Aurora

The Sustainability Opportunity of Autonomous Trucking

Executive Summary

The Opportunity

The transportation industry is in the midst of an emissions crisis. As international leaders direct resources and investments toward fighting climate change, 29% of the United States' greenhouse gas emissions are attributed to transportation. Of these, medium and heavy-duty trucks account for 23%[1]. This number is even greater in certain states, like California, where transportation represents approximately 50% of all greenhouse gas emissions[2].

The economic incentive to achieve these energy efficiency opportunities is also significant. The ATRI lists fuel as the second largest cost component of trucking[3].

This White Paper

This paper examines the opportunity that autonomous trucks present for improved energy efficiency and the corresponding benefits for greenhouse gas emissions and air quality. The paper starts with a primer on the factors which affect energy consumption and proceeds with an exploration of autonomous trucking specific opportunities and challenges. Finally, an integrated fuel consumption model was developed to estimate the relative energy savings potential for a typical over-the-road tractor-trailer in the US.

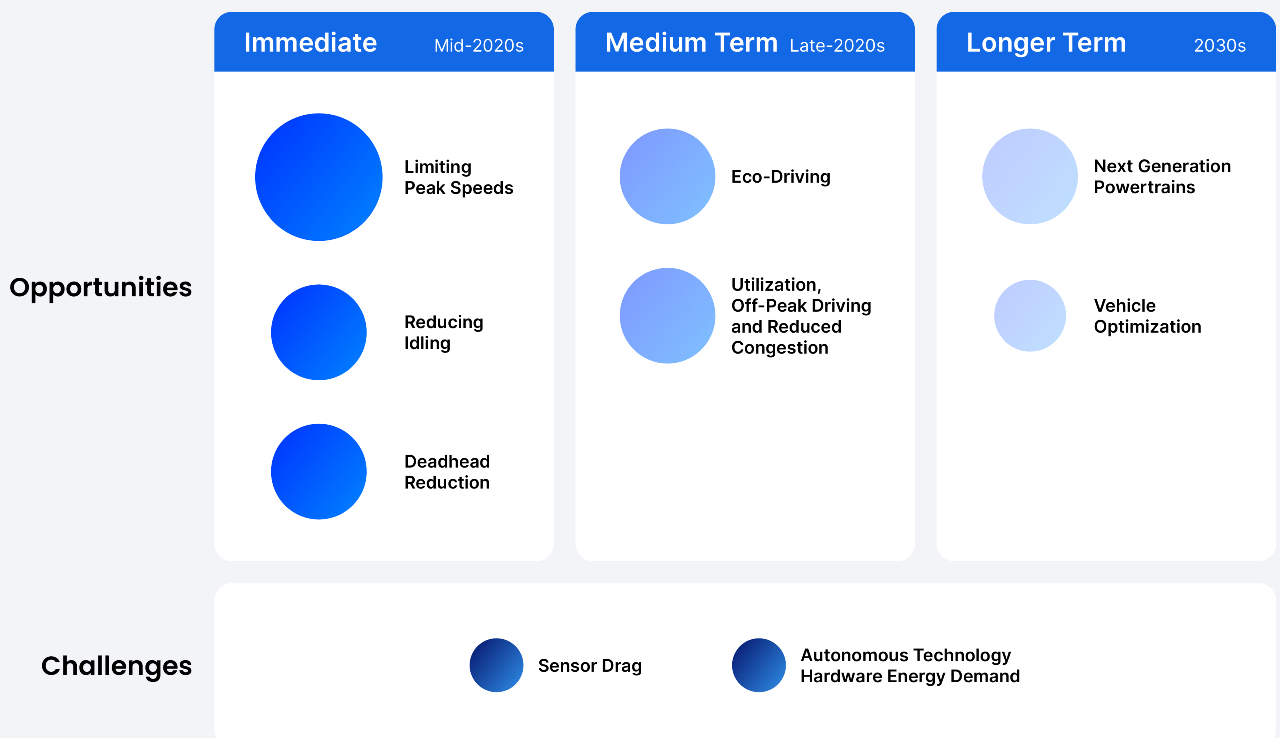

Figure 1: Autonomous trucking energy efficiency opportunities and challenges.

Our Findings

This paper finds that autonomous trucking has the potential for a 13%-32% net energy efficiency improvement per loaded mile, relative to traditional human-driven trucks. Benefits primarily derive from limiting peak speeds, reducing deadhead miles, increasing vehicle utilization and off-peak driving, reducing idling, and programmed eco-driving behavior. The potential for autonomous trucks to accelerate the adoption of next generation powertrains is not included in the above estimates and presents an additional opportunity for further energy efficiency.

While no single solution will solve the emissions crisis, autonomous trucks present a significant opportunity to improve the sustainability of freight-hauling fleets and reduce emissions in the transportation sector.

Aurora's Work to Deliver on the Sustainability Opportunity

Increased sustainability is core to the value proposition of the Aurora Driver. **Together with the strongest coalition of partners in the industry, Aurora is leading the development of autonomous trucking technology that has the potential to help carriers and shippers reduce fuel consumption, reduce greenhouse gas emissions, and fight climate change.**

In addition to developing the self-driving software that will realize much of the benefit, Aurora is working with supply partners to optimize sensor and computing hardware, with OEM partners to deploy leading edge sustainable vehicle platforms, and with carrier partners to maximize the operational opportunities enabled by the Aurora Driver from the commercial launch and beyond.

