Exploring Energy-Efficient and Sustainable Urban Mobility Strategies: An Initial Framework to Curate Data/ Models, Measure Performance, and Diffuse Innovation

Preprint

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NOTICE

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Abstract
Many cities across the United States seek to understand the maturity of data and models that are available to help manage challenges, opportunities, and uncertainties associated with the shifts in technologies, human behaviors and sustainable urban mobility strategies. One key question identified for smart city action planning includes how to best shape continuous improvements for urban populations at the intersection of mobility, energy, and quality of life? With the emerging megatrends of urbanization (more than 70% of world population in cities by 2050), on-demand shared mobility, vehicle electrification, and automated vehicles, initial "urban science" studies to date have demonstrated the potential and need for maturing the related data and model ecosystems and on-going performance measurement across multiple urban system goals: e.g., from more mobility, clean and efficient energy use, accessibility and safety to less air pollution, traffic, and resource-intensive urban sprawl. To build on emerging literature and understand city responses to disruptive change, this initial study engages researchers and practitioners across four smart city finalists (Columbus, Denver, Austin and Portland) that competed in the U.S. Department of Transportation (DOT) Smart City Challenge. The initial results emphasize the need for a suite of datasets and diverse analytical approaches that support U.S. Department of Energy (DOE)-relevant research with cities. Considering desirable energy and mobility outcomes as a first step to advancing smart city solutions strategies, we systematically review approaches of and shortcomings in four U.S. cities, and suggest improvements in three areas: measurement, modeling effectiveness of new mobility technologies, and data-driven governance.

KEYWORDS: Smart Cities, Energy Efficient Mobility, Curation of Data and Models

Introducing study framework for initial curation and use of data for seven cities
The transformations and transitions in urban mobility systems, technologies, and services (Sarkar and Ward, 2016) across cities of the United States and globally are accelerating, yet at different rates and with experimentation and prioritization of initiatives that are often emphasizing different areas of foci. At the same time, one common theme and area of interest in engaging with four U.S. DOT Smart City Challenge finalists has been the diffusion of and synergies among three key smart mobility "revolutions" (of shared, electric, and automated vehicles) in cities (Fulton et al., 2017; Sperling, 2016; Rogers, 2003). Early examples of these "revolutions" range from the uptake of Uber, Lyft, Didi, and Ola ride-hailing services (Watanabe et al., 2016; Terrien et al., 2016) in San Francisco and in global cities; to Tesla, Waymo (Google), and various auto manufacturers increasing their ambitions in the space of electric and automated vehicles and for on-demand fleets (Mahmassani et al., 2016), to Volkswagen settlement funds toward electrification of transportation. Other synergistic "revolutions" include the move towards e-business, open government, and the digitalization of city services via mobile phones, information display systems/ mobility kiosks, providing personalized information to wider-access public Wi-Fi (Ylipulli et al., 2014). This paper does not aim to capture all of the emerging technologies and transformations. Alternatively, this study focuses on curating data and models for knowledge development, "urban science" towards the effective diffusion of energy-efficient and sustainable urban mobility strategies that can also inform multiple smart city-relevant research and practitioner questions. With the common critique that "smart" cities initiatives have had limited success in effectively providing smart solutions beyond just select populations (Chatterjee, 2017), there is a demand for cities to enable inclusive advanced mobility solutions, and increasing the usability of data and models for shaping city decisions, planning, and performance/trend monitoring.

The initial framework (Figure 1) proposed here aims to guide cities on a diffusion of the three revolutions (Sperling, 2016), and other synergistic transitions (e.g., digitalization) that can help advance initial stakeholder outreach approaches, data and gap assessments, and feedback loops for creating critical

knowledge for mobility data, models, and decision processes within cities that enable effective energy-efficient mobility strategies (e.g., Kuhne, 2010) towards multiple city-performance goals (for example, addressing three "E"s: economy, environment, and equity (Saha and Paterson, 2008; Opp et al., 2012)). The five dimensions were identified through literature review and stakeholder outreach.

Cross-scale Actors & Institutions	Open Data Platforms	Key Smart City Indicators	Mapping Data & Models Maps	City-Based Literature Review

Figure 1 Study framework for curating data and models with Smart City finalists

Developing an integrated data and model foundation for accelerating smart solutions
As shown, cross-scale actors and institutions emphasized the mapping of stakeholders for curating data and models, leading into curating across these other key dimensions too.

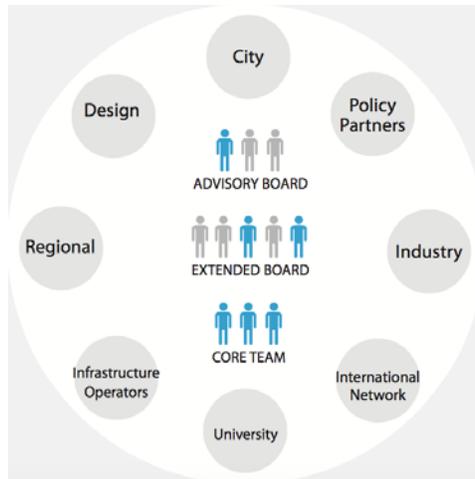**Rationale for study framework**
This study starts with why and how best to curate, assess maturity, and integrate current and emerging data sources to allow for improved data-driven predictive modeling (Toole et al., 2015), visualization (Denver Regional Council of Governments (DRCOG), 2017), and computing/analytics (Wang et al., 2014). The initial rationale for this framework is to inform multi-criteria analysis (addressing economic, social, and environmental priorities), harmonizing of scenarios in travel demand models, and participatory research processes (with analyses within the deliberative process of shaping energy efficient and sustainable mobility strategies). Given that the range of urban stakeholders in the Smart Cities space can be complex and broad (ranging from topics beyond mobility and energy to health and governance), initial emphasis of the framework focuses on engaging smart city technical experts and researchers to work together to identify solutions that can shape sustainable communities and advance innovations in energy efficiency, mobility, and quality of life across cities.

