This analysis tests the effect of changes in emissions factors, using factors from the Delucchi Lifecycle Emissions Model (LEM). Inclusion of non-CO₂ greenhouse gases and upstream emissions increases emissions, as indicated in Figure 9. The change is particularly pronounced for buses, which emit almost as much pollution per passenger kilometer under the status quo as do automobiles.

Despite the increases in absolute emissions levels, the percentage reductions estimated using the LEM factors are similar to the reductions estimated with the basic factors. One exception is particulate matter

Figure 9 | Comparison of emissions factors

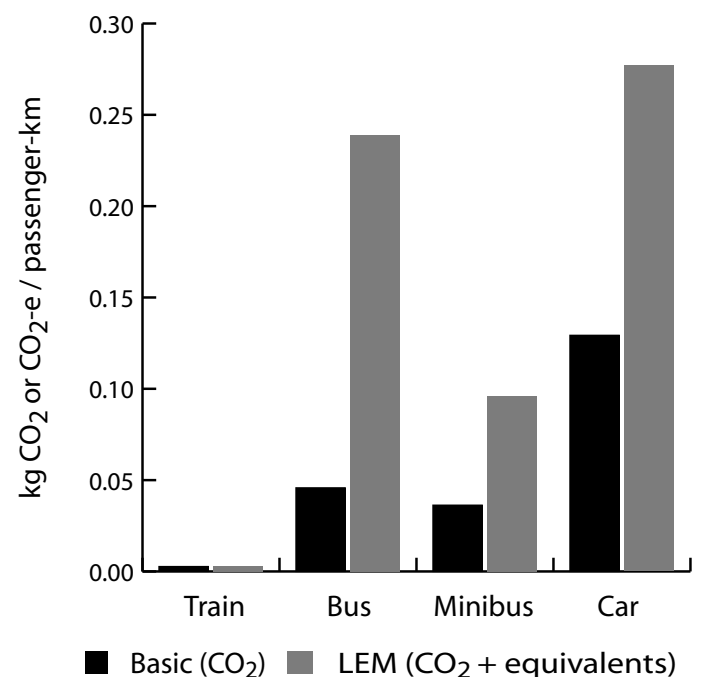


Table 10 | Central Case emissions reductions, estimated with two sets of emissions factors

Emissions factors	Change relative to status quo (%)				
	CO ₂	CO	HC	NO _x	PM
Basic	- 5.7	- 6.5	- 6.3	- 5.6	- 5.4
LEM	- 5.2	- 6.5	- 6.3	- 4.2	- 2.2

pollution, as the LEM predicts high PM emissions from buses. While the percentages are similar, the absolute decline in greenhouse gases predicted by the LEM factors is over twice as large as the estimate using the Basic factors.

5.5 Sensitivity to vehicle technology

The final sensitivity analysis compares emissions under current bus technology in use in Cape Town with emissions in the event that the City buys new buses to operate on the Corridor. Table 11 indicates local pollutant emissions reductions that would be achieved with buses that meet the Euro 2 standard. The table also shows the change in CO₂ emissions if the city uses hybrid diesel technology, which can reduce greenhouse gas emissions from 15 to 30 percent per vehicle (Feigon et al. 2003:41).

Since buses contribute a relatively small proportion of overall CO₂ emissions from the Corridor, the significant improvement in bus efficiency reduce overall emissions by a small margin. In the case of particulate emissions, on the other hand, the buses are significant contributors under the status quo, so the Euro 2 technology allows for large overall reductions.

Table 11 | Central Case emissions reductions, with changes in vehicle technology

Bus technology	Change relative to status quo (%)				
	CO ₂	CO	HC	NO _x	PM
Existing	- 5.7	- 6.5	- 6.3	- 5.6	- 5.4
Euro 2		- 7.3	- 8.3	- 9.1	- 16.3
Hybrid	- 6.8				

5.6 General characteristics of switching

In the scenarios described above, some of the emissions reductions result from the reduction of excess capacity in the bus system. This process cannot continue indefinitely. If buses operate at higher load factors, further mode switching will result in smaller marginal reductions in emissions because the additional buses brought into service increase emissions. After Romilly (1999), Table 12 indicates the average bus load factors necessary for switching to reduce emissions. Load factors for minibuses and cars are assumed to equal observed averages for the Corridor.

For example, the following combinations result in the same hydrocarbon (HC) emissions per passenger kilometer:

- 4 passengers riding in 2 cars
- 4 passengers riding in 1 bus

Buses produce high levels of particulate matter, so seated capacity must be nearly full for PM emissions to fall as a result of switching from minibuses. Table 10 further indicates the possibility of large emissions benefits if car users switch to buses.

5.7 Summary

Improvements in the BRT travel times encourage travelers to switch to buses from other modes, but the modal choice model suggests that this response will be limited. A larger change in modal shares is expected to occur if traffic congestion increases outside the BRT system's dedicated lanes, increasing travel times for minibuses and automobiles. Emissions of carbon dioxide and local pollutants fall because passengers switch from minibuses and automobiles to trains and the BRT system. Sensitivity analysis demonstrates the importance of switching from automobiles if the BRT system is to achieve a sizeable reduction in overall

Table 12 | Bus load necessary for emissions reductions through switching

Switching from ...	Pollutant considered				
	CO ₂	CO	HC	NO _x	PM
Minibuses	28	4	11	47	57
Cars	9	1	4	16	19

carbon dioxide emissions from the Corridor. The assumption in the Central Case that car users are as likely to switch to other modes as are public transportation users is somewhat optimistic. However, in light of international experience, the City of Cape Town probably can expect a sizable portion of the Central Case's predicted switching from cars to occur.

