Considerations for the Use of Autonomous Vehicles and Drones in Sustainable Food Distribution

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Innovations in the Food System: Shaping the Future of Food

Food Forum Workshop, National Academies of Sciences

Key Takeaway

- Self-driving vehicles and drones present opportunities to **improve,** or **worsen** sustainability outcomes
  - Depends on how they are used, and the conditions surrounding their adoption

- This talk will present considerations for attaining sustainability benefits while limiting potential negative effects

Our Food System is Unsustainable

- Food system contributes 19-29% of global anthropogenic greenhouse gas (GHG) emissions[1]
- 11.8% of U.S. households were food insecure at some time 2017[2]
- **Sustainability requires assessing environmental, economic, and social outcomes**

[1]Vermeulen et al., *Annu. Rev. Environ. Resour.* 2012

[2]USDA ERS, *Household Food Security in the United States in 2017*

Emerging Technologies will Shape Our Food System

Heard et al., "Sustainability implications of connected and autonomous vehicles for the food supply chain." *Resources, Conservation and Recycling,* 2018

- The food distribution industry is a likely early-adopter of self-driving vehicles and drones
  - Delivering often-perishable products on constrained timetables
  - Potential for food loss reduction (lower distribution and storage times)
  - Potential to increase food delivery capacity (e.g. 24/7 service from a vehicle)
  - Potential for lower marginal cost of distribution (fuel savings, driver wages)
- **Essential to take a systems sustainability approach**
  - Requires thinking about more that the technology's *direct effects*
  - Also how technologies may *indirectly* affect outcomes
  - React to *external factors*

Some Brief Definitions

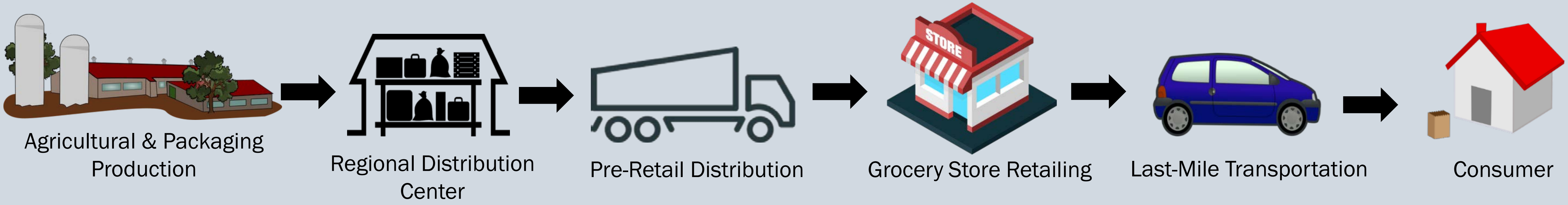
- Connected and autonomous vehicles (CAVs)
  - <u>Connected:</u> Vehicle-to-vehicle, vehicle-to-infrastructure, other cooperative communications
  - <u>Autonomous:</u> Self-driving; discussing more-independent levels of self-driving capabilities
  - Connection & autonomous capabilities expected to be realized together

Phys.org; Credit: Shutterstock / metamorworks

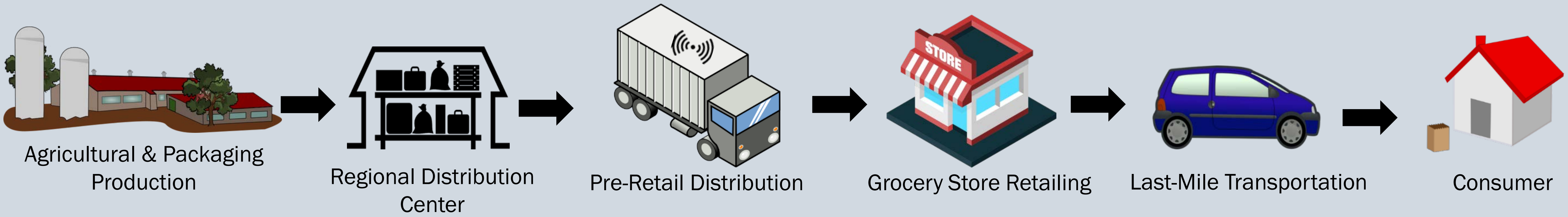
- Delivery Drones
  - Battery-powered unmanned aerial vehicles (UAVs)
  - Two main varieties: 1) Autonomous, 2) Remotely Piloted
  - Discussion in this presentation applies to both

IEEE Spectrum; Credit: iStockphoto

Food Supply Chain

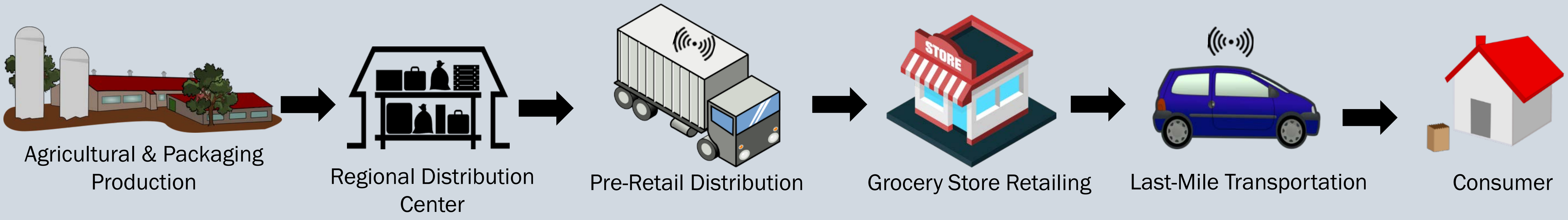


Food Supply Chain



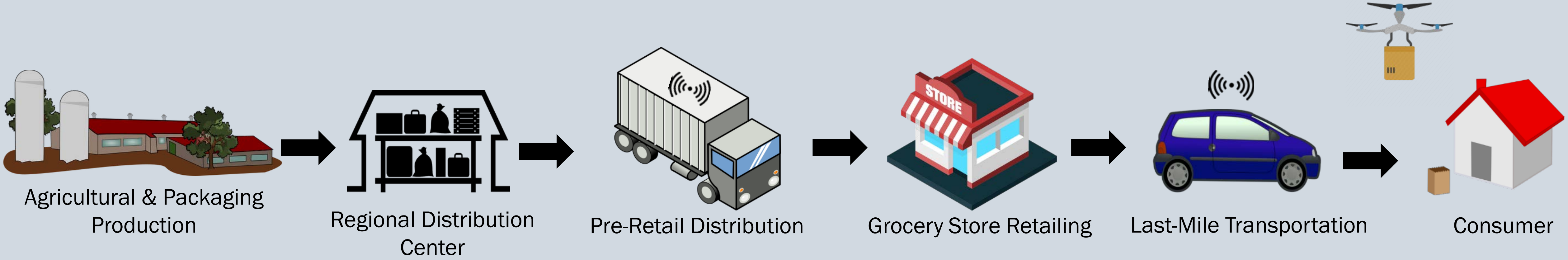
- Early CAV adoption expected for long-haul trucking

Food Supply Chain



- Early CAV adoption expected for long-haul trucking
  - Self-driving vehicles expect for last-mile as well

Food Supply Chain



- Early CAV adoption expected for long-haul trucking
  - Self-driving vehicles expect for last-mile as well

- Drones likely to be deployed for last-mile delivery to consumer

Pre-Retail Food Distribution

CONNECTED AND AUTONOMOUS VEHICLES FOR FOOD DISTRIBUTION

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CAVs provide the Technical Capacity for Efficiency & Environmental Improvements

- Particularly for trucking: 71% of U.S. food supply chain transportation emissions[1]
- Optimized routing, speed harmonization, vehicle light-weighting, among others[2]
- Platooning could reduce heavy truck energy intensity by 10-25%[3]
- Cooperative communications could reduce CO_2 emissions by 12%[4]

However,

- Higher speeds may increase fuel consumption & CAV technology may increase energy use[2]
- Unlikely, but important to ensure doesn't dramatically reduce emissions savings

[1]Weber and Matthews, *Environmental Science & Technology*, 2008

[2]Taiebat et al., *Environmental Science & Technology,* 2018

[3]Wadud et al., *Transp. Res. Part A*, 2016

[4]Barth et al., *Road Vehicle Automation*, 2014

CAVs in the Pre-Retail Food Supply Chain

- For perishable foods, optimized logistics could reduce time subject to refrigerated storage, food losses