With questions of how research can best inform a maximum mobility and minimum energy future, emphasis is also placed on data supporting decision-making, planning, and new technology/infrastructure that enables local-to-regional co-benefits, including:

- Economic (e.g., energy-efficiency cost savings and job choices via transportation)
- Environmental (e.g., congestion/pollution; building resilience to extreme events)
- Social (e.g., increased mobility/safety and social cohesion/connectivity).

Future approaches in this effort will emphasize the evaluation of the state of current urban modeling approaches, including the ability to analyze energy impacts of scenarios, future transitions, and key uncertainties. Specific questions posed by the research efforts to date, includes e.g., *How best to model what is coming instead of what has been? How and why does gaining increased observability of real-time data streams improve energy-efficient urban mobility management (e.g., Shahrokni, 2015)? What data are needed and missing in current activity-based transportation models to explore potential impacts of disruptive mobility services like automated vehicles in cities (e.g., Childress et al., 2015)?*
The design of this adaptable and flexible study framework aims to address some of these questions, and resulted from engaging core teams of smart city actors and institutions. Direct engagements have helped build an initial group of city data and modeling lead stakeholders (as an extended board of city engagement liaisons) and a larger advisory board (see Figure 2 below). Such stakeholders include representation from various entities, including mobility data managers, travel demand modelers, utilities, transit agencies, state departments of transportation (DOTs), city-related industry partners, academia, research institutions, and metropolitan planning organizations (MPOs). The study, still in the first of three years, aims to identify, curate, and extend data and models, aligning the need for analyses of use to cities and the DOE.

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Figure 2 Mapping actors & institutions relevant to SMART mobility: urban science

Many of these stakeholders are interested in the emergent conditions or drivers of innovation (Rodgers, 2003) behind technological/built environment advances (e.g., connected and automated vehicles, shared mobility, vehicle electrification) and the data systems that can support analytic deliberation (Marcotullio et al. 2017) for informed future decision making and investments. Lessons learned from these focus groups, roundtables, and workshops have included an emphasis on city data, models, and scenarios that include exploring potential risks, uncertainties, and motivations in extending current data and modeling approaches. The foundational aspects of the integrated resources developed to date included:

- Mapping actors and institutions active in U.S. DOT Smart City Challenge finalist efforts
- Identifying open data platforms and related policies
- Engaging stakeholders on how they define and measure the concept of smart cities in terms of key "smart city" indicators (that will be monitored over time as they relate to a nexus of energy, mobility, and quality of life for people in their cities)
- Curating available data sets and mobility models (including geographic information system data resources for rapid visualization of available data and current state of travel demand models in terms of sophistication and supporting data)
- City-based literature review, including peer-reviewed articles and reports relevant to research efforts and building on existing knowledge.

Methods

The cities selected as case studies are shown in the map, provided by the U.S. Department of Transportation as part of its Smart City Challenge (Figure 3). The population indicators identified in their proposals are shown in Table 1. The research described in this paper aims to test the study framework using case studies of these cities to address challenges of relevance to each of these cities, starting with top down (e.g., data available from desktop research); bottom up (e.g., direct engagement with Smart City stakeholders including researchers and data and model leads); outside-in (agenda set by DOE as to energy-efficient mobility systems interests); and inside-out (ongoing curation of available data and models with local stakeholders aware of, supporting and/or interested in the study efforts). The study offers an opportunity to compare and contrast the energy and mobility systems and data resource development patterns of these finalists, all of whom described data as a critical element to their smart city competition proposals. A full list of the finalist cities are below and the four cities compared in-depth as case studies include Columbus, Denver, Austin and Portland.
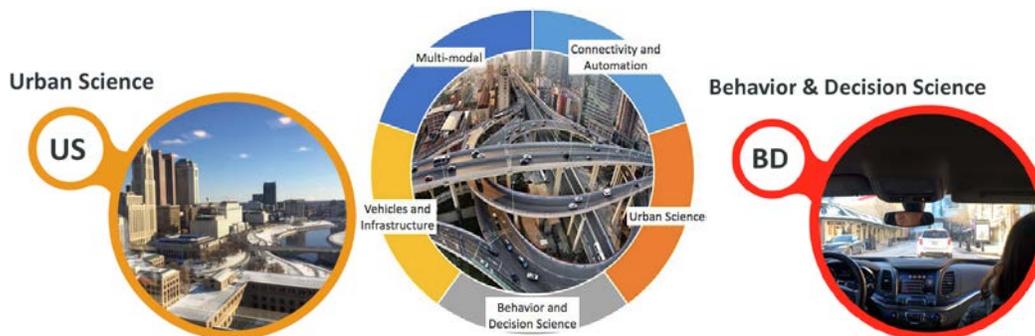
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Table 1 City populations of Smart City Challenge finalists		
Columbus	800,000	Total pop. in the cohort of Smart Cities finalists = ~ 4.4 M
Denver	600,158	
Austin	790,390	
Portland	583,776	
San Francisco	805,235	
Pittsburgh	305,704	
Kansas City	459,787	