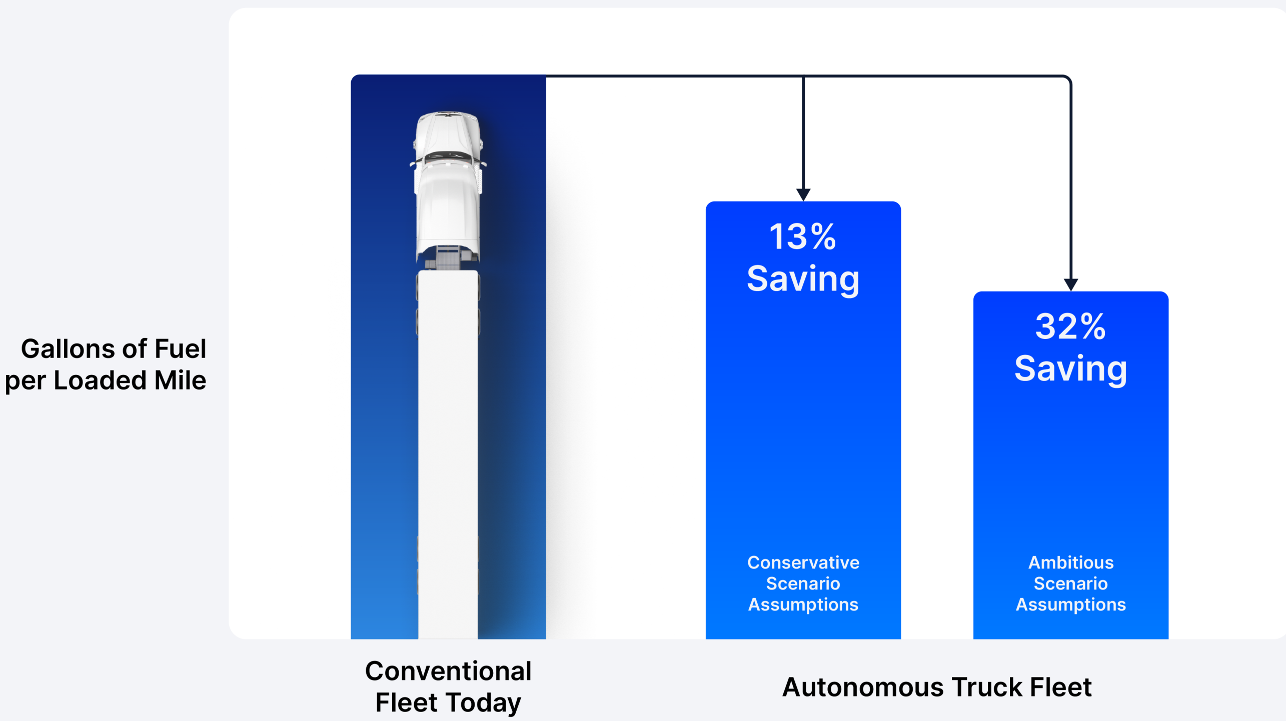

Figure 2: Estimated scale of potential energy efficiency savings.

Energy Consumption of Trucks: A Primer

In order to have a perspective on the energy efficiency opportunities for autonomous trucking, it is necessary to establish (a) what causes a truck to consume energy? and (b) which factors affect energy efficiency for a given load?

What causes a truck to consume energy?

Figure 3 below breaks down the components of energy consumption, including fundamental energy demand and energy losses. Diesel engines typically have an on-road efficiency of around 40%-45%[4]. This means that the fundamental energy demand only accounts for 40%-45% of energy consumed.

Energy demand can be subdivided into the energy needed to move the vehicle, and ancillary energy needed for things like electronics and other cabin comforts such as heating and cooling. Energy losses, which account for 55%-65% of energy consumed, arise when the chemical energy of diesel is converted to the mechanical and electrical energy needed to supply the energy demand.

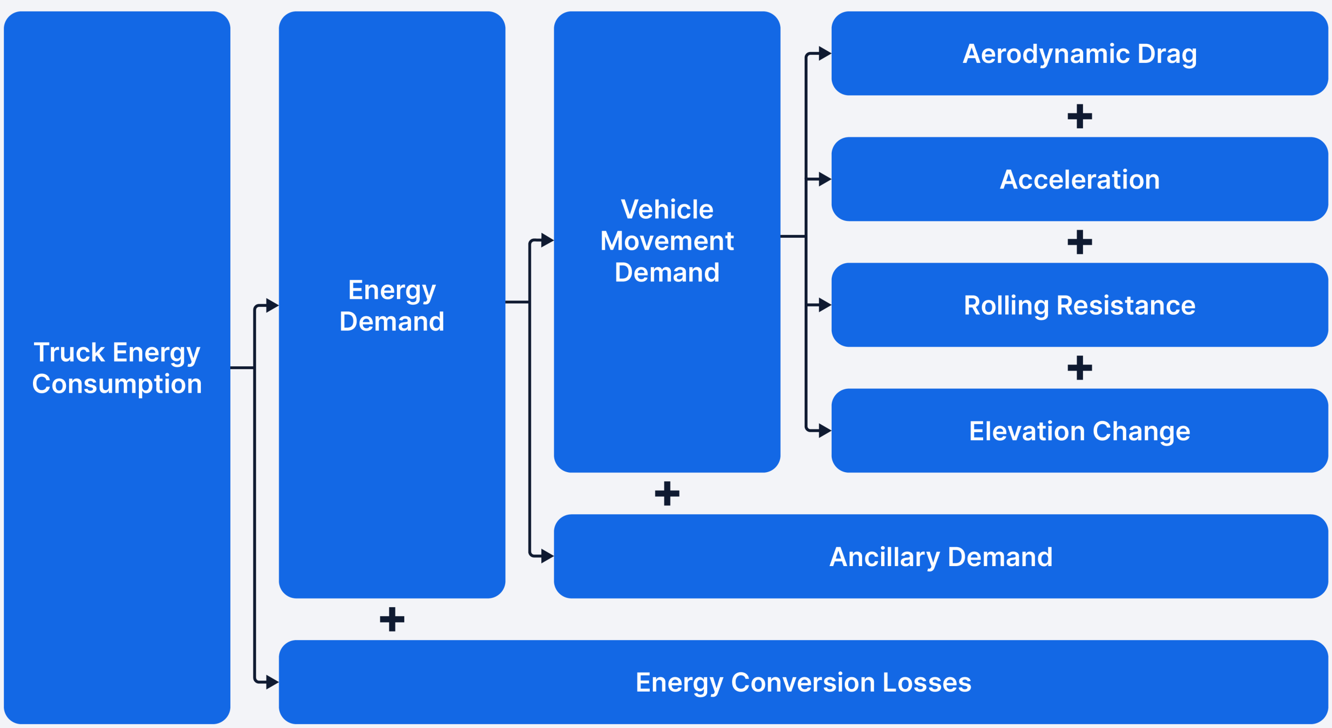

Figure 3: Components of energy consumption.