However,

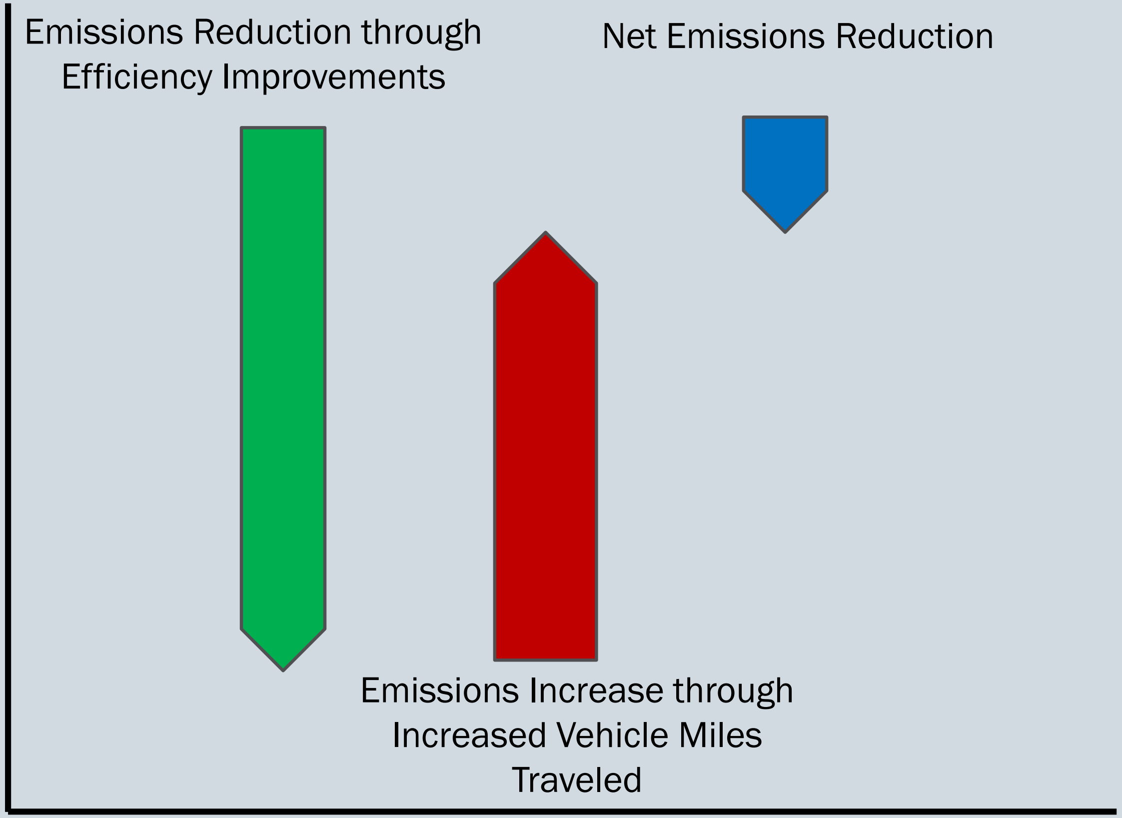
- Widespread deployment may require increased numbers of data centers
- Could displace rail or inland water (lower per-mile carbon & energy intensity than trucking)
- Electrification often assumed, not guaranteed
  - Electrified CAVs increase importance of decarbonizing electricity grid

The Potential for an Emissions Rebound Effect?

- **Rebound effect:** reduction in emissions savings resulting from behavior change

- Rebound effect from fuel efficiency for U.S. tractor trailers estimated at 29.7%[1]

- Rebound effects in UK road freight transportation modeled ranging 21-137%[2]



[1] Leard et al., *Resources for the Future* Working Paper, 2015

[2] Sorrell & Stapleton, *Transp. Res. Part D*, 2018

CAV Distribution: Economic & Social Implications

Heard et al., "Sustainability implications of connected and autonomous vehicles for the food supply chain." *Resources, Conservation and Recycling,* 2018

- Potential to lower road fatalities: 4,761 deaths from large-truck related accidents in 2017, 12% increase over 2007-2017[1]
- Increased profits for distribution firms
  - Efficiency savings, potential to increase volume of sales
  - Marginal cost savings: driver wages accounting for 36% of truck operating costs[2]
- Labor market & unemployment effects
  - Grocery & related products heavy and tractor-trailer truck driving employs over 63,000 Americans[3]
  - Unemployment would have spillover effects on truck rest stops, related food & lodging businesses
- Overall employment outcome subject to relative **displacement** and **reinstatement** effects[4]
  - Need to consider effective worker retraining programs, support for displaced workers

[1]National Center for Statistics and Analysis, 2019

[2]Grenzeback et al., NREL, 2013

[3]Bureau of Labor Statistics, 2016

[4]Acemoglu & Restrepo, NBER Working Paper, 2019

Last-Mile Food Distribution

CAVs AND DRONES FOR FOOD DISTRIBUTION

Drone Delivery: Direct Environmental Implications

Stolaroff et al., “Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery.” *Nature Communications*, 2018

- Tested a small quadcopter carrying 0.5 kg & a large octocopter carrying an 8 kg package
  - Model warehouse placement & operation, different regions of U.S.

Small drone tested, https://3dr.com/support/articles/iris/

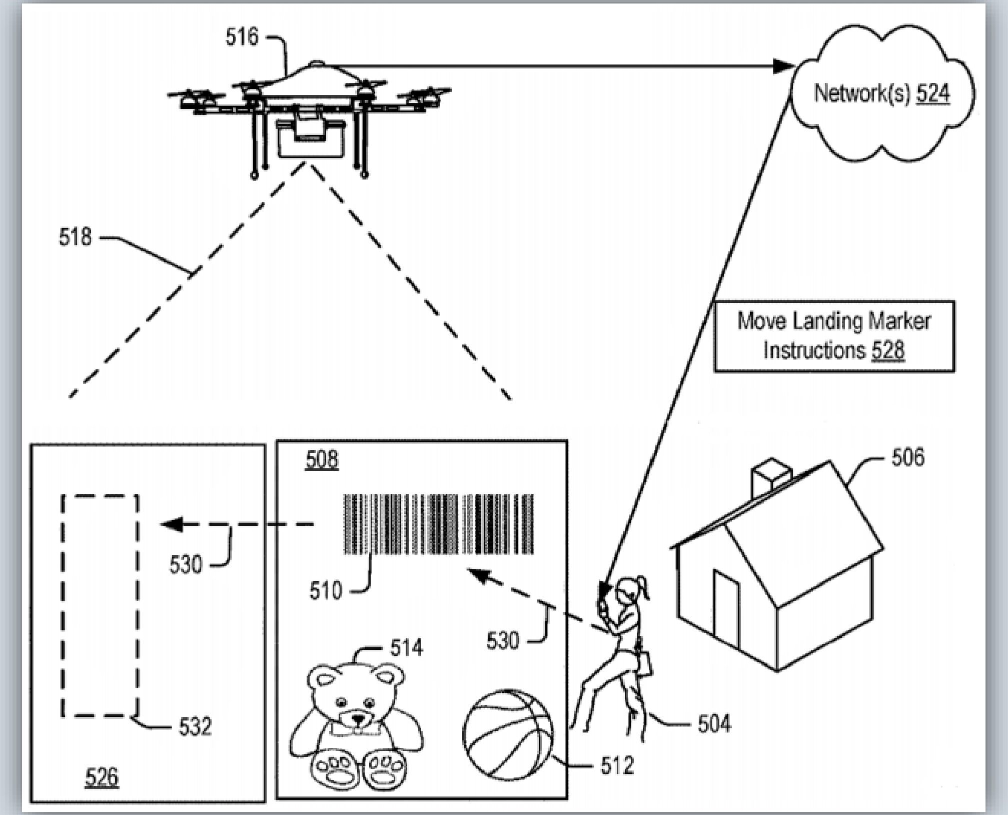
Results:

- Smaller drone has lower GHG emissions than truck delivery (23%-54% reduction)
- Mixed results for large drone
  - Charged with low-carbon electricity: 9% lower emissions than delivery truck; higher than delivery truck on U.S. average electricity mix (24%)
- **Both have lower emissions in all scenarios than using a personal vehicle to pick-up a single package**
- Food delivery likely on a large drone (12-inch pizza: 0.72 kg, excluding box)

Large drone tested, http://www.turboace.com/infinity-9pro_octocopter.aspx

Drone Delivery Economic & Social Implications

- Similar profit, employment, and accident considerations as CAVs, but for last-mile
- Zoning issues & urban planning considerations with drone flight and supporting warehouses
  - FAA currently approving drone delivery pilot projects
  - Stolaroff et al. found practical delivery range to be 4 km
- Social acceptability issues
  - Noise
  - Safety concerns/military associations



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CAVs for Last-Mile Distribution

- Self-driving vehicle efficiency gains could also be attained for last-mile delivery
- Similar accident and employment considerations
- Potential for rebound effect from impulse-purchasing
- Can displace consumer round-trip travel to store in personal vehicle
  - Enabling e-commerce and home-delivery
  - Conventional home-delivery: 18-87% emissions reduction possible, depending on delivery model[1]
  - E-commerce with home-delivery could displaces burdens from grocery retailing (overstocking food losses, retail refrigeration emissions)[2]

[1]Siikavirta et al., *Journal of Industrial Ecology*, 2003

[2]Heard et al., *Resources, Conservation, and Recycling*, 2019

Direct-to-Consumer Delivery and Diet

- Potential to mitigate effects of local limited healthy food availability (e.g. “food deserts”)
  - Especially if paired with SNAP assistance for grocery home-delivery (current pilot program in New York)

- Transportation mode could affect *types* of food delivered (nutritional & environmental implications)
  - Increased convenience for “fast foods”
  - Transportation is 11% of food’s life cycle emissions, production comprises 83%[1]

[1] Weber & Matthews, *Environmental Science & Technology*, 2008

Key Considerations

- **Self-driving vehicles and drones *could* improve sustainability outcomes under the right conditions** (not guaranteed)
  - Relies on decarbonizing electricity grid
  - Limiting rebound effects
- Large potential emissions reductions from e-commerce & home-delivery
  - Could have positive or negative dietary effects
- Must prepare to address economic & social implications
  - Employment considerations, zoning for drones and warehouses
- Considering these technologies from a systems sustainability perspective

