Compressed Air Vehicles

Drive-Cycle Analysis of Vehicle Performance, Environmental Impacts, and Economic Costs

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In the face of the climate crisis, petroleum dependence, and volatile gasoline prices, it is imperative to explore possible opportunities in unconventional alternative-fuel vehicles. One such option is the compressed air vehicle (CAV), or air car, powered by a pneumatic motor and onboard high-pressure gas tank. Although proponents claim that CAVs offer environmental and economic benefits over conventional vehicles, the technology has until recently not been subject to a rigorous analysis. This study characterizes the potential performance of CAVs in terms of fuel economy, driving range, carbon footprint, and fuel costs and examines their viability as a transportation option as compared with gasoline and electric vehicles. Subjects of analysis include energy density of compressed air, thermodynamic losses of expansion, CAV efficiency on a pump-to-wheels and well-to-wheels basis, and comparisons with gasoline and electric vehicles. Results show that although the CAV is a bold, unconventional solution for today's transportation challenges, it is ultimately not workable, and compares poorly with gasoline and electric vehicles in all environmental and economic metrics. Further, applications of the CAV are severely constrained because of its limited driving range. The results from this study, including the analysis of energy density and expansion losses, may be used to identify future opportunities for CAV applications. The pump-to-wheels and well-to-wheels methodology contained here establishes a framework for evaluating future CAV designs.

The transportation sector faces great and urgent challenges, including climate impacts of greenhouse gas emissions, local health impacts of criteria pollutants, and political and economic impacts of petroleum dependence. These problems will become magnified globally as developing nations experience hypermotorization. Although several evolutionary solutions are being developed to reduce the impact of motor vehicles, such as increased fuel economy standards and accelerated adoption of hybrid vehicles, revolutionary new approaches must be evaluated.

One such approach is found in compressed air vehicles (CAVs), also known as air cars, in which a pneumatic motor is powered by compressed air stored in an onboard pressurized tank. Proponents of this technology claim that CAVs are greener and cheaper to operate since they do not consume fossil fuels and produce zero tailpipe emissions while offering the power and performance needed for light-duty vehicle use (*1*).

Although the concept of CAVs has received great attention in the popular press (*2–4*), there have been few studies evaluating the potential of air cars as an alternative to conventional vehicles. In a recent paper the authors presented an analytical model of a full life-cycle analysis of CAVs, concluding that thermodynamic limitations severely compromise their economic and environmental performance (*5*). The purpose of the current study is severalfold: to analyze the viability of compressed air and its full fuel cycle as a transportation energy storage medium, to explore the efficiencies of compressed air as a vehicle power source, to calculate the expected fuel economy and range of a CAV, to model their environmental impacts and economic costs, and to compare CAVs with other small gasoline- and battery-powered city cars. The CAV is an unconventional alternative to transportation challenges, but results show that the technology is not workable for transportation applications, comparing poorly with existing vehicles in terms of driving range, carbon footprint, and fuel costs.

The idea of the CAV is not new. In fact, it has been implemented in several forms since the turn of the twentieth century, when several technologies were competing to replace the horse and buggy. Patent applications show CAV designs for locomotives, mining cars, and factory uses (*6*). Air cars were also envisioned in science fiction, appearing in Jules Verne's 1863 novel *Paris in the 20th Century* (*7*).

Today, more than a century later, CAVs are still on the drawing board. Several companies worldwide are currently in the design or development stages of producing an air car, with some manufacturers heavily promoting their vehicles despite the lack of production or prototype units. Today's CAVs take the form of lightweight passenger cars designed for slow-speed city driving. Their chief proponents include the companies MDI International, K'Airmobiles, and Energine. Of these, MDI has advanced the CAV concept the furthest, signing development deals with Indian car manufacturer Tata Motors (*8*). MDI promotes six CAV models ranging from single-passenger cars to six-seat urban minibuses (*9*).

The CAV fuel cycle is conceptually simple: air is compressed to high pressure at a stationary compressor station, transferred to an onboard storage tank, and slowly released to power a pneumatic motor. The motor converts air power to mechanical power, which is transferred to the wheels and is used to operate the vehicle. In this way, compressed air acts not as an energy source like gasoline but as an energy storage medium similar to an electric battery. However, unlike those fuels, the efficiency of a CAV is dictated largely by the thermodynamic properties of gases, with the accompanying

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inefficiencies of compression and expansion. These inefficiencies, along with the energy density of compressed air, determine the vehicle's pump-to-wheels (PTW) performance in terms of fuel economy and driving range. A more comprehensive well-to-wheels (WTW) fuel-cycle analysis determines the vehicle's carbon footprint and fuel costs. Since this analysis assumes that the stationary compressors are powered by electricity, the WTW analysis accounts for the full upstream impacts of electricity generation, including generator efficiency as well as energy consumed in fuel extraction and processing.

