Comparison of Emissions from Light Rail Transit and Bus Rapid Transit

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Bus rapid transit (BRT) is an evolving and promising transit mode that has emerged as a low-cost competitor to light rail transit (LRT) in providing medium-capacity semirapid transit. In addition, recent advances in diesel and compressed natural gas technology have caused the truism "electric rail is cleaner than diesel bus" to be revisited. A partial fuel cycle comparison of the regional or urban emissions of carbon monoxide, oxides of nitrogen, and volatile organic compounds from BRT and LRT is presented. The BRT analysis includes tailpipe exhaust emissions and fuel transportation, storage, and distribution emissions. The LRT analysis contains electric power plant emissions and line-loss-induced emissions. The analysis shows that whenever equal levels of technology are compared, LRT consistently performs better than BRT despite recent advances in the BRT mode. The analysis also shows that both modes are cleaner now than in the past.

Air quality in the United States has improved dramatically over the past 35 years as a result of increasingly stiff regulation and advances in technology. These improvements have occurred despite increases in gross domestic product, vehicle miles traveled, and population. This improvement in air quality is evident even in Los Angeles, the prototypical smog city, where the mountains have become visible again during summer months. Yet 146 million Americans were exposed to poor air quality at some point in 2002 (*1*). One strategy in reducing emissions is to shift travel to less polluting modes, such as a shift from single-occupancy vehicles to transit.

Bus rapid transit (BRT) is an evolving public transportation mode consisting of rubber-tired vehicles running on dedicated rights-of-way (ROWs) for all or part of a transit route. The vehicles are typically diesel powered, although some are dual diesel and electric. BRT evolved from standard bus service in North and South America as an effort to improve bus transit and make it more competitive with the private automobile (*2*). Elements that distinguish BRT from standard bus service are upgraded ROW, fare prepayment, larger station spacing, signal priority, and other intelligent transportation system elements. BRT is currently being advocated by many groups, including the Federal Transit Administration.

BRT has emerged as a low-cost contender against light rail transit (LRT) in many situations. The relative merits of both modes are often debated generically and for specific applications. One area of comparison is energy use and pollution emissions. Electric rail vehicles emit no propulsion system pollution at their point of operation. They are responsible for fuel cycle emissions from electricity-generating plants, which tend to be located on the urban periphery, and other upstream processes.

Diesel buses, however, have typically been perceived as producing strongly negative pollution-related externalities directly into the high-density areas that they serve. Diesel buses are also responsible for other emissions due to refining and other processes in the fuel cycle. In the area of energy consumption, rail, with its low-friction steel-on-steel support and guidance technology, has been assumed to be superior to rubber-tired buses. Because of these factors, electric LRT and other rail transit modes have been considered superior to diesel BRT and other bus modes in terms of emissions.

Diesel technology has improved dramatically in the past several years because of high-pressure injection systems, advanced after-treatment systems, and other measures (*3*). Compressed natural gas (CNG) combustion systems for heavy-duty vehicles have also continued to improve and have been advocated for decreasing oxides of nitrogen (NO_x) emissions in particular. Advances have also occurred in the generation of electricity. The changing technology landscape requires the periodic reexamination of old paradigms. This paper compares the emissions from two medium-capacity, semirapid transit modes—LRT and BRT. A literature review is undertaken to examine the state of the art in comprehensive fuel cycle and vehicle cycle emissions analysis and to provide additional motivation. The term "fuel cycle emissions" refers to a complete accounting of emissions and energy use from primary feedstock extraction though final energy use. Similarly, vehicle cycle emissions are the complete emissions caused by the manufacture, distribution, use, and disposal of a vehicle. Infrastructure emissions are the emissions caused by the construction of infrastructure. A proper methodology and framework for comparing emissions from LRT and BRT is then introduced. This methodology is then applied and the results are discussed.

REVIEW AND CRITIQUE OF LITERATURE

Many of the studies on emissions from transportation are either autocentric or, if transit is analyzed, have a limited treatment of system effects. One example is a paper by Shapiro et al., sponsored by the American Public Transportation Association, in which emissions, petroleum use, and greenhouse gases are calculated for transit and then compared to similar quantities for automobile-based transportation (*4*). The study found that travel by transit is cleaner and consumes less energy than travel by automobile. Argonne National Laboratory has developed GREET, a comprehensive fuel cycle model incorporating many fuel and propulsion technologies (*5*). This model calculates changes in emissions, energy consumption, and greenhouse gas emissions from technology changes relative to a normal spark-ignited, conventional gasoline-powered automobile. Louis also conducted a similar, although much less comprehensive, "well-to-wheels"

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evaluation of advanced technologies (*6*). Louis found that hybrid-electric compression ignition technology has the fewest greenhouse gas emissions when compared with all near-term and medium-term technologies.