Figure 3 Smart City Challenge finalists (U.S. DOT, 2016)

This paper emphasizes initial data collected addressing the urban science research pillar of the U.S. DOE SMART Mobility Laboratory Consortium (see Figure 4), which is also directly relevant to behavior and decision science elements of Smart City goals at the intersection of energy and mobility. The purpose of the study methods are the following, to:

- Inform Smart City data for advancing engineering, planning, policy, and behavioral/decision science across city goals and priorities
- Support mobility transformation efforts with multiple stakeholders
- Engage with /contribute to public dialogue on progress on data and models, as well as best options towards achieving smart city goals
- Diagnose and detect critical smart city challenges/ opportunities, to inform new investment decisions and key performance indicators.

Figure 4. A lens of "Urban Science" and "Decision Science" on Smart City mobility data

City engagements have included emphasis on how cities are advancing energy-efficient mobility efforts since Smart City proposals.

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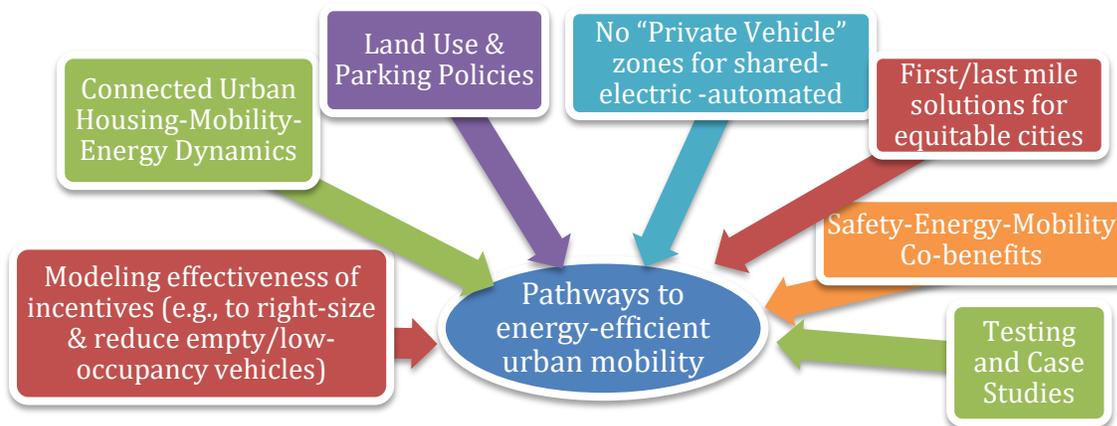A timeline of city engagements is shown in Figure 5.

Figure 5 Smart City Challenge Finalists – direct engagements / focus groups to date

These direct city engagements have helped to scope early stage research, and have also enabled the information shared here to expose at a high level data, modeling and analysis (and subsequent planning) by cities, on new mobility technology diffusion, that is coming to bear in urban areas along with the critical city data and models for decision-making.

Results

Initial synthesis of the DOT Smart City program, as relevant to measuring potential high-opportunity energy-efficient mobility strategies, is summarized first. These are areas identified in the smart city applicant proposals and as emerging themes from recent urban mobility literature (e.g., Cohen and Kietzmann, 2014; Kyriakidis et al. 2015; Guerra, 2015; IEA, 2017). This is followed by preliminary data collection and cross-city comparative analysis efforts that focuses on the five middle boxes or key elements of Figure 1, each of which are part of the initial development of an integrated data resources platform (and as a precursor to the curation of city modeling and data analysis abilities for responding/planning for new emerging mobility technologies and services). Example initial results in terms of strategies under consideration are highlighted in Figure 6.

Figure 6 Smart City Challenge Finalists - strategic pathways to energy-efficient mobility

The review of results from U.S. DOT Smart City Challenge applicant submissions (n=78; with specific proposed details from the four finalists) offers areas of interest that may support the design, planning, and diffusion of emerging urban futures of shared, electric, and automated mobility, all of which have important energy efficient impacts.

- **Shared Mobility**: Almost half of the cities proposed shared-use mobility goals (including for ride-share, car-share, or bike-share)

    o *Columbus*: CoGo bikeshare; Car2Go; Uber/Lyft (launched in Feb 2014; Lyft services were suspended in Jan 2015, until they returned in March 2016)
    o *Denver*: B-Cycle (with 87 bike share stations), five car share operators (e.g., Car2Go, eGo Carshare), Uber/Enterprise driver rent-a-car pilot
    o *Austin*: Uber/Lyft (stopped services from May 9, 2016 to May 30, 2017), Get-ME, RideAustin (as transportation network companies (TNCs)); ambition of shared electric vehicles (EVs); Bcycle; Car2Go; ZipCar; 500 pedicab operators; 85 shuttle companies, 52 airport shuttles)
    o *Portland*: Lyft impacts associated with parking meters and DUI citations; BIKETOWN bike share system.