The CAV modeled in this analysis is based on published specifications for MDI's CityFlowAIR, a small four-passenger vehicle intended for city driving (*10*). This vehicle is powerful enough to for slow-speed stop-and-go driving typical of urban drive cycles. For comparison with other vehicle types, equivalent vehicles are chosen in each class: gasoline vehicles are represented by the Volkswagen Fox and electric vehicles are represented by the Think City electric vehicle. Both are small vehicles intended for city driving with published performance metrics measured on the standard European urban drive cycle (UDC) (*11*). To allow for an apples-to-apples comparison between these vehicle types and air cars, the UDC is also used when the performance and range of the CAV are simulated. The results of this simulation are then compared against published specifications for the other vehicles on the same drive cycle.

The following topics are covered: first, compressed air is evaluated as an energy storage medium and compared with other transportation fuels, followed by a characterization of efficiency losses in air expansion. Then the efficiency of the PTW system is calculated by extending the efficiency analysis to air compressors and pneumatic motors. The performance of the CAV is simulated along the UDC in terms of fuel economy and vehicle range. A WTW analysis calculates the vehicle's carbon footprint, and fuel costs. Finally, CAVs are compared with gasoline and electric vehicles in terms of the foregoing metrics. To account for the fuel flexibility of electricity generation, a sensitivity analysis shows the WTW emissions according to three electricity generation scenarios with varying carbon intensities: U.S. average grid mix, low-carbon emissions associated with natural gas generation, and carbon-intensive emissions associated with coal generation.

COMPRESSED AIR ENERGY DENSITY

The source of energy in a CAV is the high-pressure compressed air tank. Unlike other fuel types, which store energy within the chemical bonds of the fuel, compressed air derives its energy from the thermodynamic work done by an expanding gas. A compressed air tank is an energy storage medium similar to an electric battery in that both are charged from an external source and release a portion of that power to the vehicle, with the remainder lost to inefficiencies or other limitations.

Since the power and range of a CAV depend on the amount of onboard energy, and since its small-form factor places restrictions on the size of storage tanks, the vehicle's design requires a fuel with high energy density for acceptable performance. However, compressed air is a poor energy carrier compared with conventional fuels and rechargeable batteries. Greater energy density is possible with greater storage tank pressures but creates trade-offs in terms of losses in gas expansion.

Energy Density: General Relationships

As a form of potential energy, the energy contained in a compressed air tank is equal to the work that can be done when gas in that tank expands to ambient pressure. This relationship is described as follows, which shows tank energy as a function of its volume and pressure (*12*):

$$E_T = -p_T V_T \ln\left(\frac{p_A}{p_T}\right) \tag{1}$$

where

E_T = tank energy,
V_T = tank volume, and
p_A, p_T = ambient and tank pressures, respectively.

The energy embodied in compressed air itself can be expressed independently of the storage tank, in the form of energy density per unit volume or unit mass:

$$\epsilon_V = \frac{E_T}{V_T} = p_T \ln\left(\frac{p_T}{p_A}\right) \tag{2}$$

$$\epsilon_m = \frac{E_T}{m_T} = \frac{\mathrm{RT}}{M} \ln\left(\frac{p_T}{p_A}\right) \tag{3}$$

where

ϵ_V, ϵ_m = energy density per unit volume and mass, respectively;
m_T = tank mass;
R = universal gas constant;
T = temperature of gas; and
M = molecular mass of gas.

In vehicle design, volumetric density is of prime importance, since the amount of fuel that can be stored onboard is typically limited by a vehicle's volumetric space constraints rather than its weight constraints. As shown in Equation 2, the volumetric density is solely a function of tank and ambient pressures. Thus the only way to increase volumetric density is to increase the maximum tank pressure. However, as shown later, an increase in tank pressure leads to greater inefficiencies in the expansion process, partially negating the benefits of greater energy storage. Notably, the volumetric density does not vary with the type of gas being compressed (ϵ_V is independent of M); air has the same volumetric energy density as that of heavier gases such as carbon dioxide (CO_2) and lighter gases such as helium.