Connected and Autonomous Vehicles

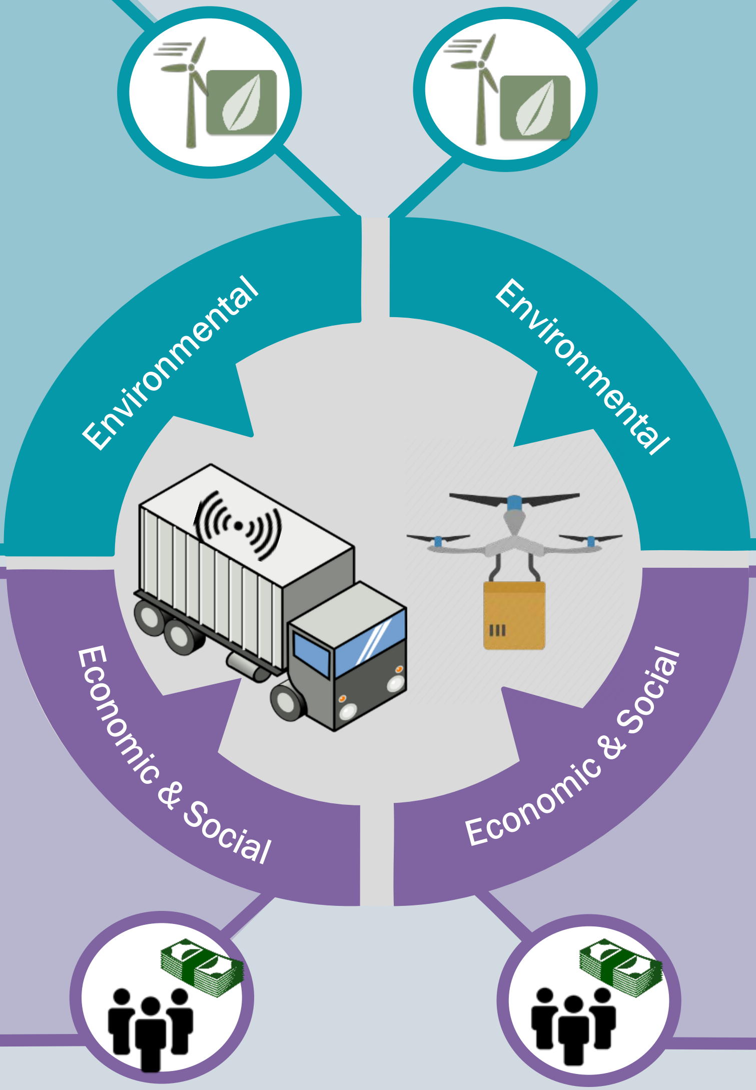
+ Fuel savings from efficiency improvements (e.g. optimized routing, speed harmonization, vehicle light-weighting, platooning, cooperative communications)
+ Lower food losses, storage time
+ Potential for e-commerce and home delivery

- Emissions increases from higher speeds
- Energy draw from onboard technology
- Need for data centers
- Potential for rebound effect

Drone Delivery

+ Lower-emissions than personal vehicle
+ Potential for e-commerce and home delivery

- Emissions savings compared to trucks less-likely for larger drones (dependent on electricity carbon-intensity)
- Warehouse requirements
- Potential for rebound effect



Connected and Autonomous Vehicles

+ Potential for reduced road fatalities
+ Increased profitability for distribution firms
+ Potential for increased food access

- Labor market and unemployment effects

Drone Delivery

+ Potential for reduced road fatalities
+ Increased profitability for distribution firms
+ Potential for increase food access

- Labor market and unemployment effects
- Potential for urban planning & zoning difficulties
- Noise, consumer acceptance

Thank you!

Any Questions?

Graphic adapted from Morteza Taiebat

Appendix Slides

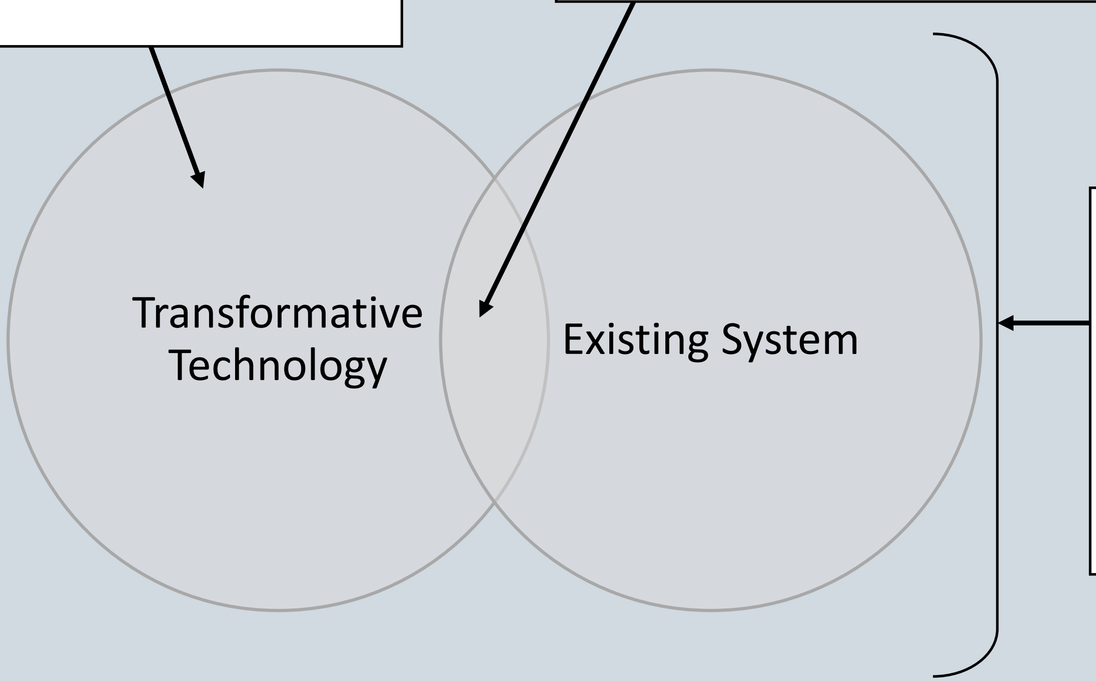
Framework for Analyzing Transformative Technologies

Intrinsic Factors

- Efficiency and functionality change
- Spatial effects
- Infrastructure change
- Resource criticality

Indirect Factors

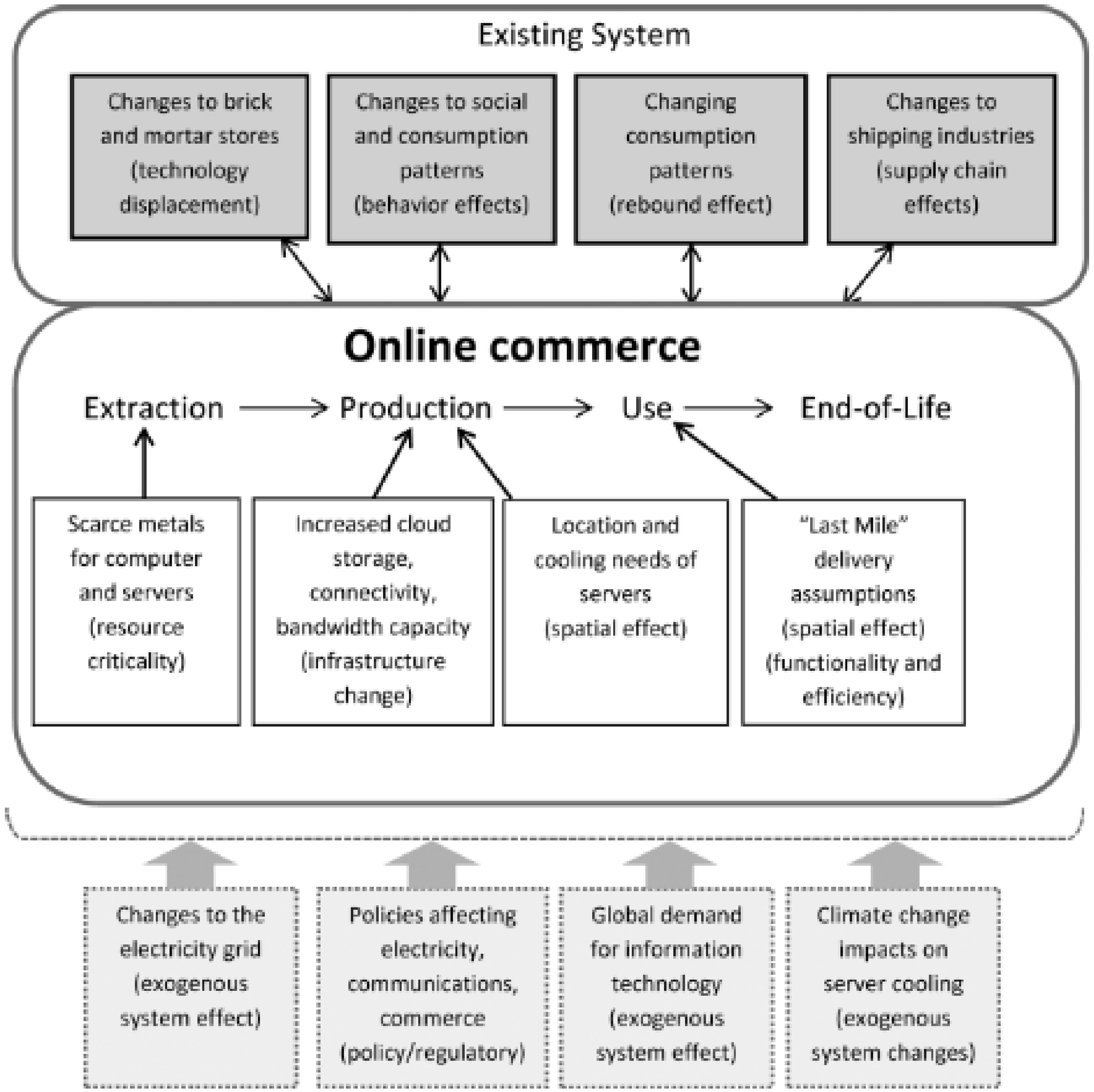
- Technology displacement
- Behavior change
- Rebound effects
- Changes to supply chain