- **Electric Mobility**: Almost half proposed installing EV charging infrastructure.

    o *Columbus*: Three hundred public EV charging stations (at the time of the proposal), investigating partial conversion of city fleets to EVs with public shared uses
    o *Denver*: Thirty-four city-owned EV charging stations (at time of proposal); strong state-level incentives for EV purchasing; wireless charging for downtown electric buses; electric automated vehicle (AV) mobility on demand; EV infrastructure expansion
    o *Austin*: Based on GM investment of $500 million in Lyft, exploring deployment of large numbers of GM electric TNC and taxi vehicles; already recognized as a top "plug-in ready" city due to utility programs/infrastructure
    o *Portland*: Leader in transportation electrification with "E-Visionary" award and as a "top ten" city for EVs and chargers per capita; low-cost and low-carbon electric power; Oregon EVs estimated to get equivalent of 94 miles per gallon.

- **Automated Mobility**: More than half of applicants wanted to implement an automated, low-speed shuttle by 2019.
    o *Columbus*: On-demand automated vehicle testing with Ohio State University; deploying on-demand automated EVs to address last-mile challenges; pilot AV shuttles on a fixed route from existing transit station in Easton Area.
    o *Denver*: The city partnered with the Colorado DOT to expand connected and automated vehicle program into urban environment and with interest in this transition for optimizing freight movement; first mile/last mile connections piloted in nearby City of Centennial with Lyft, to stimulate future AV business models; creating AV policy-enabling environment, enhancing infrastructure to support AV operations; working with automaker/technology partners to place an AV fleet in the city by 2020; increasing education and public awareness of AVs via new pilots that demonstrates mobility on demand (or shared), electric and AV technology via integrated corridors that pull these all together.
    o *Austin:* Airport electric-powered automated shuttles/circulators as a partnership with Capital Metropolitan Transit Authority (Capital Metro); increase visibility and "comfort level" with adopting AVs and via compact and connected land uses to decrease dependence on personal vehicles while increasing walking, biking, shared vehicle and transit use; downtown on-demand, electric AV service as smaller vehicles and mid-size transit shuttles to be used for enhancing transit use; sensor-based infrastructure; urban and suburban automated car share vehicles (including in underserved areas) and with varying levels of vehicle automation; urban package delivery with unmanned aerial vehicles/extensive bike facility network to reduce large truck traffic and congestion (building on Whole Foods free home delivery model).
    o *Portland*: Semi- and fully automated EVs leveraged via transportation sites and academic/institutional campuses of project partners; plans for AV pilot zones at Portland's new car-free multimodal Tilikum Crossing and with TriMet supporting Mobile-Eye transit collision avoidance systems; and perhaps at Portland State University, Portland Community College, Oregon Museum of Science and Industry and/or Mount Hood Community College.

Other high-interest projects included new sensor infrastructure, including for real-time monitoring of vehicle traffic, parking availability, pedestrian and bicycle counting, and air quality monitoring; ITS, incident management, signal coordination; unique or context sensitive amenities (e.g., ports as critical to freight movement; managing pinch points (e.g., bridges), land use / parking upgrades); to generalizable challenges (mobility services for low-income/disadvantaged residents e.g., affordable access to high frequency public transit, jobs, and healthcare; ageing infrastructure upgrades; and funding).

From this overall review, a next step in synthesis efforts was to directly engage with a subset of U.S. DOT Smart City Challenge finalist teams (bottom-up method to data collection and analysis). Mapping for purposes of future surveys and meetings are shown below in Table 2 (with the specific names of individuals at these institutions left out for purposes of privacy, and protection of personal information). The mapping helped to identify who would be most relevant to engage initially in smart city stakeholder workshops to identify how best to curate key data and models, based on city priorities and strategies for energy efficient mobility, new emerging technologies, and services.

Cross-scale actors and institutions:

Through workshops/focus groups, this study team engaged key actors and institutions (mapped in Table 2) to identify city priorities. Sample questions from data/model providers, Smart City staff, local research communities, and industry stakeholders shaping a future of energy-efficient mobility are listed below:

- Columbus:
  - Where can university researchers collaborate with DOE national researchers on Smart Columbus initiatives?
  - How to integrate new data sets into travel demand/forecasting models?
  - What are the needs of urban freight in terms of future infrastructure?
  - Keeping in mind the city/MPO is not yet capable in large ways with big data (not yet high-tech), how best to enable integrated data processes?
  - Data to inform models and better decisions: what interactions are needed? What data do we have and want? Key gaps? What will data environment look like in three years from now?
- Denver (emphasis on Electrification of Transportation and Shared Mobility):
  - What programs, projects, or policies have been successful in other cities? e.g., What are the key lessons from Austin/Los Angeles?
  - What are potential city and utility partnership enablers that can accelerate electrification of high-mileage fleets?
  - What can the city, private sector, researchers, and community engagement do to accelerate or initiate greater electrification in this market?
  - What can Denver learn from existing pilots across the country for TNC and transit synergies?
  - What are enablers and barriers to effective TNC and transit /microtransit or shared mobility /"pooling" for commutes in Denver?
  - "What program, project, or policy will help transit and ridehailing increase occupancy, and how can the City, private sector, researchers and community engagement help enable this (what is role of the city and its partners)?"
- Austin:
  - What are the elemental components to developing a shared electric autonomous vehicle plan and roadmap? Who will be involved in creating Austin's Smart Mobility roadmap?
  - What are the urban modeling capabilities to study impacts of TNCs? What data are available and what can Austin do with the TNCs data?
  - What is the impact on energy production if there is 25% increase in EVs in the city? What will be the sources for electricity?
  - What kind of policy, regulations, and human behavior issues need to be changed across Austin to accept and embrace smart city deployments? What are motivations and incentives for urban travelers to migrate to smart mobility technology deployments and new services?
  - How is Smart Austin going to get data to interoperable across all platforms and technologies?
  - What can be learned from EV pilots programs with Austin Energy? Where will existing and new EV charging stations need to be located?
  - When and how will an AV proving ground be formulated and deployed? What are the best