Comparison with Other Fuels

Even at high pressures, compressed air carries much less energy than other transportation energy sources, including liquid and gaseous fuels as well as rechargeable batteries. Compressed air holds only 0.5% of the energy in gasoline and 1.5% of the energy of gaseous compressed natural gas (CNG). Similarly, the energy density of compressed air is poor compared with the types of rechargeable batteries available for vehicle use: lead acid (Pb–acid), nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium ion (Li-ion). Although batteries are significantly heavier than compressed air and hold less energy by mass, they still outperform in terms of volume, with compressed air holding 12% of the energy of Li-ion batteries. These relationships are shown in Figure 1, which plots the energy densi-

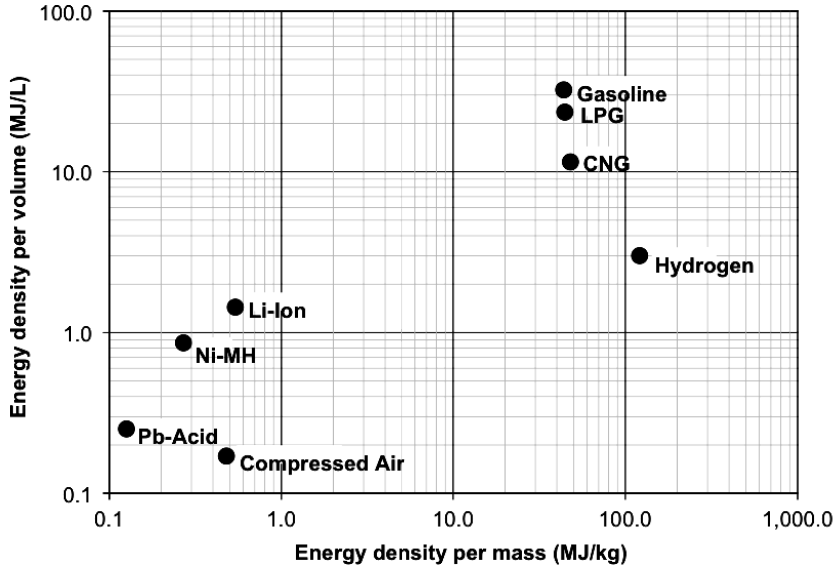

FIGURE 1 Energy density of compressed air and transportation fuels (LPG = liquid propane gas).

ties for all fuels on a logarithmic scale. This comparison is based on reported energy densities of fuels and rechargeable batteries and assumes that compressed air and CNG are compressed to 300 bar (4,350 psi) (*13, 14*).

Application to CAV Compressed Air Tanks

The low volumetric energy density of compressed air creates significant challenges in designing CAVs, which have limited storage space because of their small form factor. This difficulty could be mitigated through the use of next-generation higher-pressure tanks. Current carbon–fiber tanks, intended for use on CNG or hydrogen fuel cell vehicles, are typically pressurized up to 350 bar (5,100 psi), and new designs can accommodate 700 bar (10,000 psi). However, the benefits of higher pressures are partially offset by larger expansion losses, as discussed next.

THERMODYNAMIC EXPANSION LOSSES

The low energy storage of compressed air is compounded by inefficiencies in expansion from the gas tank to the motor. Unlike with conventional fuels, the available energy in compressed air is significantly reduced by the thermodynamics of the expansion process (*15*). The magnitude of expansion losses depends on the way that air is decompressed and is bounded by two scenarios: maximum (100%) efficiency is achieved by the isothermal process, in which the temperature of the gas is held constant; minimum efficiency is achieved by the adiabatic process, in which no heat is transferred into or out of the system. In practice, isothermal conditions are approximated by very slow expansion, whereas adiabatic conditions are approached through extremely rapid expansion. Because the CAV relies on rapid expansion of gas to power the pneumatic motor, it is assumed in this analysis that the CAV's expansion process is adiabatic.

The efficiency of expansion is measured as the ratio of adiabatic work to isothermal work. For the CAV analyzed here, with maximum pressure of 300 bar (4,350 psi), the expansion efficiency would be 53%. However, this efficiency can be increased by using multistage expansion.