The majority of energy demand comes from moving the vehicle. The vehicle has to overcome **aerodynamic drag** as the vehicle pushes through the air, overcome **inertial force** any time the vehicle accelerates, overcome **rolling resistance** between the tires and road any time the vehicle is moving, and overcome gravity any time the vehicle is **increasing its elevation**. These different components can vary in relative impact depending on the context. For example:

- Aerodynamic drag is a function of the area and shape of the truck pushing through the wind as well as the square of the speed (i.e. a 20% increase in speed will result in a 44% increase in energy required for aerodynamic drag). This also means that a truck driving at high speeds will have a higher proportion of its energy demand associated with aerodynamic drag.

- Acceleration requires a driving force to overcome inertia to get the vehicle moving at higher speeds. The energy spent on this component varies depending on how much acceleration is required (both the rate of acceleration and the time spent accelerating), as well as the total mass of the vehicle being moved. More energy is required for acceleration in environments which result in frequent stops or braking events, such as heavy traffic or dense urban environments.

- Rolling resistance refers to energy required to overcome the friction between the road and the tires. This component is affected by the vehicle mass and the coefficient of friction between the road and the tires.

Ancillary energy demand (while moving) typically represents a small fraction of energy demand (<1%-2%)[5].

Which factors affect energy efficiency?

Figure 4 below provides an overview of different factors which can impact how efficient a vehicle is for a given load. Three categories of factors are identified:

- **Vehicle,** which relates to the characteristics of the tractor, trailer, and powertrain;

- **Environment,** which relates to the driving context in which the truck is being driven; and

- **Driver,** which relates to how the truck is driven and used.

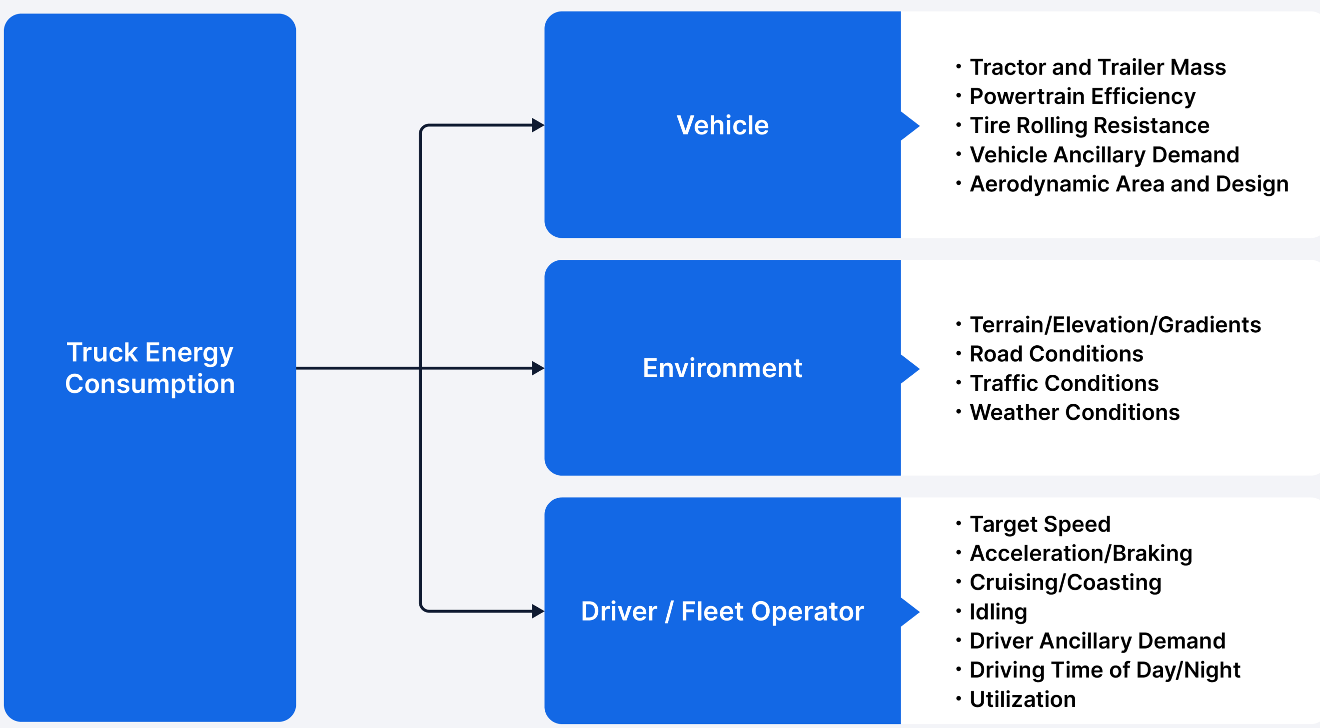

Figure 4: Factors affecting energy efficiency.