funding mechanisms/financing options?
- o What are return on investment results and economic benefits for smart investments?
- o Ridehailing services—what resources will TNCs need to increase a larger participation rate? How to electrify TNCs fleets and provide sustainable economic models for TNC drivers?
- o What will be the key land use, infrastructure, and parking impacts?
- Portland:
  - o What will equitable smart transportation services look like?
  - o What are climate benefits of a Smart Portland and the measurable improvements? What are necessary technology advancements for more affordable mobility? What is that timeframe?
  - o Do AVs provide the solution to meet Portland sustainability goals?
  - o What are funding sources for Smart Portland projects?
  - o How does Portland identify the digital transformation of systems within the urban ecosystem? What are measurable environmental, financial, social outcomes with 'digitalization' transition?
  - o With cities competing for talented employees, how does Portland attract and retain them?
  - o What impact will Autonomous Connected Shared Vehicles have on Smart Portland in the near term? How do Vision Zero goals integrate with smart initiatives?
  - o What data sets or data themes exist across all Portland stakeholders? How can Smart Portland use live data to help move Portlanders through the transportation system better, faster, cheaper, and safer?
  - o What are the Smart Portland use cases for smart mobility? What outcomes-based answers does Smart Portland seek? What is the true value of data (any and all types)? How can Portland get better real-time survey data? What does the services (by mode) look like in Smart Portland? How can data get from agency to agency at a faster rate for use in other models and simulations?
  - o What are the near-, mid-, and long-term mobility data needs for transport and community decision making in Portland?
  - o How can and will Portland benefit from multi-modal data studies in urban-scape changes and mobility strategic planning?
  - o What metrics does Smart Portland use to baseline post smart technology implementations? What are the standards? How do environmental data collection sensors and systems integrate within deployed smart technologies?
  - o What are the regional needs for smart technologies? How are those smart technologies integrated in order to benefit regional stakeholders?

From cities engaged to date (as shown in Figure 5), further analysis interests included:
- *Columbus* has an interest in analyses around energy-efficient access to jobs and healthcare using TNCs, bus rapid transit (BRT), and siting transportation electrification/automated electric shuttle infrastructure development pilots.
- *Portland* has interest in EVs, air quality, and integrated payments.
- *Pittsburgh* on driverless cars/robotics, smart parking, and mobility data analytics.
- *San Francisco* on right-sizing, electrifying, and advancing TNC data.
- *Austin*: Shared, electrified, and automated vehicles; utility EV innovation; and transit near affordable housing.
- *Denver*: transit and TNCs, EVs, and design for population growth.

A common priority analysis area of interest included key mobility system performance enhancements resulting from transitions to shared, electric, and automated vehicles - this includes focus on affordability, access to jobs/healthcare, reduced congestion, clean and efficient energy use, safety to less air pollution, traffic, and resource-intensive sprawl.

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Table 2 Cross-scale and cross-sector institutions relevant to DOE and engaged with DOT Smart City Challenge finalists

City	Level	Government	Research	Private Service Providers	Non-Govt. Organizations
Denver	National	U.S. DOT, DOE, and HUD	NREL, NIST, NCAR; EPRI	EasyMile; Car2Go; Lyft; Uber; Enterprise; AECOM; Jacobs; CH2M; Xerox	RMI; APTA;
	State	CDOT, CEO, CDPHE, CPUC, EPA Region 8	CU-Boulder / CSU	Denver International Airport; FERC/NARUC;	SWEEP; CISC; Bicycle CO; Open Colorado;
	Regional	DRCOG, RTD, RAQC, DIA, Denver Metro Chamber of Commerce	UC-D; DU; Mountain Plains Consortium UTRC	Xcel Energy; GoDenver; Navigant	Transit Alliance; Transportation Solutions; Clean Cities
	Local	Public Works-Transport; Mayor's Office- Sustainability;	UC-Denver/DU	Lyft-Denver office, EasyMile, Panasonic	Denver B-cycle; WalkDenver; Mobility Choice Blueprint
Columbus	National	U.S. DOT, DOE, HUD, FHWA	Battelle	GM; Uber; Car2Go; Siemens; PB; INRIX; Fleet Carma; AT&T;	Electrification Coalition; Transport for America
	State	ODOT, with MI & PA DOTs (Smart Belt)	OSU, Cleveland State Univ (UTRC)	AEP; HNTB; Ohio TechAngels; Third Frontier;	Clean Fuels Ohio; Engage
	Regional	MORPC; Franklin County; COTA;	OSU with a smart belt coalition of UM/CMU	Rev1 Ventures; Nationwide Insurance; Honda of America; IBM;	SPARC; Electrification Coalition; Columbus Partnership
	Local	Dept of Public Service; Division of Technology/ Power/Infr/Fleet Mgmt.	IBM Analytics Data Center	Car2Go; Columbus2020; MyColumbus	Columbus Collaboratory; Experience Columbus;
Austin	National	DOT; NIST; HUD	NREL;	Peloton; Google; GM	RMI; NEDTA
	State	TxDOT	TTI	Ridescout; TomTom	TX Tech Council
	Regional	EUC; Metro; CAMP; CTRMA; Travis Co.; CAPCOG; Commerce;	UT-Austin; SRI;	Austin Energy; Whole Foods; H.E.B Stores; Fasten; Uber; Lyft; BuddyTruk; GetMe	Austin City Up
	Local	City of Austin	MIT	BCycle; Car2Go	Tech Incubator
Portland	National	DOT; NIST; Commerce	PNNL	Urban.Systems; PlugShare; Inrix; Intel; RideScout; GM; Lyft; MobileEye; Savari;	T4 America
	State	ODOT; Port of Portland	PSU; OSU; U of OR	PG&E; DKS Associates;	Tech Assoc. of Oregon; NAMAC; Drive Oregon
	Regional	Metro; Trimet;	TREC at PSU	FreedomPop; Kittelson & assoc	RideConnection
	Local	City Smart Cities Office	PORTAL	Car2Go; Transcore; GetAround	PBA; Biketown