Work Done by Expansion

The work done when gas (W_E) expands from tank pressure (p_T) to ambient atmospheric pressure (p_A), shown in Equation 4, can be described as a function of the tank pressure and volume p_T and V_T, atmospheric pressure p_A, and the coefficient *n,* which indicates the degree to which the expansion process is adiabatic or isothermal. The process is isothermal when $n = 1$ and is closer to adiabatic at greater values. For compressed air, the perfectly adiabatic process is represented by $n = 1.37$ (*16*).

$$W_E = p_T V_T \left(\frac{n}{n-1}\right)\left(\left(\frac{p_A}{p_T}\right)^{\frac{n-1}{n}} - 1\right) \quad (4)$$

In the limit where $n = 1$, the thermodynamic work can be expressed in a simplified form in Equation 5, which is equivalent to Equation 1, for the energy stored in a tank of compressed air, and is consistent with the definition of tank energy, in which the energy contained in a compressed air tank is equal to the maximum work done when gas in that tank expands to ambient pressure.

$$W_{E,\text{isothermal}} = p_T V_T \ln\left(\frac{p_A}{p_T}\right) \quad (5)$$

Expansion Efficiencies

The efficiency of expansion captures the degree to which the expansion work is maximized or compression work minimized.

This attribute is expressed as the ratio of actual work done, as shown in Equation 4, to isothermal work done, as shown in Equation 5.

The efficiency of expansion can be improved by separating the process into several stages, allowing the gas to return to ambient temperature in between. In multistage expansion, the pressure between stages grows by a constant ratio, where the ratio of the initial (p_i) and final (p_f) pressures between n stages is $(p_f/p_i)^{1/n}$ (*16*). This multistage approach significantly improves the efficiency of the adiabatic process, from 51% for single-stage expansion to 70% for two-stage expansion.

For this analysis, the vehicle is conservatively assumed to use two-stage expansion, based on published descriptions of CAV prototypes. One manufacturer states that the vehicle uses a form of passive or active heating to increase expansion efficiency (*10*). This heating activity is represented here as two-stage expansion, increasing the CAV's overall efficiency.

EFFICIENCY OF CAV PTW COMPONENTS

In addition to expansion losses, the air car PTW efficiency is dictated by energy losses in components that convert between mechanical power and air power: the high-pressure air compressor and the pneumatic motor. The technology behind each component is well established, with high-pressure air compressors and high-power pneumatic motors used extensively in industry and manufacturing. In this analysis, the efficiency of these components is characterized by using published performance specifications of existing high-pressure pneumatic equipment.

The following calculations show the compressor to be 53% efficient and the pneumatic motor to achieve an average of 40% efficiency when the conversion between air power and mechanical work is made. When the compressor and motor efficiencies are combined with losses from expansion, the total PTW system is 14.7% efficient at converting energy consumed by the compressor into energy supplied to the wheels.

High-Pressure Air Compressor Efficiency

The first stage of the PTW cycle is the high-pressure air compressor, which effectively creates the fuel consumed by the CAV. In this analysis, the compressor is assumed to be a stationary device that creates compressed air at the fueling station, eliminating the need for upstream transportation or distribution of fuel. Although different compressor types operate on electricity or diesel fuel, this analysis assumes electric operation because of the availability of detailed data on electric compressors. The compressor model included in this analysis is based on published equipment specifications from a pneumatics manufacturer (*17*).

In order to accommodate the CAV's maximum tank pressure, the selected compressor unit operates at 345 bar (5,000 psi) pressure. At maximum load, the unit produces 13.2 ambient cubic feet per minute of air with a temperature differential of 40 F above ambient. Because the machinery is not constrained by size, it can include heat sinks and multiple compression stages to increase efficiency and control thermal variations.

The overall efficiency of the unit is expressed as the ratio of air power produced per electricity consumed. This air power, 4.0 kW at maximum load, is produced while electricity is consumed at a rate of 8.6 kW, resulting in an efficiency of 53%.

Pneumatic Motor Efficiency

The pneumatic motor is the final component of the PTW system as modeled here. Although many pneumatic motor designs are available, ranging in power from a fraction of a horsepower to greater than 30 hp (25 kW), the majority of motors above 2 hp are air piston motor designs (*18*). For modeling purposes, this analysis calculates the efficiency of a pneumatic motor that closely matches the CAV description using published equipment specifications (*19*). The motor, with a power of 24 kW (30 hp) at 6.2 bar (90 psi), consumes 850 standard cubic feet per minute of compressed air at maximum load. Calculation of the power embodied in the input airflow determines that the motor is 43.4% efficient at maximum power.

However, the load on the pneumatic motor is not fixed but rather varies depending on the demand on the CAV at any point of the drive cycle. Motor efficiency depends on the relationship between air consumption and power output, both of which vary independently by motor load and speed. It is possible to simplify this relationship to solely a function of load, assuming that for a given load the motor operates at the optimum speed to maximize efficiency. This relationship can be achieved in theory by designing a drivetrain that selects the proper gear ratio to optimize motor efficiency at any speed. As such, the efficiency of the motor is expressed as a function of power output and is based on published power, efficiency, and air consumption curves as a function of motor speed and input pressure.