External Factors

- Exogenous system effects
- Policy and regulatory effects

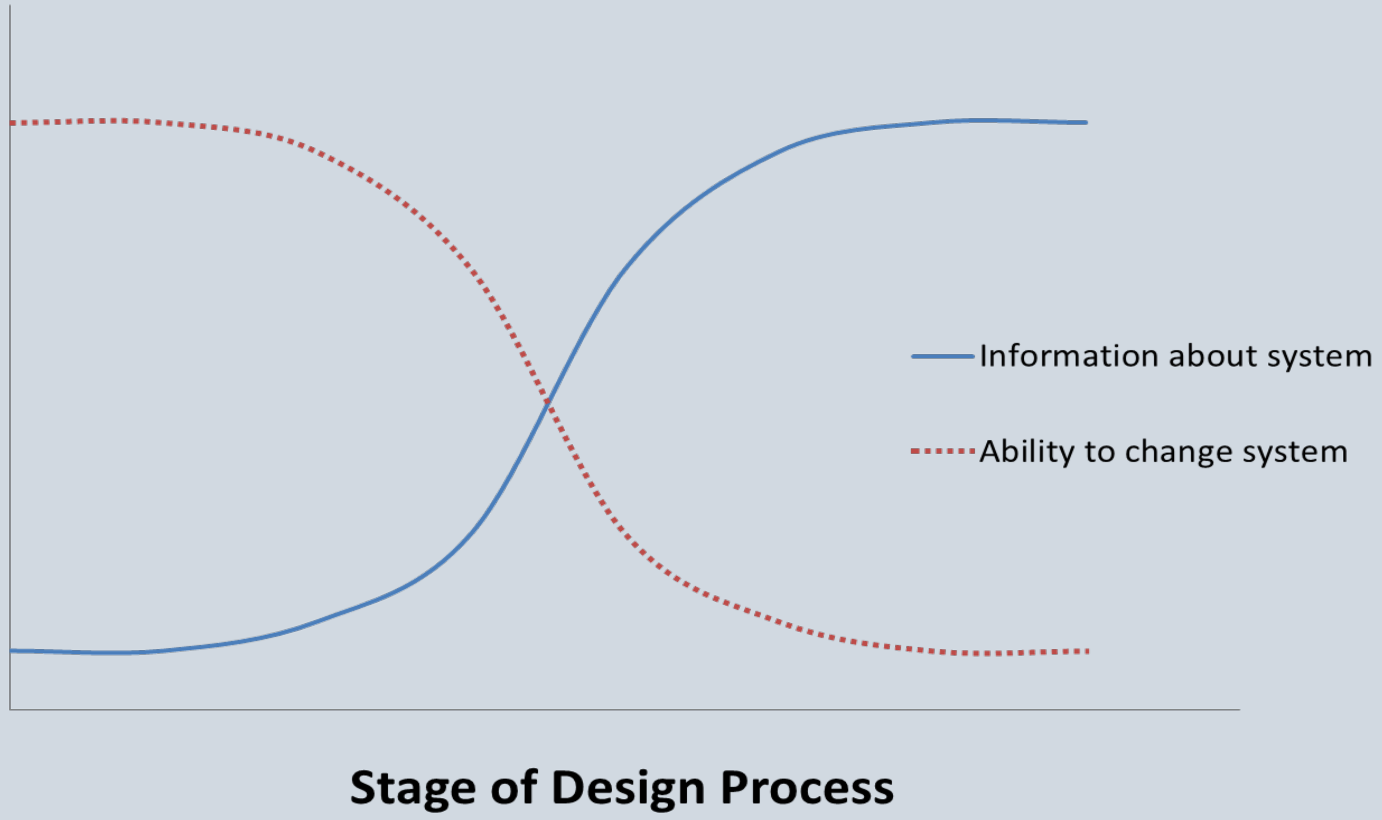
Miller and Keoleian, *Environmental Science & Technology*, 2015



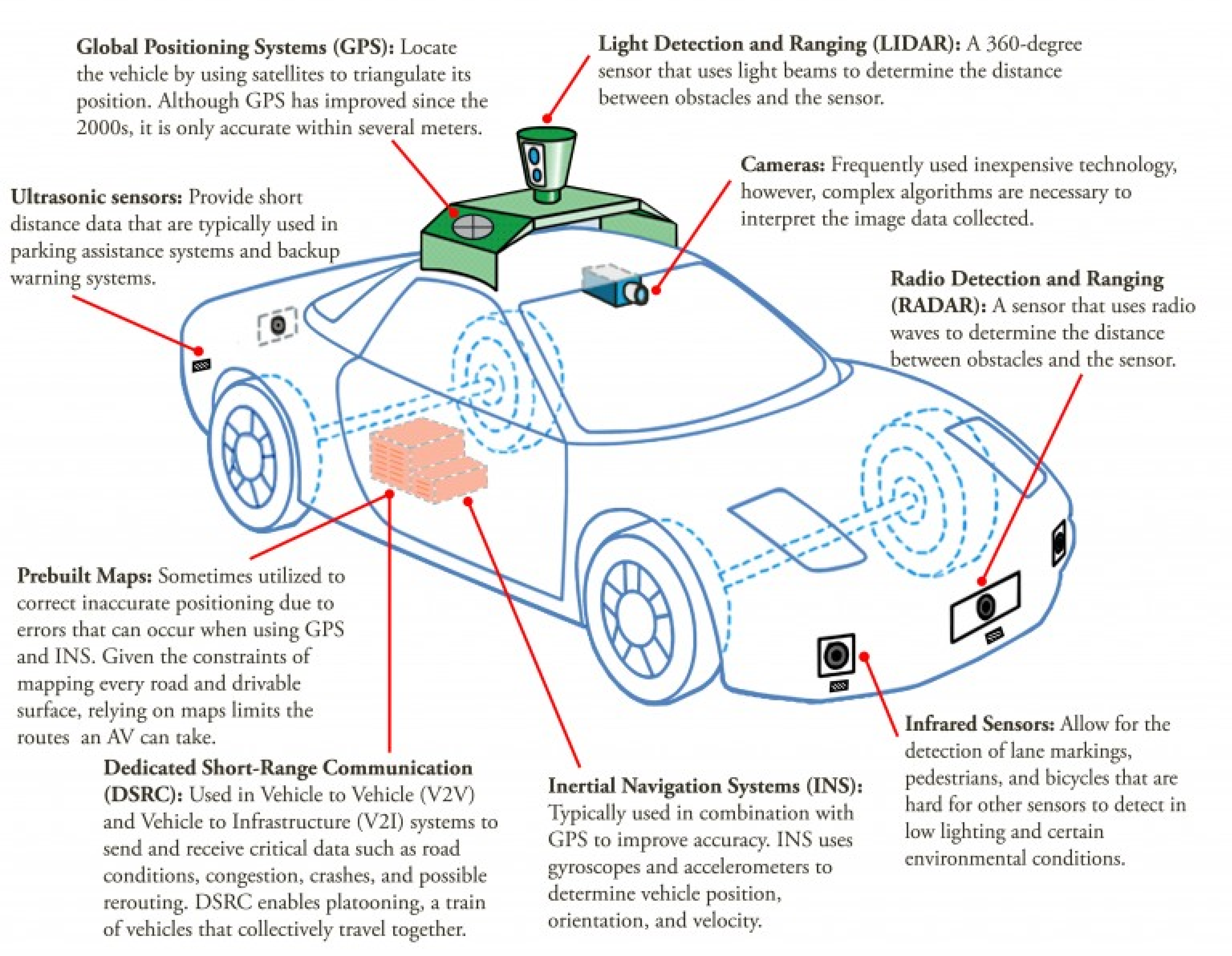
Miller and Keoleian, *Environmental Science & Technology*, 2015