Comparing the State of City and Metro Region Open Data Platforms: Figures 7 and 8 show some initial independent analyses conducted (as a top-down approach), and that focuses on the state of open data in the four Smart City case studies. An open data set is defined as data that can be freely used, re-used, and redistributed, and with most cities and MPOs now aiming to produce and provide open data e-catalogues with a wide array of data, maps, and models in support of city and regional planning and decision-making.

Figure 7 Total Number of Open Data sets by March 2017.

Figure 8 Emphasis on transportation-focused data as part of city open data: percent of data sets explicitly focused on transportation of the total open data sets provided

*These results were based on the city and the regional metropolitan planning organizations (MPO) websites, where the total number of open and geographic information system data sets were reviewed online after the 2016 DOT smart city competition.

Smart City indicators at the nexus of energy and mobility: This initial comparative analysis focuses on potential benchmarking indicators that can be tracked over time by the smart city finalists and other cities for comparison. Figures 9 to 14 illustrate the summary analyses on EV fueling stations, congestion related fuel consumption, vehicle miles traveled, traffic counts, emissions, parking spaces, and travel demand models, emphasizing the pursuit of ongoing key performance measurement, modeling effectiveness of new mobility technologies, and data-driven governance.
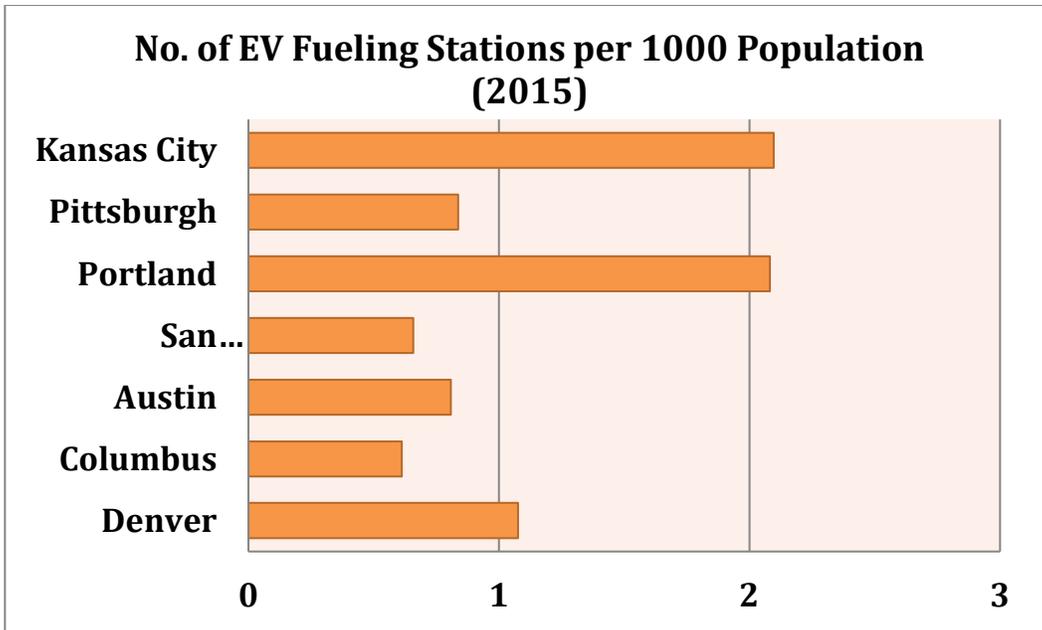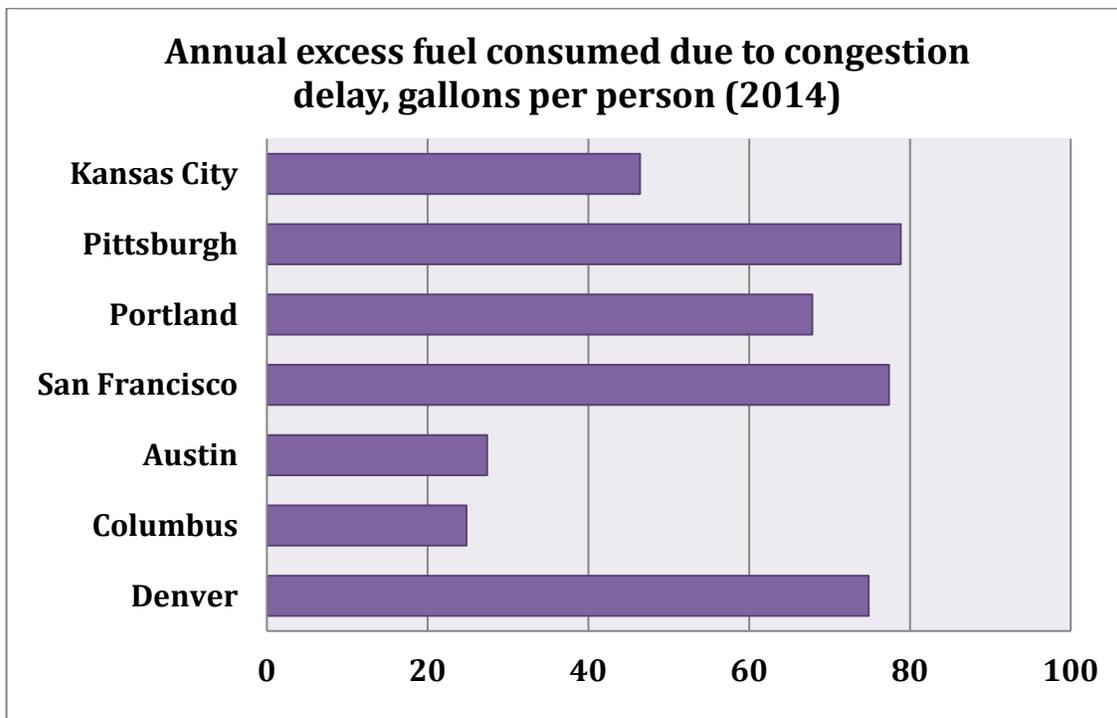
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Figure 9 U.S. DOE Clean Cities database (*https://cleancities.energy.gov/coalitions/*)