The efficiency curve is near maximum between 40% and 80% power and drops to 27% at lower power settings. This behavior significantly affects the efficiency of the CAV over the UDC, since the vehicles spend much time in low-power states while cruising at constant speeds. As such, the pneumatic motor achieves an average efficiency of 39.7% on the UDC, 8.5 percentage points less than the maximum possible efficiency.

Total PTW Efficiency

All the components described combine to determine the PTW efficiency, or the efficiency of converting energy consumed at the compressed air pump to energy transferred to the vehicle wheels, which is used to power the vehicle. The PTW efficiency is the product of compressor, expansion, and motor efficiencies. When the CAV is tested on the UDC, the total PTW efficiency is 14.7%.

PTW PERFORMANCE ANALYSIS

With the PTW efficiency as described earlier, the performance of the CAV is simulated on the UDC to calculate vehicle fuel economy and driving range. The simulation applied here relies on an energetic analysis of vehicle performance, determining how much power is consumed at the wheels to operate the CAV at each point in the drive cycle. By an application of the efficiencies of each component in the PTW cycle, this value is converted to power consumed both at the vehicle tank and at the compressor pump. This analysis is based on drive-cycle methodologies established by the PERE and AVCEM fuel economy and emissions models (*20, 21*).

Vehicle range is modeled as the distance the vehicle travels on the drive cycle before the energy consumed by the vehicle exceeds the total storage energy of the tank. In this case, energy consumption is measured at the tank rather than at the pump. In contrast, fuel economy is modeled on a full PTW basis and is defined as the energy consumed at the pump to drive 1 mi, converted to gallons of gasoline equivalent by using the lower heating value of gasoline.

Vehicle Parameters

The CAV simulated here is based on published specifications of the MDI CityFlowAIR vehicle. The CityFlowAIR is ideal for this analysis because it is comparable in size and intended function with conventional small urban cars, allowing for a valid comparison across vehicle types.

The drive-cycle simulation used here requires few parameters to calculate energy consumption. The CAV is modeled with the following parameters based on specifications from the vehicle manufacturer: a vehicle with mass of 1,200 kg (2,640 lb), a compressed air tank with 300-L (79.2-gal) volume and 300-bar (4,350-psi) maximum pressure, and a pneumatic motor power with 19 kW (25 hp) maximum power (*10*). Since no information is provided for CAV's tires, the characteristics of current low-rolling-resistance tires are substituted (*22*).

Drive-Cycle Characteristics

This analysis relies on the UDC, a standard drive cycle representing city driving. The European Union developed this cycle as a standard methodology for measuring fuel economy through dynamometer testing of vehicles with drive cycles intended to mimic real-world driving patterns. Driving patterns on city streets are represented by the UDC, which is characterized by low speeds and many stops. The UDC is a 0.6-mi (1.0-km), 3.3-min driving loop comprising second-by-second values of instantaneous speed. When tested on the UDC, a vehicle is driven to follow the specified speed trajectory, which mimics stop-and-go driving with a maximum speed of 31 mph (50 km/h). The drive cycle consists of three stop-and-go segments (*23*).

The UDC was chosen for this analysis over the equivalent drive cycle developed by the U.S. Environmental Protection Agency, the urban dynamometer driving schedule (UDDS). Because the UDDS is more demanding than the UDC, with faster acceleration and higher top speeds (*24*), vehicles tested under the UDDS have lower fuel economy and range than those tested on the UDC. As currently configured, the CAV is not powerful enough to complete the UDDS cycle. For these reasons, the European UDC is a better choice than the UDDS to represent the situations in which the simulated CAV would be used.

Energy Analysis

The simulation performed here calculates the power load on and fuel consumed by the vehicle at every point of the UDC. This analysis is composed of two parts: calculating the power at the wheels, or the power that the engine must provide to move the car, and calculating the internal losses and inefficiency in the flow of compressed air from the air compressor to the tank, pneumatic motor, and the wheels. The final result is the amount of fuel required to move the car along the UDC, determining both the tank-to-wheels (TTW) and PTW energy usage. These values, combined with the driving distance and onboard energy storage, determine the vehicle's driving range and fuel economy.

When the CAV is traveling along the UDC, its fuel is used to overcome three forces operating on the vehicle throughout the drive cycle: rolling resistance, which is constant; air resistance, a function of speed; and work to overcome inertia, a function of acceleration. The energy that the vehicle must supply to the drive cycle is equal to the sum of the power to overcome these forces at each second of the drive cycle. From the energy required at the wheels, the energy consumed at the tank and at the pump is calculated over the entire UDC, by using the PTW efficiencies determined earlier.