Levinson et al. conducted an early study of emissions from various modes using a systems perspective (*7*). This paper presents a vehicle–infrastructure cycle analysis that compares life-cycle energy consumption of various modes, including automobile travel on freeway, arterial, and two-lane roads; diesel urban bus transit; and various modes of rail transit. The analysis does not include any fuel cycle effects and shows that infrastructure cycle effects can be a significant factor in subway systems.

A very comprehensive analysis of emissions and greenhouse gases from public transportation modes was conducted by Delucchi et al. (*8*). This report has a very comprehensive literature review that will not be repeated here. The present analysis uses a similar methodology but with a different focus and with changes resulting from the analysis of the BRT mode with advanced propulsion systems versus conventional buses.

The most pertinent publication to the present analysis is a paper by Vincent and Walsh (*9*). Vincent and Walsh analyze emissions and greenhouse gases from BRT, LRT, and heavy rail–metro-type systems. The authors attempt to perform a systems analysis by including power plant emissions and line losses when calculating electric rail emissions. The authors conclude that BRT systems utilizing advance propulsion technology outperform electric rail systems in the areas of particulate matter (PM), NO_x, and CO_2 emissions per passenger mile. But the analysis has several severe flaws that invalidate its conclusions. Two of the most serious flaws are worth mentioning here. Vincent and Walsh make somewhat poor choices when choosing examples of each mode for comparison. Very clean buses with high occupancy rates are compared to moderate rail systems with power derived from relatively dirty sources. Very good examples of BRT technology are compared to average or poor examples of electric rail technology. The other major flaw is the inclusion of power plant emission and line-loss-induced emissions, while refinery emissions and emission from the transportation, storage, and delivery (T&S&D) of diesel fuel or CNG are not included, even though they might reasonably occur in the region of interest. The flaws in this study are a major motivation for the present analysis.

METHODOLOGY

This paper presents a comparative analysis of the pollution impacts of LRT and BRT. An attempt is made to conduct a correct comparison of the two modes for a subset of important emissions.

Scope of Model

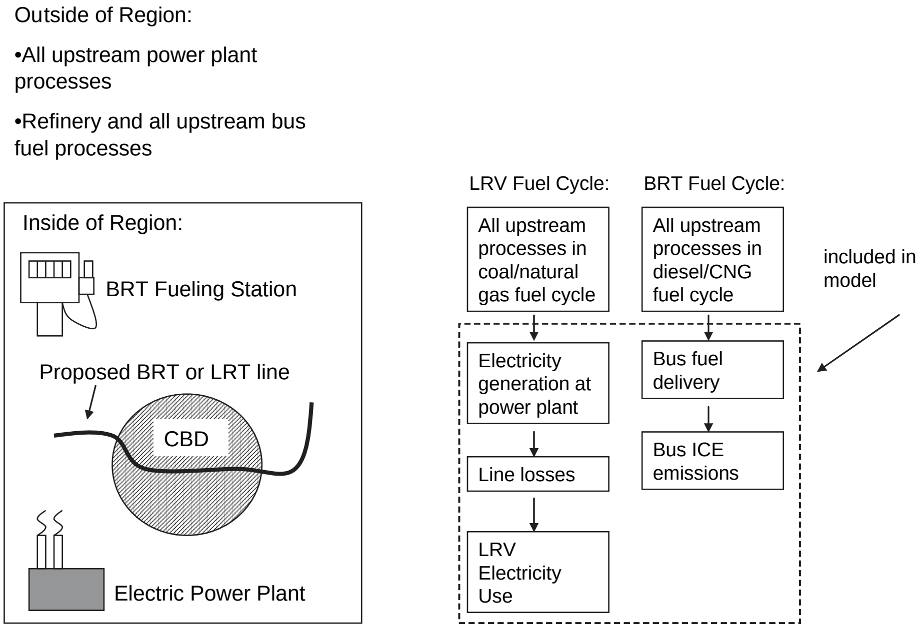
The present study is focused on policy makers considering the effect of a new semirapid, medium-capacity transit line on regional air quality. As such, the pollutants of interest in the present analysis will be urban or regional (synonymous in this paper) emissions of carbon monoxide, volatile organic compounds (VOCs), and NO_x. The urban calculation of sulfur dioxide (SO_2), PM, and mercury (Hg) emissions will be left for another study. The concept of urban emissions versus emissions on a greater global or national scale is used in Shapiro et al. (*4*). Some emissions, such as CO_2, are relevant only on a global scale. Such a gas does not have stronger impacts in the area in which the emission occurs versus its impact globally. Emissions of CO_2 between different modes can only be meaningfully compared on the basis of a complete fuel cycle (well-to-wheels) analysis. Furthermore, transit officials and policy makers at the metropolitan planning organization level and local government level, while perhaps concerned with the issues of global warming and pollution in areas outside of their region, have little incentive or power to control such emissions. Therefore, even though the global warming impact of these two modes is important, it is out of the scope of this paper.