Early Assessments Can Inform the Most-Sustainable Use of Technologies

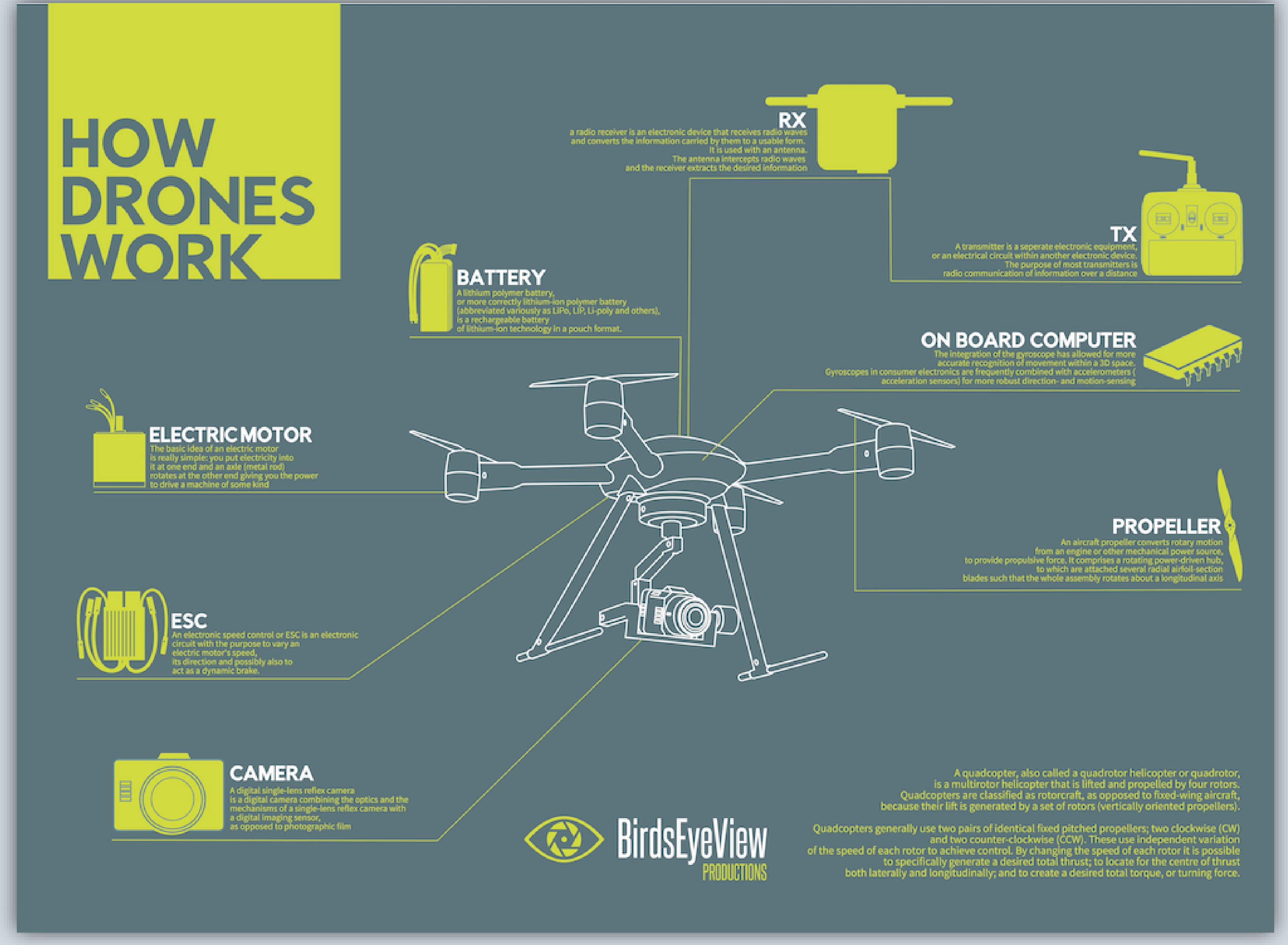
- Data limitations: these technologies have not been widely deployed in a commercial setting



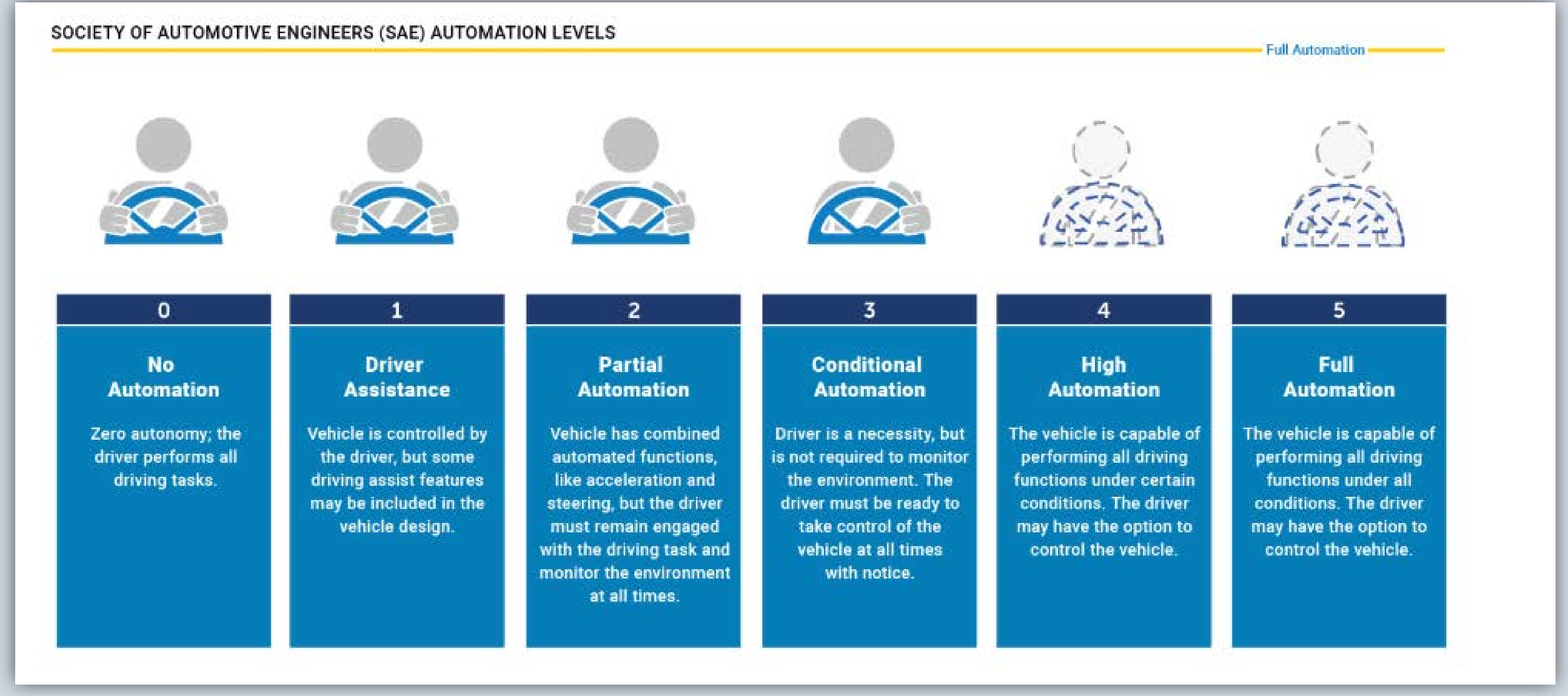
Graphics Credit: Shelie A. Miller



Center for Sustainable Systems Factsheet: “Autonomous Vehicles”



https://uavcoach.com/infographic-drones-work/



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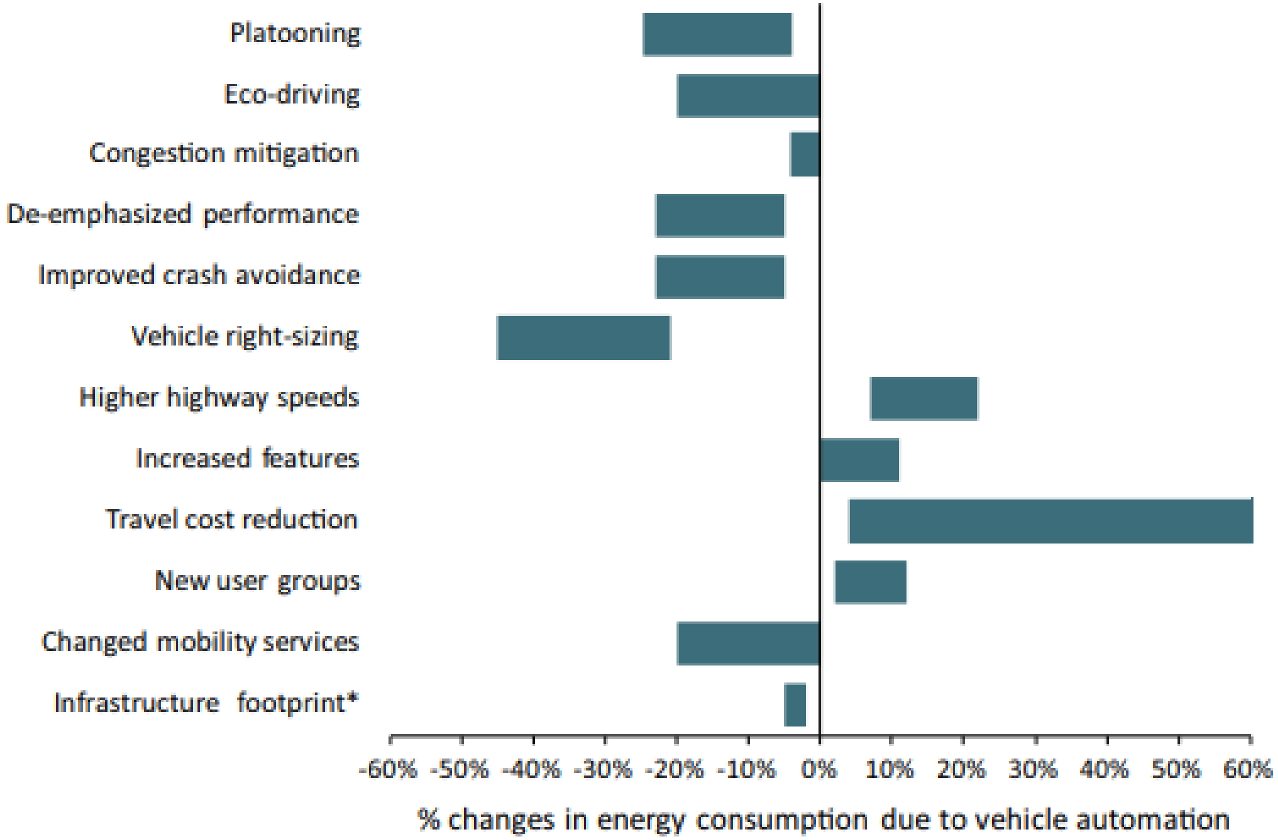


Fig. 1. Summary of estimated ranges of operational energy impacts of vehicle automation through different mechanisms (*please see Appendix A for lifecycle infrastructure impacts, which has not been considered in later calculations due to our focus on operational impacts).