Measurement Challenges and the Levers-Based Approach

From the breakdown of energy consumption in the preceding section, we can infer the energy efficiency benefits of autonomous trucks will be different in different circumstances. Therefore any claim regarding the relative energy efficiency benefits of autonomous trucks compared with human-driven trucks needs to be accompanied by underpinning assumptions that account for the differences, answering questions such as:

- **For vehicle factors:** What were the trailer loads? Was it the same tractor and engine? Were the tires and tire pressure the same?
- **For environmental factors:** What route was used? Was it primarily highways, or was there a high proportion of surface streets? What was the elevation profile across the route? What traffic interactions were there? What about the weather? What was the strength and direction of the wind?
- **For driver factors:** Who was the human driver? Were they an aggressive or a conservative driver? What speeds did they typically target? When did they conduct the mission? Were there route diversions for breaks or other stops? When was the engine left idling? How was the autonomous truck set to drive differently?

As the above shows, there are significant challenges in making assumptions around the vehicle, environmental, and driver characteristics for an autonomous truck and in establishing a human baseline to compare it against.

To appropriately respond to this measurement challenge, this paper adopts an 'opportunities and challenges' based approach. In this approach, a number of levers are identified where a credible difference is expected to exist between autonomous trucks and today's human-driven trucks. The facts and arguments associated with each lever can be laid out and assessed for their merits, along with their individual nuances.

Where possible, we have attempted to provide some quantification of individual opportunities and challenges, where appropriate using a simplified energy consumption model as described in the paper by Bray and Cebon (2022)[6]. The model adopts an idealized drive cycle consisting of a consistent peak 'target speed', a sequence of 'stop-start' braking events at a 25 mile frequency, a flat terrain, and a 75,000lb combined tractor and trailer mass.

To provide some structure, the opportunities have been placed into three categories (immediate, medium, and longer term) based on perceived applicability of the levers, given their dependencies for implementation.

In order to ascertain the net potential impact, an integrated model was developed which incorporated lower bound and upper bound scenarios for each of the identified opportunities and challenges against a baseline scenario which involved a set of reasonable assumptions for today's typical over-the-road human driven truck. The details of the assumptions made for each scenario are detailed in the Appendix.

Category 1: Immediate Opportunities

These are levers with low levels of dependencies which could take effect immediately or in the very near term following commercial launch of autonomous trucks.

Limiting Highway Speeds

What is this opportunity and why are autonomous trucks well placed to take advantage?

At highway speeds, one of the most significant components of energy consumption is aerodynamic drag. Aerodynamic drag increases in proportion to the vehicle speed squared. Figure 5 below shows the indicative energy demand for highway driving for different speeds as well as the proportion of the energy which is associated with overcoming aerodynamic drag.

Limiting highway speeds is an operational decision that can be made by operators of both human-driven trucks and autonomous trucks, however there is greater incentive for autonomous trucks to adopt lower peak speeds due to two reasons:

1. **Limited Direct Driving Hours:** Human drivers are limited by their hours-of-service to a maximum of 11 hours per day[7]. Drivers today do not spend all 11 hours driving, with a recent MIT study finding that drivers spent around 7 of the 11 hours actually driving. Non-driving time includes time on breaks, finding parking for overnight rest stops, waiting to manage pick-up and delivery time window constraints, and also allocating trip buffer[8].

2. **Compensation for Miles Driven:** For long haul trucking in the US, human drivers are generally compensated for miles driven, which incentivizes drivers to drive faster in order to increase their effective hourly pay. While autonomous trucks may also be compensated by miles driven in some circumstances, their longer daily available operating hours mean there is less of an incentive to drive faster. This could enable them to meet customers' needs while driving slower – saving fuel and therefore reducing the cost of operating the vehicle.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

There are many variables which affect the estimated scale of this impact. Firstly, it is important to note that this opportunity is most relevant for high-speed highway driving. The impact of aerodynamic drag is much lower in low speed environments such as along surface streets or in traffic congestion. Fortunately, highway driving makes up the vast majority of long-haul routes where autonomous truck deployment is planned.

Second, to compare speeds there must be a baseline speed for a human driver and an assumed target speed for an autonomous truck. Aurora's experience in Texas has shown that, on I-45 where there are speed limits of up to 75 mph, and human-driven trucks without speed governors adopt speeds of 70-75 mph. Because it is neither restricted by hours-of-service limitations nor subject to the competing priorities of a human driver, the Aurora Driver is designed to cruise at a nominal speed of 65 mph, only increasing its speed for overtaking. This change from 70-75 mph to 65 mph, which matches a long-time energy efficiency recommendation by the American Trucking Associations[9], represents a reduction in aerodynamic drag of 14%-25% and an overall reduction in highway driving energy consumption of 9%-17%. See Bray & Cebon (2022) for a detailed study of this opportunity in a UK context[10].

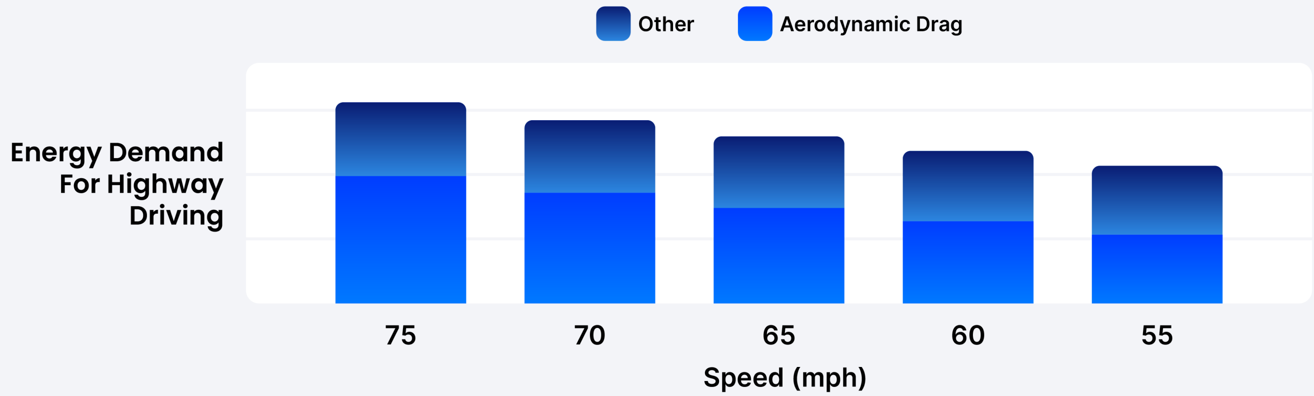

Figure 5: Highway driving energy demand vs. speed.