Analysis of emissions on a regional level versus a local level is discussed in a recent report for the Edmonton Transit System (*10*). An analysis of street-level emissions would be trivial because a LRV emits no localized (tailpipe) emissions. The importance of street-level emissions should not be underemphasized. Transient levels of certain pollutants can be up to 10 times higher than ambient levels at distances of up to 10 meters from a bus stop (*10*). For a line traveling though a high-density area with pedestrian traffic, sidewalk cafes, and so forth, a LRT system might be chosen over a BRT system with lower regional level emissions because the effect of the BRT system's emission on the populace might be greater than that of the LRT system. For certain pollutants, the location of the emissions and the corresponding exposure of the population to pollution are just as important as the overall emissions level within a certain locale. While emissions of pollutants such as VOC might have regional (ozone formation) or global (global warming) impacts, they also have street-level impacts on the population (carcinogen).

The regional model for the analysis can be seen in Figure 1*a*. A diametrical semirapid transit line, either BRT or LRT, can be seen traversing though a central business district (CBD). The analysis is the same for a radial line, circumferential line, and so forth. For LRT, the power plant is assumed to be in the region. Therefore, all LRV and line loss electricity consumption must be considered. All upstream processes in the fuel cycle, such as coal or natural gas extraction, transportation, and processing are considered to take place outside the region and are therefore neglected. For BRT, all tailpipe omissions occur inside the region, as do all emissions from bus fueling processes. All upstream processes, especially the diesel refinery, natural gas compression, and so forth, are considered to be outside of the region and therefore neglected. The effect of the regional model on what elements of the fuel cycle are included/excluded from the emissions model can be seen in Figure 1*b*.

Technology Selection

Technically correct comparisons must be made when examining the relative strengths of different modes. That is, one must not compare the most technologically advanced example of one mode to an obsolete example of a different mode. This paper makes two comparisons when evaluating emissions from BRT and LRT systems: an average versus average analysis, which compares current representative samples, and a best versus best analysis, which uses the best examples of each technology that are reasonably available for current use. The technologies in the average comparison can be thought of as typical of current operations. The technologies in the best comparison can be thought of as typical for new starts today or in the very near future. Because this paper is written from the prospective of policy makers and planners making decisions on new medium-capacity modes, the inclusion of the average system (i.e., typical of current installations) is designed to point out the range of values possible and the results of recent improvements in technology. Comparisons using the worst examples of each mode will not be made. Neither will comparisons be made of the theoretical best of each mode [e.g., a solar-powered-derived hydrogen fuel cell bus versus a wind-powered electric light



(a) (b)

FIGURE 1 Model of (*a*) regional emissions and (*b*) effect on fuel cycle modeling (ICE = internal combustion engine).

rail vehicle (LRV)] because neither is economically feasible now and possibly will not be feasible even in the future.

Comparing emissions (or other data such as cost) across modes in terms of vehicle miles can be misleading because vastly different types of vehicles might be under consideration. The total emissions produced therefore need appropriate normalizing factors. Comparisons will be made on a per-passenger mile basis for both technology levels. A comparison using per-offered space (capacity) as a normalizing factor will also be made for the best versus best level. Comparisons will not be made on a per-offered capacity basis for the average category because of the difficulty in disaggregating the LRT data, which come from many different LRVs.

Rail Emissions Calculation

For the average LRT system, the U.S. averages for electricity consumption per passenger mile were used. These were calculated using total rail electricity consumption divided by total passenger miles from the National Transit Database (NTD) (*11*). The energy consumption data were then multiplied by average U.S. electricity emission factors (EF) (*12*) to get pollution in terms of mass per passenger km. The data for the average LRT system are highly aggregated and include some systems that are closer to traditional streetcar systems than modern LRT systems.