The CAV's driving range is modeled as the distance at which the vehicle's TTW energy consumption exceeds the energy stored in the vehicle's tank, hence depleting the tank contents. With this approach, the simulated CAV achieves a range of 29 mi (47 km) on the UDC. Unlike driving range, fuel economy is measured across the full PTW cycle, including the energy consumed at the air compressor when the vehicle is fueled. This approach accounts for additional losses that occur in the compression stage. For the simulated CAV on the UDC, the fuel economy is 38 miles per gallon gasoline equivalent (mpg-e).

The extremely low driving range is a result of the small amount of energy that can be stored in the CAV's onboard air tank. Although the calculations show that the vehicle's per-mile energy consumption is low because of its small size and mass, the vehicle's range is limited by three factors: (*a*) the simulated CAV's storage tanks can only store 51.2 MJ of energy, or the equivalent of 0.42 gal of gasoline; (*b*) over 72% of the vehicle's tank energy is lost when it is converted to power at the wheels; and (*c*) energy dissipated by braking is not recaptured by a regenerative braking system. As a result, its driving range is much lower than that of gasoline and electric vehicles.

WTW GREENHOUSE GAS ANALYSIS

For a full accounting of the environmental and economic costs of CAVs, it is necessary to consider the complete WTW impacts of operation, including the upstream emissions associated with electricity generation, fuel extraction, and processing. Since electricity can be generated from several fuel pathways, the analysis presented here includes a sensitivity analysis of three generation scenarios: a typical scenario assuming the average U.S. fuel mix, a low-carbon scenario assuming natural gas generation, and a carbon-intensive scenario assuming coal generation. These scenarios demonstrate the range of a CAV's carbon intensity that can be expected depending on the source of electricity.

The three scenarios utilize the following emission factors: a U.S. average generation WTW emission factor of 694 g CO_2/kW-h; a low-carbon natural-gas generation WTW emission factor of 500 g CO_2/kW-h; and a carbon-intensive coal generation WTW emission factor of 950 g CO_2/kW-h (*25–27*). The calculated CAV carbon footprint, measured in grams of CO_2 per mile, is presented in Figure 2 for each scenario. The results show that the CAV emits 626 g CO_2/mi on a WTW basis.

Finally, the CAV's fuel costs are calculated by combining fuel economy with the cost of electricity, represented by the average U.S. electricity cost of $0.091/kW-h in 2007 (*28*), resulting in fuel costs of $0.21/mi.

RESULTS AND VEHICLE COMPARISON

When the CAV's PTW and WTW performance metrics are compared with those of similar gasoline and electric vehicles, the air car is revealed to fare poorly in terms of driving range, carbon footprint, and fuel cost. As an exception, the air car's fuel economy slightly

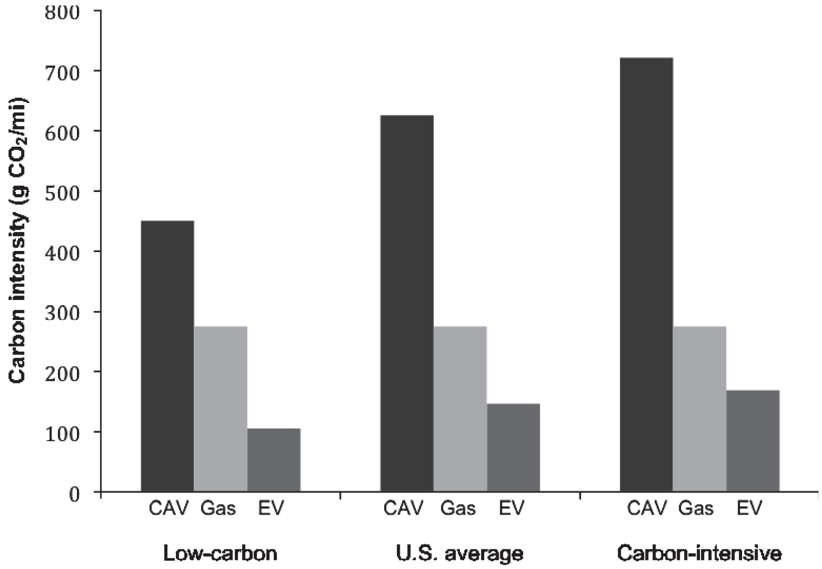

FIGURE 2 Comparison of vehicle carbon intensity across electricity generation scenarios.

exceeds that of the gasoline vehicle, and both are dwarfed by that of the electric vehicle. A comparison of performance metrics is presented in Table 1.