Reduce Idling

What is this opportunity and why are autonomous trucks well placed to take advantage?

According to the North American Council for Freight Efficiency, engine idling can represent up to 45% of operating time or more, with the idling time attributed to where the driver is sleeping, eating, working, or relaxing in his or her vehicle when they are not driving[11].

In 2015, the US Department of Energy published a study which showed that a long-haul truck spends approximately 1,800 hours per year idling, consuming about 1,500 gallons of diesel[12]. While there has been increased adoption of idle reduction equipment such as Auxiliary Power Units (APUs), these still consume ~0.35 gal/hour[13], or 630 gallons per year. Autonomous trucks are well placed to achieve idling savings by virtue of the fact that they do not require rest stops and can maximize operating time spent driving.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

Based on the above data, 1,500 gallons of diesel attributed would represent approximately 9% of fuel consumed and a truck with an APU would be ~4%[14]. A large proportion of this opportunity should occur automatically as autonomous trucks do not require rest breaks; however some idling may still continue at origins and destinations. To maximize the potential savings, operators of autonomous trucks will need to limit idling at end points as much as possible.

Deadhead Reduction

What is this opportunity and why are autonomous trucks well placed to take advantage?

"Deadhead miles" represent miles driven on the road by a truck with an empty trailer or no trailer at all. According to the American Trucking Associations, about 15% of miles run by trucks in America are considered deadhead miles[15]. Some of these empty miles can be attributed to load schedules, where a driver needs to travel from one drop-off location to a different pickup location, but many are attributed to human driver-specific reasons, such as when a driver takes an empty truck back home or off their commercial route to visit a rest stop.

There are four mechanisms by which autonomous trucks can reduce deadhead miles:

1. **Return to Origin:** A human driver may need to drive deadhead miles to get home after their shift, which could take place daily, weekly, or even monthly. Because autonomous trucks have flexible start points and end points depending on the needs of the business using them, they do not have such a requirement.

2. **Optimized Load Capacity:** Today, there are scenarios where a driver makes a dropoff and then the optimal action to reduce costs and increase energy efficiency would be to wait for hours until another nearby load is available. This would, however, frustrate the driver who may not be paid for that time. Carriers avoid this by dispatching Drivers to a different pickup location to get a load that is available sooner – incurring additional deadhead miles. Autonomous trucks are not limited in this fashion, and are capable of waiting for the next optimal action without the same consequences as human drivers.

3. **Terminal-to-Terminal Model:** A terminal-to-terminal model can create efficiency by decoupling long haul freight from local shuttle operations – creating flexibility that can help optimize logistics management and may reduce deadhead. The longer terminal-to-terminal trips can be highly utilized while the factors that drive deadhead are more constrained to the shorter local trips, thereby reducing overall miles.

4. **Network Density:** Because autonomous trucking will give carriers the opportunity to operate larger, more consolidated fleets, these carriers will have the opportunity to increase network density – allowing for better optimization and the ability to match evolving freight flows.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

While autonomous trucks are unlikely to eliminate the occurrence of all deadhead miles, they may – through a combination of the above mechanisms – enable a reduction of today's 15% deadhead mile occurrence. Some of this reduction should occur immediately, such as the removed need for drivers to return to the point of origin, the alleviated need to keep human drivers busy, and the decoupling of long hauls from local shuttle through the terminal-to-terminal model.

The opportunity to reduce deadhead miles through improved network density will be enabled with increased adoption of autonomous trucks, industry consolidation, and fleet operator network optimization.

Category 2: Medium Term Opportunities

This category of opportunities may not be immediately apparent upon commercial launch, however the nature of the technical and operational barriers are such that it could be reasonably expected to see such opportunities materialize within the near term years that follow.

Eco-Driving

What is this opportunity and why are autonomous trucks well placed to take advantage?

One of the most significant components of energy consumption is the energy required to accelerate a truck up to speed. When a vehicle brakes, it is effectively losing energy through the dissipation of heat into the brake pads. Driving behaviors such as the rate and timing of acceleration, braking, and coasting have an impact on energy consumption, creating opportunities to save energy. For example, accelerating more in advance of an incline, coasting near the top, and coasting in advance of upcoming traffic.

In addition, engines can operate more efficiently at certain torque and RPM operating points, unique to each engine and transmission configuration. By maximizing time at these efficient operating points, a driver can lower their overall energy consumption.

Autonomous trucks can uniquely minimize energy consumption due to their acute awareness of upcoming road grade, features, and traffic. Because many autonomous trucks will travel the same routes, enhancing one vehicle's ability to optimize acceleration, braking, and coasting for specific freight lanes will benefit the entire fleet – increasing energy efficiency and reducing emissions broadly.

There are additionally existing energy saving technologies that could be more precisely controlled by an autonomous driver due to these predictive planning benefits. One example is SmartCoast, where the driveline is disconnected when propulsive torque is not expected to be required[16]. By precisely anticipating this need in advance, autonomous trucks can enable efficiency improvements beyond what those features realize with a human driver.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

Various studies of existing automated eco-driving technologies have indicated a range of potential savings opportunities. While many eco-driving studies focus on passenger mobility, an increasing set of studies are examining the potential in trucking, for example:

- A 2015 study in the Netherlands by Thijssen, Hofman, and Ham concluded that fuel savings of 9.5% were possible by increasing the coasting distance of trucks via greater anticipation and noted that this ability is often limited by visibility but could be addressed with driver support systems with enhanced understanding of the route[17].