For the superior analysis, the LRT system with the best energy consumption, Denver, Colorado, was chosen. Although Denver's LRT system has the best electricity performance for its particular mode, it is not drastically better than its peers. The choice of emission factors was trickier. One could have chosen the very best state CO emission factor, the very best VOC emission factor, and so forth. But this approach would have ignored trade-offs between different emissions implicit in the technologies used in the various states. The approach that was used was to choose a state with very good emission factors in each of the three pollutants considered. Perhaps the best choice would have been Oregon. But Oregon relies heavily on hydroelectric power, which is not readily available in every region of the country. In order to facilitate a reasonable comparison, Rhode Island was chosen. It has very low emission factors but also has a considerable amount of relatively clean fossil-fuel-derived power in its mix.

The choice of what emission factors to use in the analysis addresses the concept of marginal electricity. New LRT systems will, especially over time, facilitate the need for additional generating capacity. This new electricity is the marginal electricity over that already being produced. The marginal electricity used to power a new system is not likely to come from the dirtiest of current power plants, because they are only allowed to continue to pollute as a result of being grandfathered into new regulations. Neither is the electricity likely to come from the cleanest, and possibly most expensive, wind or solar instillations. The use of average U.S. emissions factors for the average analysis might be conservative, but is used to maintain parity with the average bus analysis. The use of Rhode Island emission factors, instead of emission factors from the newest natural gas cogeneration plant, is also slightly conservative, but these factors are used to maintain a degree of real-world feasibility.

Emissions performance on the basis of per offered capacity (per offered space) was measured by taking capacity data for the Siemens SD-100 (used in Denver). This figure was adjusted in order to match with the buses in terms of space per standee. Because the SD-100 is an articulated vehicle, the capacity for a single car was used instead of the total vehicle capacity. The LRV capacity was not adjusted to harmonize with the buses in terms of seat–standee ratio for the given seating arrangement. The SD-100 had a capacity of 63 per car and a seat–standee ratio of 1.0.

A line loss of 3% was used in the calculations (*10*). This is somewhat less than the line losses typical for residential electricity use, which were used in the Vincent and Walsh analysis (*9*). After generation at a power plant, electricity is typically stepped up to several hundred kilovolts for transmission and distribution. The electricity is then stepped down to the medium voltage range, 10 to 20 kV (much higher than for residential use), for delivery to transit company rectifying substations (*13*, p. 329). The electricity consumption reported in the NTD is the consumption for which the transit company pays the utilities at these substations. Any additional losses though rectification to 750 volts DC (typical) and transmission are already accounted for in the data. The line loss factor is 100% plus the line loss.

Equations representing the calculations for emissions per passenger mile and emissions per offered space capacity can be seen in Equations 1 and 2, respectively:

$$\text{emissions [g/pass. mile]} = \frac{\text{EF(g/kWh)} * \text{total electricity consumption [kWh]}}{\left(\begin{array}{c}\text{total passenger miles [pass. miles]}\\ * \text{ line loss factor [kWh/kWh]}\end{array}\right)} \quad (1)$$

$$\text{emissions [g/offered space mile]} = \frac{\text{EF (g/kWh)} * \text{total electricity consumption [kWh]}}{\left(\begin{array}{c}\text{total vehicle miles [veh. miles]}\\ * \text{ vehicle capacity}\\ \text{[pass. miles/veh. mile]}\\ * \text{ line loss factor [kWh/kWh]}\end{array}\right)} \quad (2)$$

Bus Emissions Calculation

Bus emissions data came from a study by the Northeast Advanced Vehicle Consortium (NAVC) (*14*). For the average versus average bus, the standard diesel bus tested in the NAVC study for comparison and benchmarking purposes was used. This is a recent model (1998), three-speed NOVAbus brand diesel bus that had low mileage at the time of testing. It is a fair choice for an average bus, although a better vehicle would have been one in the middle of its service life.

Two buses were chosen for the best versus best analysis to capture the competing propulsion technologies for heavy-duty vehicles. As a best example of a hybrid electric bus, an Orion-LMCS VI hybrid electric bus running on ultra-low sulfur synthetic diesel was picked from the NAVC report as an outstanding example of hybrid-electric (HE) diesel technology. An Orion V CNG bus with good NO_x emissions was used as an outstanding example of that technology.

The concept of marginal electricity presented in the previous section has an analog here—the concept of the marginal bus, the buses that will be used for a new line. The buses for both the average and best analyses were chosen using the same concepts used to choose the rail vehicles and electricity sources.

Data from the CBD test cycle were used. The test cycle can be seen in Figure 2. The CBD test cycle is slower and with more stops than what might be typical of bus operations on a dedicated ROW but faster and with fewer stops than typical for operation on congested urban mixed-use facilities. Two test cycles were used in the NAVC study with longer cruises and higher top and average speeds that might be more representative of typical BRT operating conditions. But these data are not used because not all vehicles were tested.