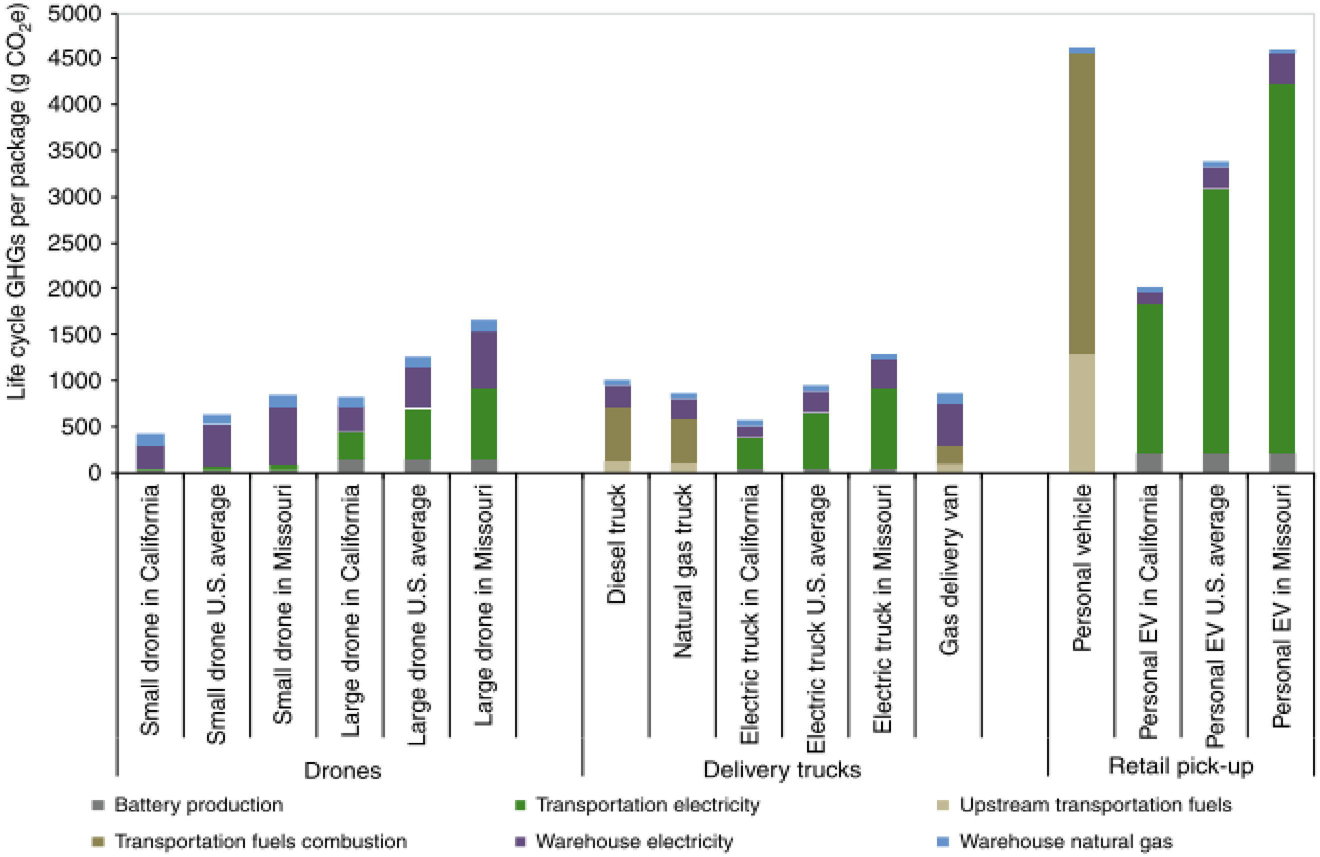


Fig. 5 Comparison of life-cycle greenhouse gas emissions per package delivered for drone and ground vehicle pathways under base case assumptions. The analysis focuses on the final delivery of the package, after the package is delivered to the regional warehouse. Emissions from battery and fuels production, as well as fuels combustion and electricity production required for transportation and warehousing, are included. The range of regional greenhouse gas (GHG) intensities of electricity in the U.S. is represented by comparing results from low-carbon California to relatively high-carbon Missouri. Additional warehousing requirements for drone and van pathways are included. The results show that small quadcopter drones across all U.S. regions have lower life-cycle GHG emissions than conventional delivery trucks powered by diesel and natural gas, electric vehicle (EV) trucks in most regions, and gasoline-powered vans. Large octocopter drones are shown to have lower GHG emissions than diesel and natural gas vehicles only when charged with low-carbon electricity. Both small drones and large drones are shown to have lower GHG emissions than use of a personal vehicle to pick-up a single package. Numerical values of these results are presented in Supplementary Tables 13-17

Stolaroff et al. "Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery." *Nature Communications*, 2018

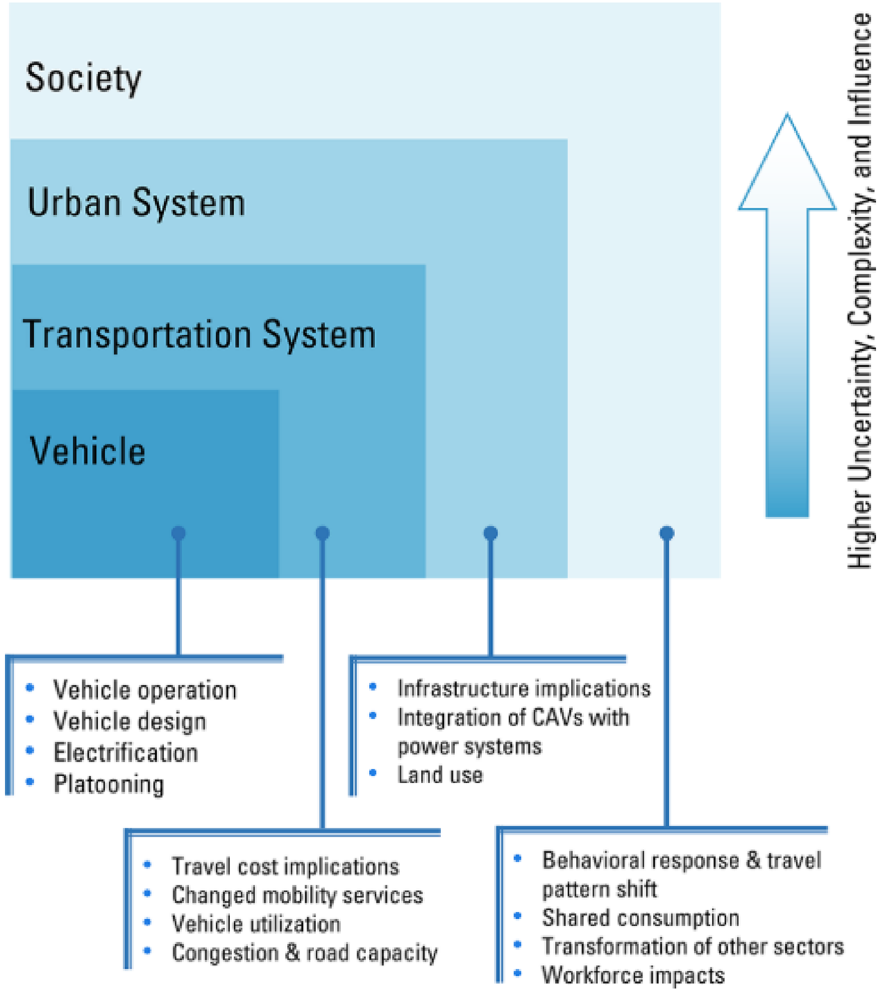


Figure 1. Levels of interactions between CAVs and the environment and corresponding major influence mechanisms.