- A 2017 study in Columbia by Diaz-Ramirez et al examined the opportunities for eco-driving programs for long distance freight transport of heavy and medium duty truck fleets in Latin America and concluded savings opportunities of 5.5-6.8%. The authors found that acceleration, braking, and speed excesses were the most significant factors addressed with eco-driving training[18].

- A 2021 study in the UK by Subel et al examined the potential for greater adoption of coasting for trucks and concluded that by advising an experienced driver on predetermined coasting opportunities, coasting distance increased by up to 47% and led to a 4.4% improvement in energy efficiency[19].

In order to capture this opportunity, autonomous technology companies will need to partner with OEMs to best leverage engine torque and RPM optimization information for autonomous trucking platforms.

Utilization, Off-Peak Driving, and Congestion Reduction

What is this opportunity and why are autonomous trucks well placed to take advantage?

Human drivers are limited by hours-of-service regulations and the use of human-driven trucks often skews towards daylight hours as it is better for human vision and drivers' sleeping habits. This coincides with busier and more congested times of the day on the road, which translates to more energy-consuming braking and accelerating events and therefore more energy consumption per mile driven.

By comparison, autonomous trucks can be used close to 24 hours per day, creating several opportunities for energy efficiency.

- First, autonomous trucks can shift a greater proportion of freight to low congestion times, translating to reduced energy consumption as trucks have reduced exposure to driving environments with additional traffic-induced braking events.
- Second, shifting a portion of truck traffic to off peak times can help reduce congestion for other roadway users, thereby inducing an indirect benefit to the broader transport sector.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

Quantifying the scale of this opportunity is particularly challenging given the potential variation between different locations, customer requirements, times of day, and assumptions around how operations could change.

An analysis of (Handbook Emission Factors for Road Transport) highway HBEFA drive cycles[20] using a simplified model for fuel consumption indicated that, when compared with 'freeflow' traffic conditions, 'saturated' traffic conditions (average speed ~60% of 'freeflow') resulted in ~40% higher fuel consumption than for 'freeflow' traffic conditions. For more extreme 'stop and go' traffic conditions (average speed 10%-20% of 'freeflow') the energy consumption was estimated to be around 140% higher[21].

Capturing this opportunity will primarily depend on autonomous fleet operators establishing operations which take advantage of the significantly higher uptime potential of autonomous trucks and in particular maximize deployment at low congestion times.

Category 3: Longer Term Opportunities

This category reflects opportunities where there are more complex dependencies in order to unlock the opportunities and involve either greater uncertainty or time in order to realize the benefit potential.

Next-Generation Power Trains

What is this opportunity and why are autonomous trucks well placed to take advantage?

In addition to having zero tailpipe emissions, next generation powertrain trucks (such as battery electric or hydrogen fuel cell electric) offer substantial potential for decarbonization. Autonomous trucks and next-generation power trains can be thought of independently, i.e. it is possible to have autonomous diesel or autonomous electric, or human-driven diesel or human-driven electric. However, there are four reasons why autonomous trucks can act as a catalyst for faster adoption of electric trucks and unlock the substantial energy efficiency potential of next generation powertrain trucks. These are as follows:

- **Better Range Management:** Autonomous trucks are better able to manage the range and charging/fueling limitations of electric trucks because they do not have hours-of-service limitations and hourly labor cost. Therefore autonomous vehicle technology is well-positioned to be a leading use-case for next generation powertrains in long-haul trucking.

- **Fixed Routes Bring Infrastructure Benefits:** The fixed route/restricted ODD (Operational Design Domain) rollout of autonomous trucks enables focused deployment of high utilization on-route charging/refueling infrastructure, helping solve the chicken/egg problem of infrastructure rollout for both charging and hydrogen refueling.

- **Higher Utilization Benefits Operating Costs:** The economic benefit of lower operating costs of next generation powertrain electric trucks are best realized by the anticipated utilization mileage of autonomous trucks (i.e. faster payback on up-front investment.)

- **Terminal-to-Terminal Model:** By decoupling long-haul operations and local shuttle operations, the terminal-to-terminal model makes it easier to integrate next generation powertrain trucks into local hauls, as those vehicles will not need to be used for long-haul routes.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

The scale of the opportunity can vary depending on the powertrain and the energy source used. In 2022, an independent energy efficiency test of a fully loaded heavy duty Volvo FH Electric used 50% less energy than its diesel counterpart[22]. The greenhouse gas emissions also vary depending on the carbon intensity of the energy source, for example a location where the grid is powered with high level of renewables or low carbon fuels[23]. Similarly, hydrogen can be derived from high carbon or low carbon sources.

To capture the opportunity there are a few dependencies:

- Vehicle manufacturers will need to continue to seek improvements in vehicle range.

- Autonomous technology providers will need to collaborate with vehicle manufacturers on the development of an autonomous enabled electric truck platform.

- Infrastructure suppliers will need to gain familiarity and sufficient confidence to invest in charging infrastructure.

- Autonomous fleet operators will need to gain sufficient confidence to invest in a transition to autonomous and electric fleets.

Vehicle Optimization

What is this opportunity and why are autonomous trucks well placed to take advantage?

This opportunity refers to how trucks may be modified due to the removal of the human driver and the unique nature of autonomous trucking operations.

The design of trucks are currently centered around the human driver to provide a safe, functional, and comfortable driving environment with internal furnishings (driver's seat and sleeping area for sleeper cabs), comfort features (entertainment, air-conditioning), safety features (airbags, seatbelts), and the broader space. Removal of the driver can lead to removing these features and the associated materials, weight, energy use, and cost.

Different driving environments have different dominant factors which affect energy consumption. For example, aerodynamic drag is particularly relevant for higher speed interstates, and frequent braking and acceleration are the more significant energy consumption factors for local or urban, lower speed traffic environments. Currently trucks are designed to account for both environments and often omit certain vehicle features that are available to address environment specific energy consumption factors. For example, the shape of the cab or the presence of trailer skirts can reduce aerodynamic drag[24].