The calculation of emissions from the LRT system relies on real-world data and implicitly contains an actual occupancy rate. But as the BRT emissions data come from laboratory dynamometer data, an occupancy rate needs to be assumed to normalize the emissions from a per vehicle mile basis to a per passenger mile basis. This study used the possibly optimistic assumption that a BRT line's ridership will be the same as that of a LRT line. As such, the occupancy rate for Denver's system of 26.2 passenger miles per vehicle mile was used. This is the biggest difference between this analysis and the analysis of a typical bus system. Average U.S. bus occupancy (which includes several vehicle types) in 2001 was 10.75. The assumption here is that BRT systems do a much better job at attracting riders at all times of the day.

For the calculation of emission on a per offered space basis, typical data for the Orion VI and V chassis were used for the HE and CNG vehicles, respectively. They have capacities of 55 and 61, respectively, and seat–standee ratios of 0.72 and 0.56, respectively. They thus have a lower comfort standard than the LRV with which they are being compared.

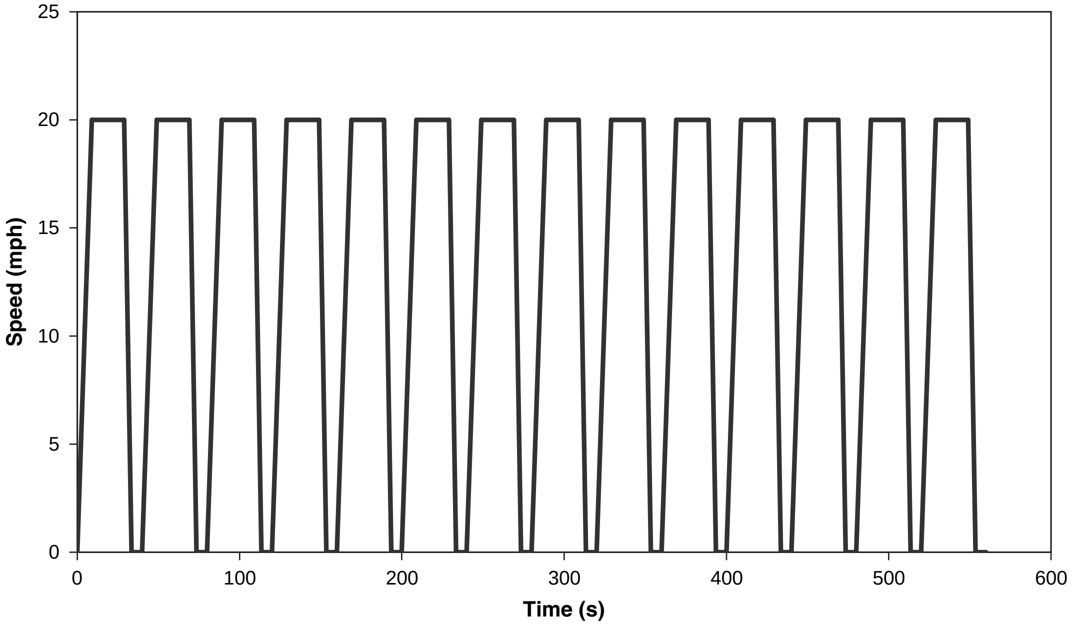


FIGURE 2 CBD test cycle.

Although the NAVC study directly measured NO_x and CO emissions, it did not measure emissions of VOC but nonmethane organic gases (NMOG). For the purposes of this analysis, VOC can be considered a subset of NMOG that does not contain certain hydrocarbons with a low atmospheric reactivity, mainly ethane. In diesel exhaust the amount of ethane is considered to be small. For the diesel bus, the NMOC numbers were used directly for VOCs. In CNG exhaust, the percentage of ethane resulting from incomplete combustion of the CNG fuel is significant. For the CNG bus, the NMOC emissions were reduced by 80% to account for the large amounts of ethane in the exhaust stream. This is based on data from other studies presented in the NAVC report that indicate the percentage of ethane in the NMOC emissions of CNG engines ranges from 33% to 80%.

Although the petroleum refinery is not assumed to be in the region, the fuel is transported to the region and stored there before bus fueling. VOC spillage emissions occur during these processes. On the basis of data in Wang (*5*), these emissions are assumed to be 3.38 g VOC/10^6 Btu. For CNG vehicles, natural gas is typically delivered to the transit facility and compressed on site. Methane, although a greenhouse gas, is not a VOC. CNG leakage in transport and fueling is therefore irrelevant for this analysis. The emissions due to the electricity needed to compress the CNG were calculated by using both the average and best electricity mixes in the electric rail analysis and by using the figure of 2.2% energy consumed to energy compressed given in Delucchi et al. (*8,* Table 10). These emissions were negligible and at most two orders of magnitude less than the tailpipe emissions. Emissions inside the region caused by the transportation of diesel and CNG via truck or pipeline are ignored.