**Figure 10 Texas A&M Transportation Institute annual urban mobility scorecard
(*https://mobility.tamu.edu/ums/congestion-data/*)**
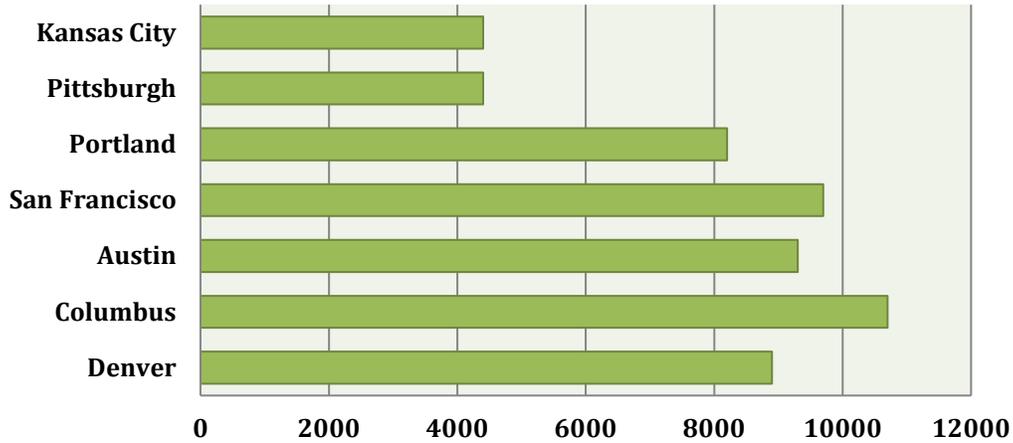
Total Vehicle Miles Travelled / Capita

Figure 11 NREL state & local energy data (SLED), 2017

Example Visualizations and Comparative Analysis of Curated Data and Models:

Denver Regional Traffic Counts
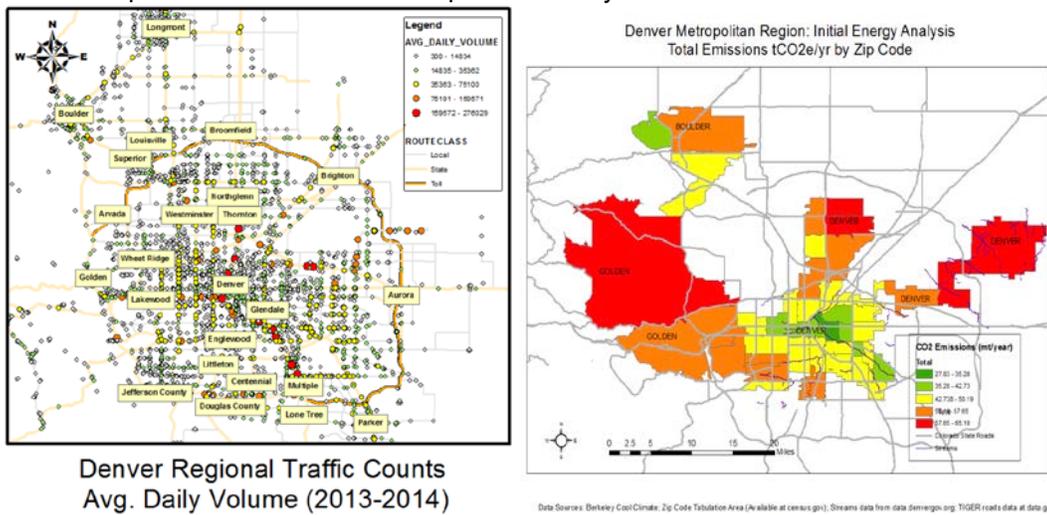Avg. Daily Volume (2013-2014)