As autonomous trucks may be more exclusively deployed in environments such as higher speed interstates, the case for incorporating such environment specific features increases, likely leading to overall better energy efficiency.

How does the scale of the opportunity vary and what is needed to capture the opportunity?

This opportunity has been classified as longer term as that is the likely time frame for the more significant aspects of this opportunity to come into effect. The most significant of which would involve removing or redesigning the entire driver's cab. We estimate that for every ton of mass reduced, energy consumption would improve by ~1.5%[25].

In order to pursue this opportunity, autonomous technology developers and truck manufacturers will need to collaborate on the development of future generation vehicle platforms.

Challenges to Offset

Two factors are identified which could partially offset the scale of the above opportunities are new hardware energy draw and sensor drag[26]. These are described below.

New Hardware Energy Draw

Autonomous technology involves a suite of technologies which require electrical power to function. Compared to the energy demand required to move a truck, these are small and are decreasing with each generation. We estimate that power draw requirements represent ~1%-1.5% or less of baseline energy demand for a typical truck targeting 65 mph[27]. Power draw requirements are also decreasing, with future generations expected to draw less than 1% of energy demand as architecture becomes more efficient.

Sensor Drag

The presence of sensor pods on the tractor unit can have an impact on the air flow over the truck, changing the coefficient of drag on the truck.

Current designs have an incremental impact of the order of 2%-5% or less for typical highway driving. Net aerodynamic drag impacts could be offset by simple changes such as folding in the wing mirrors, which alone could improve energy consumption by ~1%. Further, cab designs that shift away from being human centric could see the impact of sensor drag be entirely negated, potentially creating an opportunity for increased aerodynamics over today's trucks.

It is also important to note that autonomous technology sensor kits are being integrated into platforms such as the Volvo VNL and the Peterbilt 579 which are industry leaders for low aerodynamic drag with coefficients of drag of the order of 10%-20% better than day cab tractor models and even prior generations of sleeper cabs.

Sizing the Overall Opportunity

The identified opportunities and challenges were combined into an integrated model which analyzed fuel consumption for three scenarios:

i) A typical over-the-road human driven truck as today's baseline.

ii) An equivalent future autonomous truck scenario with more conservative assumptions.

iii) An equivalent future autonomous truck scenario with more ambitious assumptions.

The outcome of the model indicated that autonomous trucks represent fuel savings opportunities of 13%-32% for load-carrying miles[28]. The opportunity for next generation powertrains was excluded from the analysis as that transition can occur independent of the transition to autonomous trucks and the energy consumption implications can vary significantly depending on whether the powertrain is battery electric or fuel cell electric, and the energy source that the power or hydrogen was derived from.

The details of the assumptions made for each scenario and common across all three scenarios is detailed in the Appendix. The 13% fuel savings represents the lower bound 'conservative' scenario and the 32% fuel savings represents the upper bound 'ambitious' scenario.

The most significant factors contributing to this opportunity was limiting highway speeds and deadhead mile reduction. The second largest category of opportunity included increased utilization, off-peak driving, reducing idling time, and eco-driving. Vehicle optimization by further decontenting was relatively small, as were the offsetting factors of hardware energy draw and sensor drag.

How Aurora is Working to Realize the Sustainability Opportunity

As noted throughout this whitepaper, delivering on this significant energy efficiency and emissions reduction opportunity requires coordination between many stakeholders including autonomous vehicle developers, OEMs, suppliers, and carriers.

Overall, at Aurora we believe we have a responsibility to deliver a product that is not only safe and efficient, but meaningfully beneficial to the world around us. A thoughtful approach to sustainability is a significant part of how we deliver on that commitment.

Aurora is working with ecosystem partners to achieve the positive outcomes that result from reducing emissions and pollution for all users of our product and in the communities in which we operate. This includes:

OEM partners: Aurora is working with OEM partners to deploy vehicle platforms that are on the leading edge of sustainability.

- Aurora is working closely with Volvo Autonomous Solutions to integrate and deploy our autonomous trucking technology on the all-new Volvo VNL, creating up to a 10% improvement in fuel efficiency versus prior models with its aerodynamic profile and powertrain efficiency setting new industry standards.

- As cited by Volvo, autonomous trucking technology can be scaled to battery electric and hydrogen fuel cell trucks[29].

Developing the software: The driving behaviors of the Aurora Driver are constantly being optimized.

- The Aurora Driver has the ability to limit peak speeds. As adoption grows, Aurora will work with carriers to program appropriate target speeds that optimize energy consumption amongst other important outcomes.

- Aurora will continue to invest in software development that enables the Aurora Driver to demonstrate optimized eco-driving behaviors.

Developing the hardware: Aurora is working with suppliers to optimize the aerodynamic profiles of sensors and further reduce the power draw.

- Aurora has worked with OEM partners to integrate sensors into autonomous trucking vehicle platforms, and recently finalized this design with Continental[30]. This integrated sensor design is already more aerodynamic than earlier sensor stack hardware designs, and there are opportunities for additional improvements in the future.

Realizing sustainable operations: Aurora will continue to work with partners to maximize the operational opportunities enabled by the Aurora Driver.

- From commercial launch to the growth over the years that follow, Aurora will work with carriers to help deliver reduced idling time and dead miles whilst increasing vehicle utilization and off-peak, low congestion deployment.

We will continue to share our work in this area as we make progress. To learn more, visit **www.aurora.tech**.

About the Author

Dr Garrett Bray holds a PhD in Engineering and a Masters in Engineering for Sustainable Development from the University of Cambridge, UK, and an MBA, Bachelor of Engineering, and Bachelor of Commerce from the University of Western Australia. His PhD thesis was entitled 'Autonomous goods vehicles: implications for fleet operating models'.