Equation 3 represents the calculations involved in determining the per passenger mile and per offered capacity space:

$$\begin{array}{c}\text{emissions}\\ [\text{g/normalized mile}]\end{array} = \frac{\begin{array}{c}\text{dynamometer-derived emissions}\\ \text{rates [g/veh. mile]}\end{array}}{\left(\begin{array}{c}\text{normalizing factor}\\ [\text{normalized miles/veh. mile}]\\ +\ \text{T\&S\&D emissions}\\ [\text{g/normalized mile}]\end{array}\right)} \tag{3}$$

where the normalizing factor is either average bus occupancy (for g/passenger mile) or bus capacity (for g/offered space mile). The T&S&D emissions are zero for CO and NO_x for all buses and for VOC for the CNG bus. For the diesel bus, the VOC T&S&D emissions are calculated via Equation 4:

$$\begin{array}{c}\text{T\&S\&D emissions}\\ [\text{g/normalized mile}]\end{array} = \frac{\left(\begin{array}{c}\text{LHV}_{\text{diesel}}\ [\text{Btu/L}]\\ *\ 3.38\text{E-}6\ [\text{g/Btu}]\end{array}\right)}{\left(\begin{array}{c}\text{FE [veh. miles/L]}\\ *\ \text{normalizing factor}\\ [\text{normalized miles/veh. miles}]\end{array}\right)} \tag{4}$$

where FE is the fuel economy for each bus determined in the NAVC report (*14*) and $\text{LHV}_{\text{diesel}}$ is the lower heating value of diesel.

RESULTS AND DISCUSSION

Figure 3 shows NO_x emission results. The figure shows that LRT has a clear advantage over BRT in both the standard (average versus average) and superior (best versus best) comparisons. The best performing bus (CNG) has emissions slightly below that of the average LRT and BRT vehicle.

Data for VOC emissions are presented in Figure 4. Again the electric rail modes outperform the BRT vehicles in both the average and best categories. The CNG vehicle with comparatively low NO_x emissions had particularly bad VOC emissions, even given the somewhat generous 80% reduction when going from NMOC to VOC. A significant portion of the VOC emissions from the diesel buses was from T&S&D spillage. If the T&S&D emissions are ignored, the HE bus's VOC emissions are better than those for the average LRT system, but not as good as the best LRT system.

Figure 5 shows data on CO emissions using the high bus occupancy figure. Similar to the VOC chart, LRT outperforms BRT in both standard and superior comparisons with the CNG bus performing especially poorly. The HE bus's CO emissions are better than those for the average LRT system, but not as good as the best LRT system. Both VOC and CO result from incomplete combustion.

A number of conclusions can be drawn from these results. The first is that the old paradigm of electric rail being cleaner than diesel bus is still valid. The LRT systems were both better than their BRT counterparts. The second is that emissions performance has improved dramatically regardless of the mode in question. The best systems are much improved, sometimes by orders of magnitude, over their average counterparts.

Some caveats are also necessary when interpreting the results. The first concerns the CNG bus's somewhat poor performance in terms of VOC and CO. In CNG systems there is a trade-off between VOC and CO emissions on the one hand and NO_x emissions on the other that can only be partially eliminated though technology improvements. The CNG bus had very good NO_x performance, indicating that this bus probably had been optimized for NO_x performance. Because NO_x is such a strong O_3 precursor, one might choose the lower NO_x emissions despite the higher emissions of other pollutants when choosing between buses. An additional caveat is that one should also be careful when directly comparing the emissions from LRT and BRT, because all the emissions from both modes do not occur at the same place, at the same time, or at the same proximity to population centers. Tunnel operation is one example in which the location of emissions is just as important as absolute amount.

Another caveat has to do with regulation. All of the emissions under discussion are regulated, and the emissions performance has as much to do with relative regulatory strictness as it has to do with technology. If the emissions regulations on one of these modes continue to tighten while those for the other mode stand still, then the present picture could change. Therefore, as the component technologies that combine to form a BRT or LRT system evolve and improve and as regulations tighten, these results should not be considered valid for all time but only as a snapshot of the performance of current and near-future technologies.

CONCLUSIONS

The results show that, although advances in diesel technology have radically improved bus emissions, LRT systems still produce less regional or urban emissions in the three categories considered than BRT systems. This is true whenever equal technology levels are compared and even when superior BRT technology is compared with standard LRT systems for some pollutants. In addition, emissions of both modes have improved over time. These results are only applicable to the effects of these technologies on regional air quality and not on street-level air quality or emissions on a national or global scale.