Taiebat et al., "A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles." *Environ. Sci. Technol*, 2018

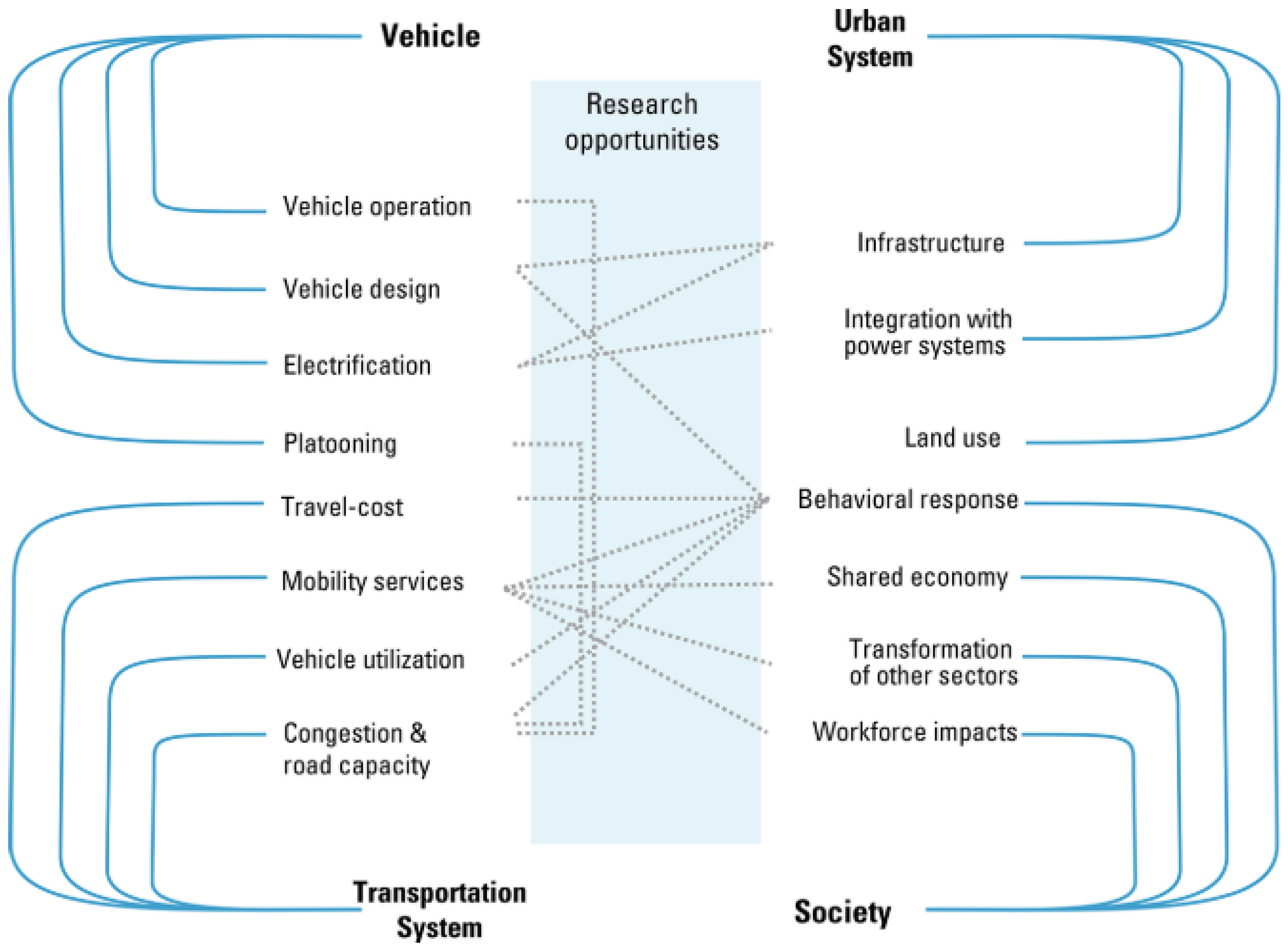
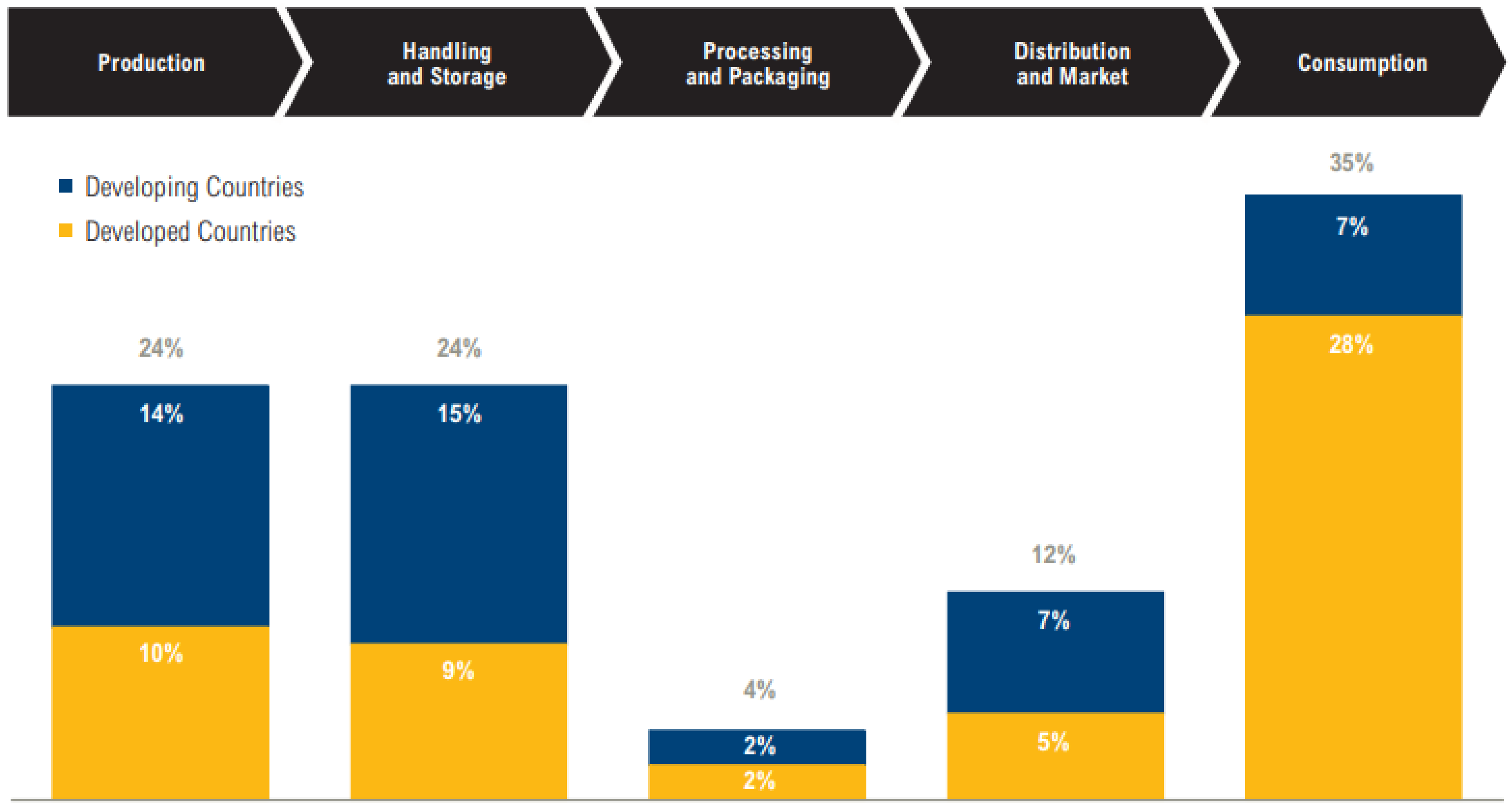


Figure 3. Interactions and linkages between system levels that entail energy, environmental, and sustainability impacts. The linkages are illustrative and not necessarily exhaustive.

Taiebat et al., "A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles." *Environ. Sci. Technol,* 2018

Figure 5 | Share of Total Food Loss and Waste by Stage in the Value Chain, 2009 (100% = 1.5 quadrillion kcal)



Note: Number may not sum to 100 due to rounding.

Source: WRI analysis based on FAO. 2011. *Global food losses and food waste—extent, causes and prevention*. Rome: UN FAO.

Lipinski, B. et al. 2013. "Reducing Food Loss and Waste." Working Paper, Installment 2 of Creating a Sustainable Food Future. Washington, DC: World Resources Institute. Available online at http://www.worldresourcesreport.org.