To allow for a meaningful comparison across vehicle types, the CAV is compared against gasoline and electric vehicles of similar size and intended use. In both cases, the selected comparison vehicles are small cars intended for city driving. The small gasoline car is represented by the Volkswagen Fox, and the small electric car is represented by the Think City. Both vehicles have been tested on the UDC, which allows for meaningful comparisons of vehicle performance and environmental impacts. Performance metrics for each vehicle are published by the respective manufacturers (*29, 30*).

Vehicle Performance

The CAV's limited driving range allows for just 29 mi of travel on a single tank of compressed air, primarily because of the low energy density of compressed air and the limited storage space available on the small form-factor vehicle. Because of this, the CAV carries the energy equivalent of 0.42 gal of gasoline. In contrast, the gasoline vehicle carries 12.8 gal of gasoline, enabling its range of 408 mi. Although the electric vehicle carries less energy than the gasoline vehicle, its greater efficiency enables a range of 127 mi. The short driving range of the CAV is its most significant limitation as a transportation option, allowing for just one 14.5-mi round trip before refilling. Although there are several strategies to increase driving range, as discussed later, each carries a trade-off that limits its effectiveness.

The air car performs better in terms of efficiency, achieving a fuel economy 19% greater than that of the gasoline vehicle. The CAV's fuel economy, measured on a PTW basis, is influenced by two factors: the energy needed to propel the vehicle through the UDC, and the efficiency of the vehicle engine (in the case of the CAV, the vehicle compressor–expansion–motor system). Although the CAV's energy requirements are low, its poor PTW efficiency limits overall fuel economy. Thus, the CAV's fuel economy is greater than that of the gasoline vehicle, but it is 77% less than that of the electric vehicle.

TABLE 1 Performance Characteristics of CAVs Versus Gasoline and Electric Vehicles

	Compressed Air Vehicle	Urban Gasoline Vehicle	Urban Electric Vehicle
Fuel type	Compressed air	Gasoline	Electric battery
Fuel economy	38 mpg-e	32 mpg	163 mpg-e
Urban range	29 mi	408 mi	127 mi
Fuel cost ($/mi)	0.21	0.09	0.05

Carbon Footprint and Environmental Impacts

Across all three scenarios of electricity generation, the CAV's per-mile carbon emissions are greater than those of the gasoline and electric vehicles. Since both the CAV and electric vehicle operate on electricity, their carbon footprint varies according to the fuel mix. In contrast, the emissions associated with gasoline are constant at 11.3 kg CO_2/gal, as calculated by the GREET fuel-cycle model (*31*). As such, the difference in emissions between each vehicle type varies greatly across scenarios. These differences are shown in Figure *2*.

Because of the CAV's low fuel economy and fuel mix of generation, its greenhouse gas emissions greatly exceed those of the gasoline vehicle. The air car's per-mile emissions are 1.6 to 2.6 times greater than those of the gasoline vehicle, depending on the scenario. In addition, the CAV's emissions are 4.3 times greater than those of the electric vehicle in all scenarios.

Economic Impacts and Fuel Costs

Finally, the CAV underperforms other vehicle types in terms of fuel operating costs. Its per-mile fuel costs, based on the average U.S. price of electricity in 2007, is $0.21/mi. This cost is over twice as large as that of the gasoline vehicle, based on the average 2007 fuel cost of \$2.80/gal (*28*), and four times greater than that of the electric vehicle on the basis of the same electricity cost.

When the effects of fuel taxes are considered, the fuel premium of CAVs over gasoline vehicles is even greater. The price of gasoline contains built-in fuel taxes for highway construction and maintenance activities, adding between 1 and 3 cents to the gasoline vehicle's per-mile fuel cost (*32*). If similar taxation were levied on electricity for transportation use, the fuel cost of CAVs on a per-mile basis and the cost differential between CAVs and gasoline vehicles would increase an additional 5% to 15%.

DISCUSSION OF RESULTS

Although the CAV underperforms gasoline and electric vehicles in terms of the metrics shown in Table 1, there may be opportunities to improve the viability of air cars. First, strategies may be employed to increase the CAV driving range (albeit with trade-offs). Second, the air car may have greater utility in certain applications other than as a city car. Finally, when analyzed under environmental metrics including tailpipe emissions and local criteria pollutant emissions, CAVs can be considered advantageous when compared with gasoline vehicles.