6 economic evaluation

The bus rapid transit system is the core of a broader effort to revitalize communities along the Klipfontein Corridor. Besides building the BRT infrastructure, the City plans to enhance public spaces and improve pedestrian and bicycle access throughout the Corridor. Altogether, these projects are estimated to cost approximately USD 70 million (Gophe 2004). In addition, the BRT system will involve yearly operating costs.

This section estimates the monetary value of two important effects of the BRT system, CO₂ pollution avoidance and time savings. These quantities, which would be expected to fall in the benefits category for the project, can be weighed against the system cost. The pollution and time effects are monetized based on the following assumptions:

- South African annual gross domestic product per capita: \$10,000 (CIA 2003).
- Travel time valued at 2.77 times the wage rate of \$5 per hour
- Weekday passenger and vehicle volumes apply for 260 days per year. For the remaining 105 days, the volumes equal half their normal levels
- Discount rate: 4 percent per year

- Benefit of avoided CO₂ damage: \$20 per ton

A reduction in greenhouse gas emissions would yield a benefit in the form of avoided climate change damage. Estimations of the economic value of climate damage vary widely (IPCC 1995). For a value of \$20 per ton of CO₂, the Central Case emissions reductions yield a benefit of \$32,013 annually or \$435,061 over 20 years.

Calculations of time savings assume that the representative trip described in Table 6 constitutes the average for the Corridor. Status quo bus riders who use the BRT system under the Central Case spend 18 minutes less per trip, adding up to 2,296 hours per week-day. However, riders who continue to use minibuses or cars experience a loss of 5 minutes per trip, a loss of 4,763 hours overall. In addition, train, minibus, and car users who switch to new modes see travel times rise. These losses amount to 1,276 hours per day. Therefore, the Central Case predicts a net travel time loss of 3,743 hours per day or, in monetary terms, a \$16.2 million annual loss.

The travel time valuation is extremely sensitive to the level of congestion. If cars and minibuses are not delayed, the value of travel time is a positive \$6.7 million. The sum over 20 years, \$92 million, compares favorably with the project costs.

Table 12 | Monetized benefits (or losses) from BRT

Policy intervention	Valuation (USD)	
	Annual	20 years (discounted)
Central Case		
Avoided CO ₂	32,013	435,061
Travel time savings	- 16,200,379	- 220,168,431
Total	- 16,168,366	- 219,733,370
No congestion		
Avoided CO ₂	7,718	104,891
Travel time savings	6,737,937	91,570,759
Total	6,745,655	91,675,650

7 conclusions

The foregoing analysis indicates that train travel results in the lowest rate of greenhouse gas emissions. Buses, if sufficiently full, produce the next lowest amount of greenhouse gas pollution. Therefore, a strategy that encourages a shift toward trains or buses from cars and minibuses should reduce emissions. Indeed, Cape Town's proposed bus rapid transit (BRT) system appears beneficial from an environmental perspective: the present study predicts reductions in greenhouse gases and local pollutants. For the Central Case assumptions, passengers switch from minibuses and cars to trains and the BRT system, and emissions fall 5 to 7 percent. Furthermore, emissions are expected to fall under a variety of different assumptions about the BRT system and its impact on other road users. However, the bulk of the reductions from mode switching is induced by the negative effect of congestion on cars and minibus users. If the congestion effect fails to materialize, emissions are predicted to decline only between 1 and 2 percent relative to the status quo.

The congestion effect is also crucial in determining the size of the economic benefits from the project. Greater delays for cars and minibuses offset the time benefits for bus riders, leading to net loss of travel time. Without delays, the monetized time savings constitute a benefit of similar magnitude to the project cost. Within the present study's modeling process, environmental and economic benefits are sometimes at odds. Congestion leads to a greater drop in pollution by encouraging a stronger modal shift toward buses and trains, but the detrimental impact on travel times swamps the comparatively small monetary benefit of avoided pollution.

The impact of the BRT system on travel times raises important equity concerns. Status quo bus riders benefit from improved travel times, but at the expense of car and minibus travel times. Car and minibus users tend to be more affluent than bus riders, so the policy intervention has the effect of establishing a more eq-

uitable distribution among the transportation services available to different segments of the population.

The BRT system will have many effects outside the scope of the present study. Topics for further research include the following.

- As part of the Klipfontein Corridor project, the City of Cape Town is improving infrastructure for bicyclists and pedestrians. The availability of bicycle routes between the BRT line and surrounding neighborhoods could expand the "catchment" area for the system, leading to increased ridership and reduced emissions if users switch from more polluting modes.
- The City hopes that the public investment in BRT will spur in-fill residential and commercial development along the corridor. Densification might contribute to a decline in transportation emissions by allowing new residents to locate within walking distance of existing urban amenities and in proximity to convenient public transportation service.
- The national Department of Transport is in the midst of a minibus recapitalization process, which will provide incentives for minibus operators to exchange their vans for larger 18- and 35-seat vehicles that run on diesel rather than gasoline. The emissions performance of the new vehicles is uncertain, and could either expand or reduce the benefits of mode switching to buses.
- The long-term transportation strategy in Cape Town and elsewhere in South Africa aims to integrate public transportation services, with minibuses serving as a feeder system for mainline bus and train routes. This restructuring could reduce emissions by encouraging a modal shift toward buses for long-distance routes.

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