TABLE 1. Energy and Greenhouse Gas Emissions Per ton-km for Different Modes of Transport[a]

	MJ/t-km	t CO_2e/t-km $\times 10^6$	source
inland water	0.3	21	(*23*)
rail	0.3	18	(*23*)
truck	2.7	180	(*23*)
air[a]	10.0	680[a]	(*25*)
oil pipeline	0.2	16	(*23,24*)
gas pipeline	1.7	180	(*23,24*)
int. air[a]	10.0	680[a]	(*25*)
int. water container	0.2	14	(*26*)
int. water bulk	0.2	11	(*26*)
int. water tanker	0.1	7	(*26*)

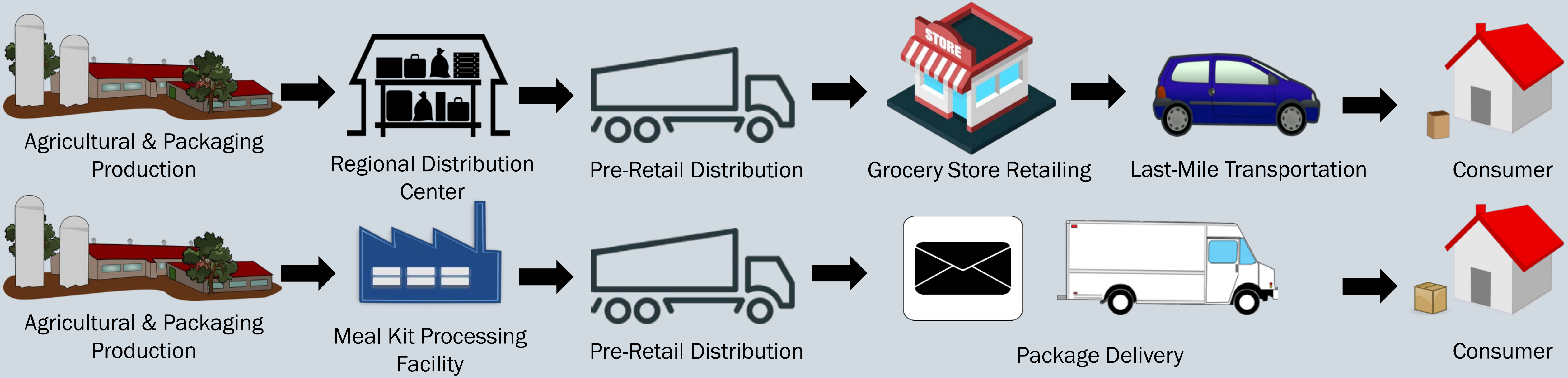
[a] CO_2 emissions were used as an indicator for the radiative forcing effects of aviation, which are actually higher than just CO_2 emissions (*27*).

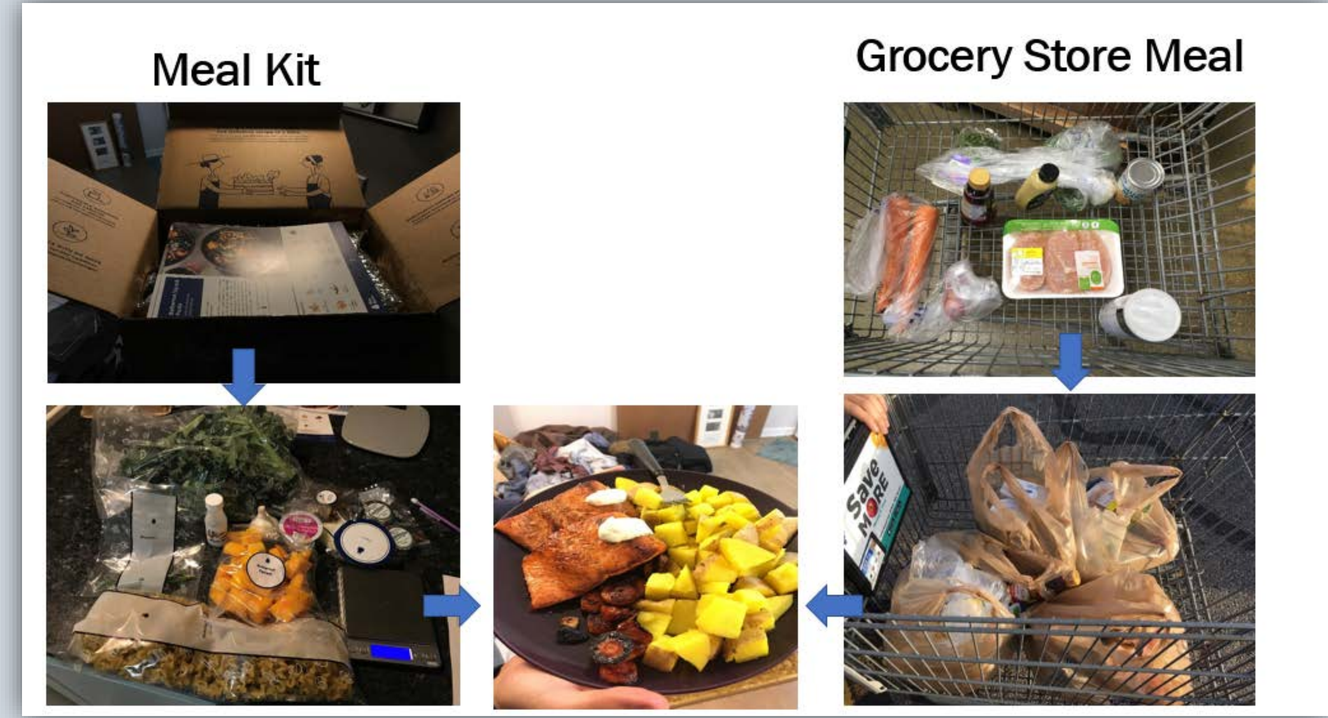
Weber and Matthews, "Food-Miles and the Relative Climate Impacts of Food Choices in the United States." *Environmental Science & Technology*, 2008

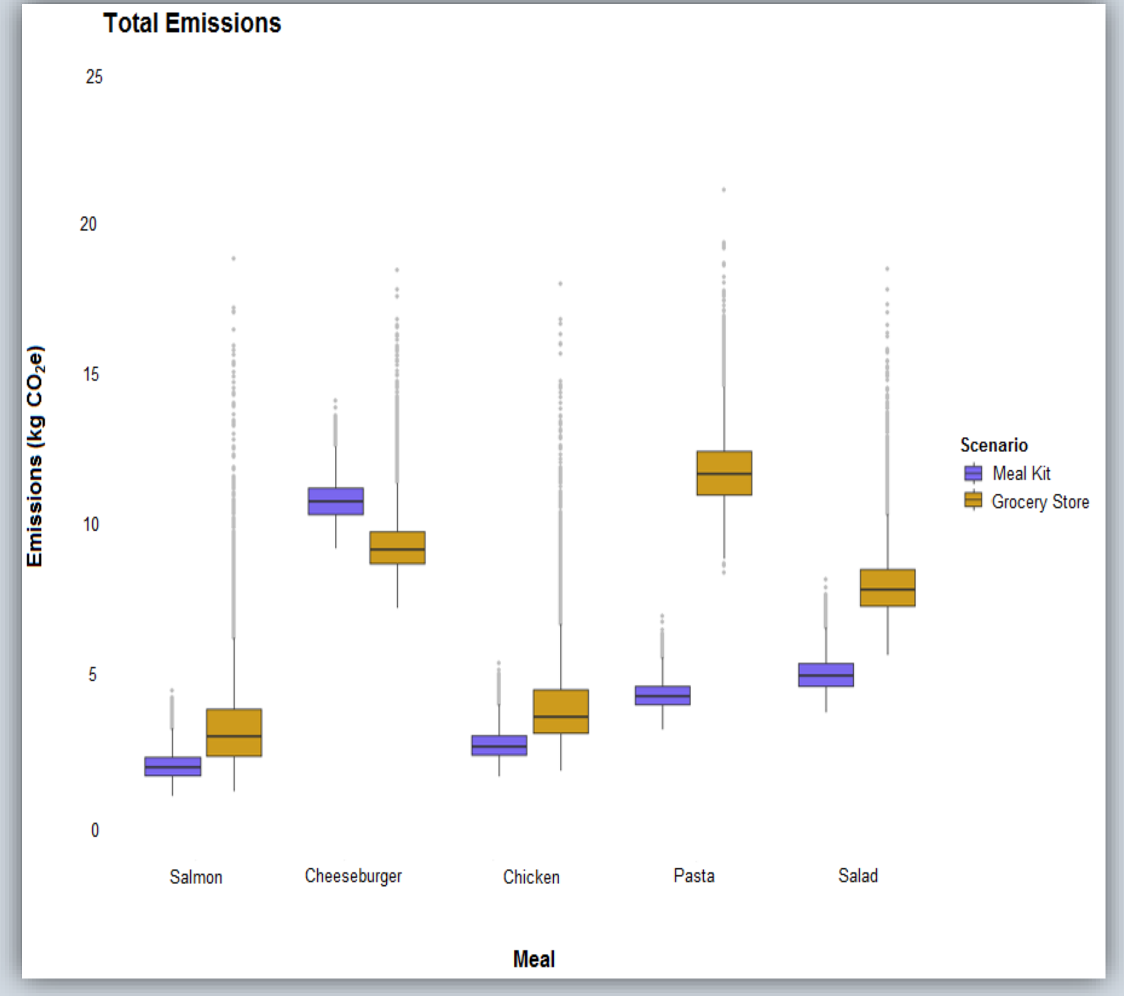
E-Commerce & Home Delivery: Circumventing Brick-and-Mortar Retail

Heard et al. "Comparison of life cycle environmental impacts from meal kits and grocery store meals." *Resources, Conservation, and Recycling*, 2019

- Meal kits are an illustrative example
- Meal kits are delivered in a box containing pre-portioned, often individually-packaged food and a recipe
- Ordered and obtained five meal kits and equivalent grocery store meals, modeled supply chains
- Meal kits average 33% lower life cycle GHG emissions[1]
  - No retailing emissions (refrigeration, overstocking and food loss), improved last-mile efficiency







Grocery Meal Emissions Exceed Those for Meal Kits:

4 out of 5 Meals, on average 33% higher (2 kg CO_2e/meal)

Emissions reductions in part by:

- Last-mile delivery (0.45 kg CO_2e/meal)
- Circumventing brick-and-mortar retail (1.05 kg CO_2e/meal)

Heard et al. “Comparison of life cycle environmental impacts from meal kits and grocery store meals.” *Resources, Conservation, and Recycling*, 2019