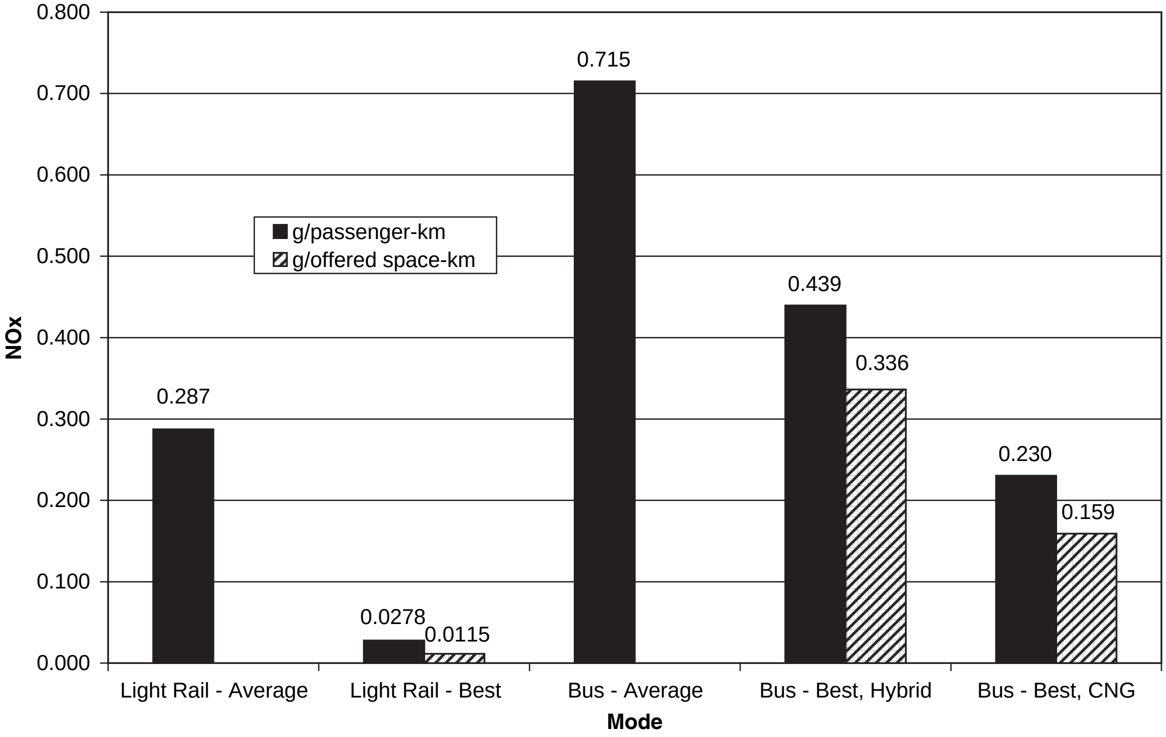


FIGURE 3 Comparison of NO_x emissions from LRT and BRT systems.