Garrett has over 16 years professional experience and is a Product Director at Aurora where he leads Product for Command Center, Field Support, and Sustainability. Prior to joining Aurora, Garrett was the Head of Strategic Problem Solving for Transport for London, where he led several initiatives related to the transition to zero emission transportation. Earlier in his career, Garrett served a range of clients as a management consultant with McKinsey & Company and as an engineer with BG&E Consulting Engineers. Garrett has previously lectured for the University of New South Wales and the University of Cambridge.

APPENDIX - Integrated Model

The table below lists the assumptions used in the development of the integrated fuel consumption model referred to in this paper:

Aspect	Today's human driven trucks	Autonomous trucking opportunity	
		Conservative scenario assumptions	Ambitious scenario assumptions
Limiting peak speeds			
Target highway speed	70 mph Some trucks travel up to the 75 mph limit on on Texas freeways, others may have speed governors targeting 65mph	65 mph Aurora trucks currently designed for targeting 65mph	60 mph It is feasible that target speed could be reduced further
Reducing idling			
Annual hours of idling per truck	1,800 hours	1,440 hours (assumes a 20% reduction)	720 hours (assumes a 60% reduction)
Deadhead reduction			
Deadhead miles	15% of miles	12% of miles (assumes a 20% reduction)	6% of miles (assumes a 60% reduction)
Eco-driving			
Incremental rate of MPG fuel consumption saving for all miles	0% (baseline)	2% on-road MPG improvement (i.e. excludes idling time)	6% on-road MPG improvement
Utilization, off-peak driving and reduced congestion			
Annual miles per year	100,000 miles / year	200,000 miles / year	300,000 miles / year
% miles in 'freeflow traffic'	85%	88% (a 20% reduction in proportion of time in 'non-freeflow' traffic)	93% (a 50% reduction in proportion of time in 'non-freeflow' traffic)
Vehicle optimization			
Truck without cargo load	35,000lb	34,650lb (assumes a 1% reduction)	33,250lb (assumes a 5% reduction)
Sensor drag			
CdA (Drag coefficient x frontal area)	4.30m^2	4.72m^2 (assumes a 10% increase in CdA)	4.49m^2 (assumes a 4% increase in CdA)
Autonomous tech hardware power demand			
Net incremental hardware energy demand	0 kW (baseline)	1.5kW	0.5kW
Next generation powertrains			
Not modeled	N/A	N/A	N/A

Other general assumptions (all scenarios):

- 95% of miles are on highways, 5% on surface streets.
- Assumed 75,000lbs mass for loaded trips (35,000lb for dead-head miles).
- Assumed drive-cycle consisting of a consistent peak 'target speed', a sequence of 'stop-start' braking events at a 25 mile frequency.
- Assumed energy required for gradients as 10% of energy required for inertia and rolling resistance components on flat terrain.
- Assumed energy required per mile of 'non-freeflow' traffic is 50% greater than per mile of 'freeflow' traffic.
- Assumed 42% baseline engine efficiency.
- Assumed coefficient of rolling resistance of 0.005.
- Assumed rate of fuel consumption while idling 0.58 gal/hour.

Note about forward-looking statements

Various statements in this whitepaper, including statements regarding our goals, predictions, objectives, and expected results, are "forward-looking statements" within the meaning of the Private Securities Litigation Reform Act of 1995, Section 27A of the Securities Act of 1933, and Section 21E of the Securities Exchange Act of 1934 and are generally identified by the words "believe," "expect," "intend," "opportunity," "will," "should," "could," "would," "likely," and similar expressions. Forward-looking statements are based on current assumptions that are subject to risks and uncertainties that may cause actual results to differ materially from the forward-looking statements, including the risks and uncertainties more fully described in our filings with the Securities and Exchange Commission, including our Form 10-Ks, Form 10-Qs and Form 8-Ks filed with the Securities and Exchange Commission. We undertake no obligation to update or revise publicly any forward-looking statements, except as required by applicable law.

Industry and market data

Unless otherwise indicated, estimates and information contained in this whitepaper concerning our industry and the market in which we operate, including our general expectations, market position, market opportunity, and market size, are based on industry publications and reports generated by third-party providers, other publicly available studies, and our internal sources and estimates. This information involves a number of assumptions and limitations, and you are cautioned not to give undue weight to such estimates. Although we believe the information from the industry publications and other third-party sources included in this report is reliable, we have not independently verified the accuracy or completeness of the data contained in such sources. The content of, or accessibility through, the below sources and websites, except to the extent specifically set forth in this report, does not constitute a portion of this report and is not incorporated herein.

Footnotes

[1] EPAv 2020 Fast Facts on Transportation Greenhouse Gas Emissions **Web Article**
[2] California Energy Commission 2019 Transforming Transportation Available from: **Link**
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[22] Volvo Trucks (2022) Volvo's heavy-duty electric truck is put to the test: excels in both range and energy efficiency **Link**
[23] Electricity Maps. Accessed on 03/20/2024 from: **https://app.electricitymaps.com/zone/US-CAL-CISO**
[24] Viscelli 'Stalled: Make Big Trucks More Fuel Efficient' **Link**
[25] Using the simplified fuel consumption model and assuming 0% gradient per Bray, G., & Cebon, D. (2022). Operational speed strategy opportunities for autonomous trucking on highways. Transportation research part A: policy and practice, 158, 75-94.
[26] We assess the potential impact of additional mass due to the sensors, compute and incremental mass associated with a redundant base platform to be negligible once accounting for the removal of the mass of the human driver and their personal effects
[27] Net of human power draw requirements such as cabin climate control with future generations expected to draw less than 1% of energy demand as architecture becomes more efficient.
[28] Loaded miles are miles exclusive of deadhead miles. This was considered the most appropriate metric and it enables recognition of the value of reducing the proportion of deadhead miles.
[29] **Guided by Safety: The Path to Driverless Trucks with Volvo** | Aurora Blog
[30] **Continental and Aurora Finalize Design of World's First Scalable Autonomous Trucking System** | Aurora Press Release