Strategies for Improving Driving Range

As currently designed, CAVs suffer from such a limited driving range that they are not usable as an alternative to current vehicles. Although there may be opportunities to improve this fatal flaw through a variety of strategies to increase energy storage, fuel economy, or refueling capacity, these strategies often trade off increased range with losses in other performance measures.

Driving range would be improved by increasing the maximum pressure of the storage tank, but this benefit would be partially negated by the reduced efficiency of the air expansion process. The additional fuel weight would also contribute to a reduction in fuel economy. In addition, future research would need to address the greater thermal fluctuations that would occur when gas is expanded from such great pressures.

Alternatively, driving range can be improved by increasing the size of onboard storage tanks. However, the mass of the added fuel would significantly increase total vehicle weight, which would result in lower fuel economy. In addition, it would be challenging to install a significantly larger air tank inside the CAV's small body.

A third option for improving range, suggested by CAV manufacturers, is to outfit the vehicle with an onboard air compressor. This strategy would allow drivers to refill their vehicles on the go and not have to rely on fueling stations. However, this option presents several challenges, not the least of which are the energy limitations of using onboard fuel to power a device for refueling the vehicle. Further, the feasibility of developing a small, lightweight compressor for high-pressure applications is unclear. Given these issues, the benefits of this strategy are not evaluated here.

Finally, a more feasible strategy may be to utilize regenerative braking to increase range and fuel economy. This option would also reduce environmental impacts and operating costs, without the performance trade-offs of prior strategies. Under this strategy, during braking, the pneumatic motor would act as a compressor, absorbing mechanical power from the axles to partially refill the compressed air tank. This form of hybridization would be analogous to that of hybrid hydraulic trucks currently in operation. In fact, some studies indicate that such a strategy may be a realistic and cost-efficient option (*5*).

Opportunities for Alternative Applications of CAVs

Although the CAV as currently envisioned for urban driving is not a compelling alternative to existing vehicles, there may be other situations or niches in which the technology is better suited. Some of these opportunities may warrant future study.

One alternative application for CAVs would be as low-speed, short-range vehicles similar to neighborhood electric vehicles. The low speed of the vehicle would increase fuel economy, and the short driving distances, when combined with small air compressors for home use, would mitigate the constraints of the CAV's limited driving range. If air cars can be shown to be competitive with EVs in this context, these neighborhood vehicles may offer a functional alternative to existing choices.

In addition, CAVs may be appropriate for use in certain harsh environments. A unique aspect of the CAV is the absence of combustion or electrical sparks during operation. This feature may make the air cars a suitable option for applications that contain poor ventilation or low oxygen levels that would limit the use of gasoline engines or a flammable environment that could be problematic for both gasoline and electric vehicles. The use of CAVs in this situation would mirror current applications of industrial pneumatic motors, which are often used in such environments.

Other Environmental Considerations

Although air cars underperform gasoline and electric vehicles in the metrics analyzed in this study, there are certain environmental concerns in which CAVs outperform gasoline vehicles. Since the CAV has zero tailpipe emissions, it does not contribute to local concentration of criteria and toxic air pollutants. To the extent that the electricity generation for powering CAVs occurs outside of population centers, air cars may have fewer overall health impacts than gasoline vehicles. However, a rigorous analysis of these effects is outside the scope of this paper.

Further, inasmuch as CAVs can act as a replacement for gasoline vehicles, they would reduce petroleum consumption in the transportation sector. However, extensive adoption of CAVs would be required for this reduction to have a measurable impact on total U.S. petroleum use. If CAVs were to compose 1.0% of the U.S. passenger car fleet, they would annually displace 10.3 million barrels of oil, or 0.21% of U.S. annual consumption (*33, 28*). However, these incremental benefits are not limited to CAVs and would also be realized by electric vehicles.

CONCLUSIONS

The environmental and economic challenges posed by passenger cars are significant and require a broad range of evolutionary and revolutionary solutions. Although CAVs offer the potential for addressing these impacts, the analysis contained here reveals that their application is limited by poor vehicle performance and high environmental impacts. The CAV performs worse than gasoline and electric vehicles in terms of driving range, carbon footprint, and fuel costs. In its current form, the CAV is not a solution for today's transportation problems. Most notably, the vehicle's limited driving range of 29 mi (47 km) challenges its feasibility as a passenger car. The results of this drive-cycle simulation are consistent with and expand upon the authors' prior work in CAV life-cycle modeling (*5*).

There may be opportunities for CAV technology in other applications, including as an alternative to neighborhood electric vehicles. However, these applications will need to address and overcome limitations in compressed air energy density and expansion efficiency losses.

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