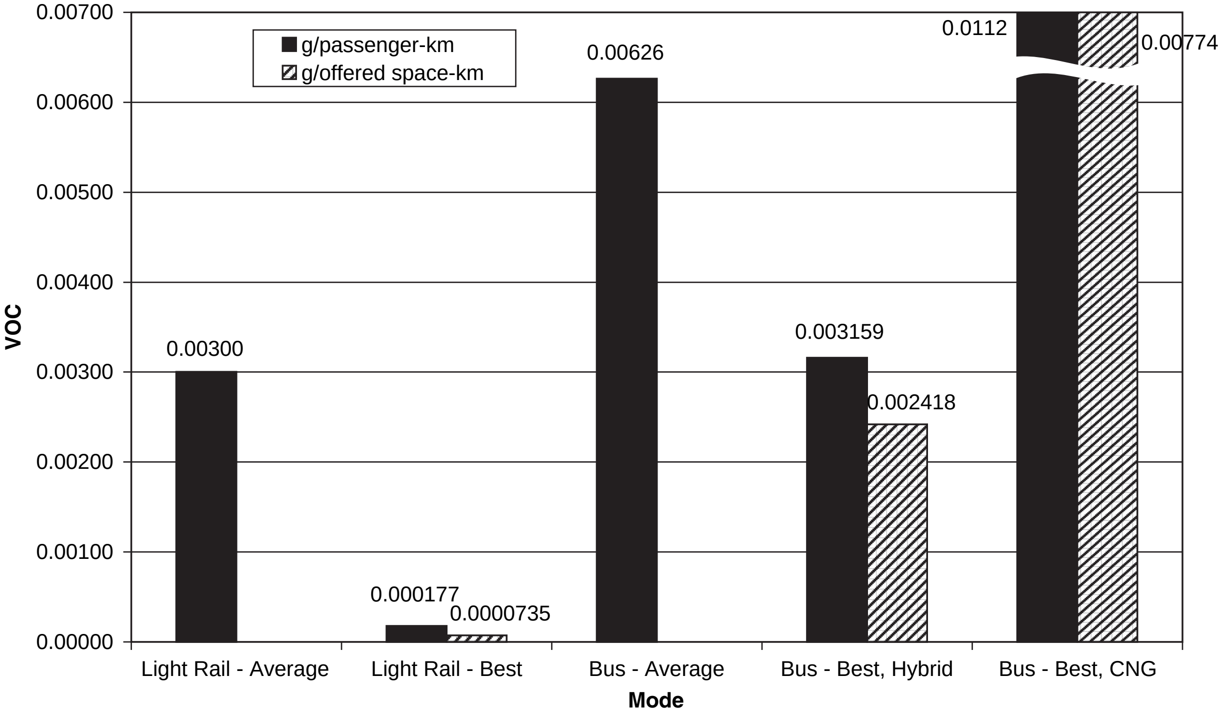


FIGURE 4 Comparison of VOC emissions from LRT and BRT systems.

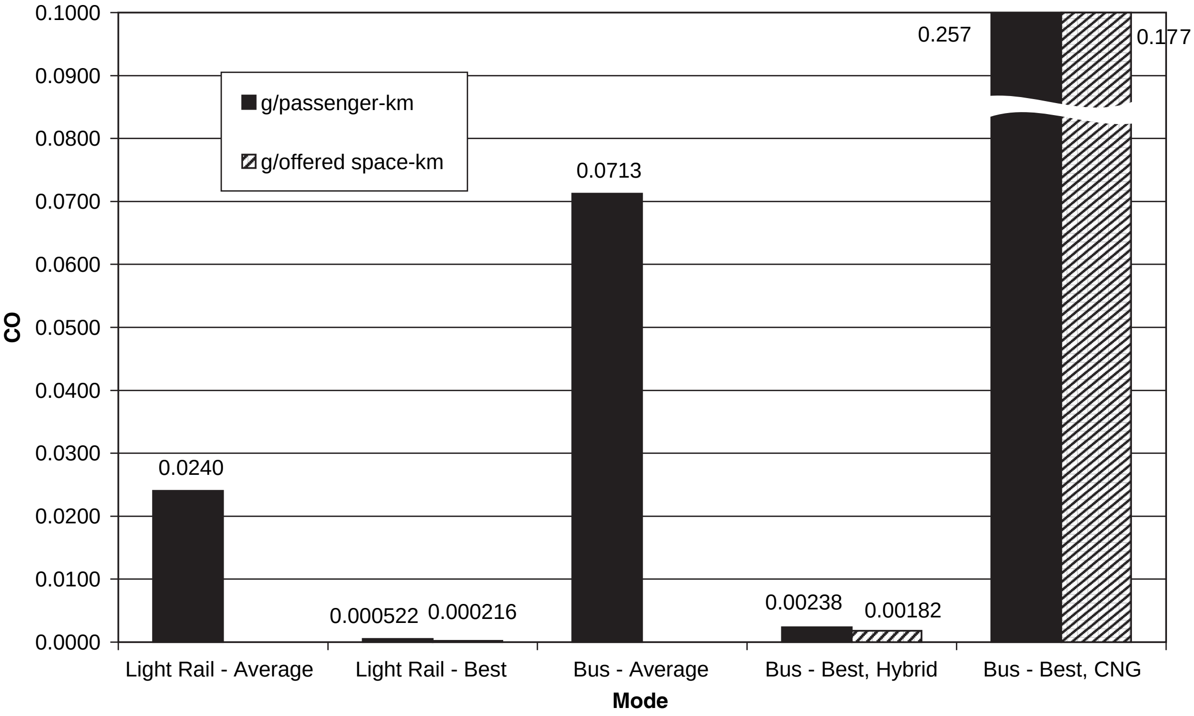


FIGURE 5 Comparison of CO emissions from LRT and BRT systems.

An area for further research would be to add an exposure model that includes not only the absolute amounts of emissions from each source included in the urban model, but also the exposure of these emissions to population. Other possible areas for further analysis would be to calculate urban emissions of other criteria pollutants and complete fuel cycle emissions of greenhouse gases.

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