Figure 12 Spatially mapping Denver regional traffic counts and energy analyses
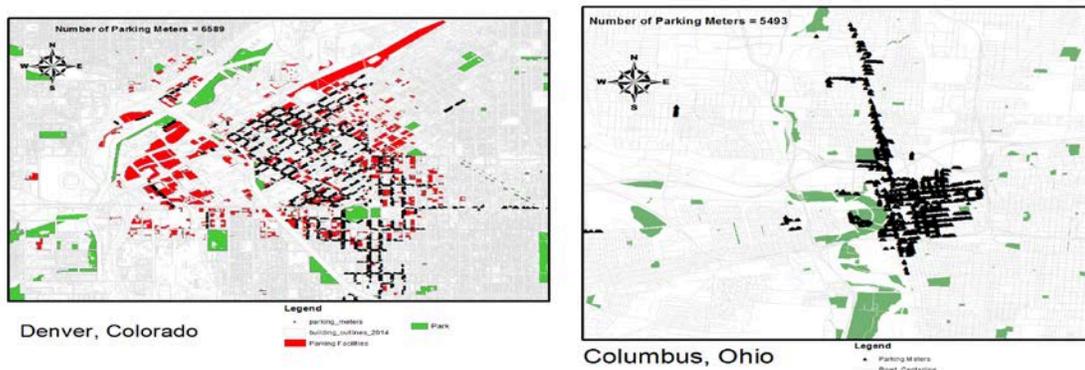

Figure 13 Comparisons of City Parking (initial analysis) and Pricing (future analysis)
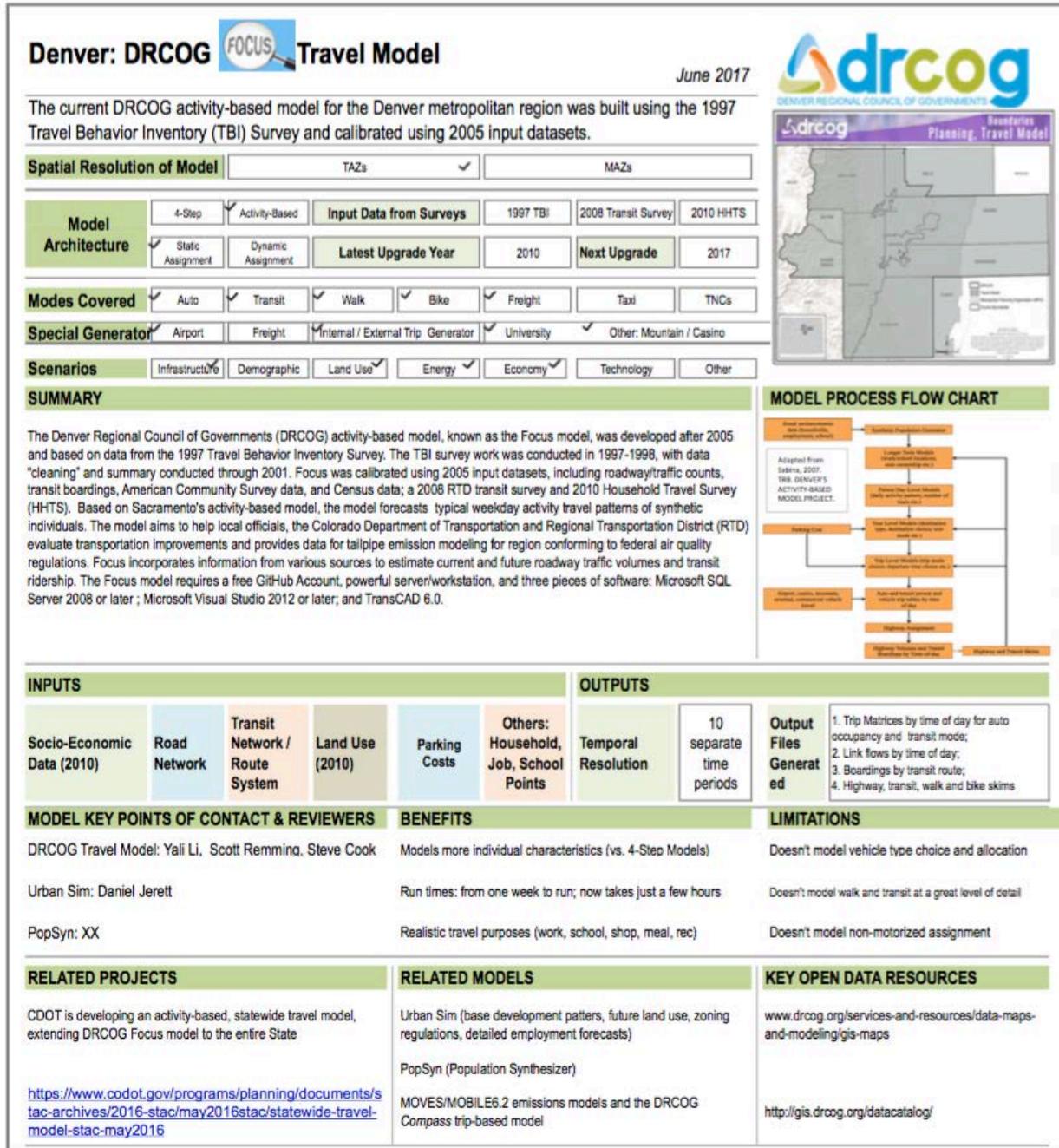
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For Columbus, and in their Smart City application, the following indicators were proposed as related to existing performance-driven and outcome-oriented city goals and targets:

- Reduce the crash rate by 15% by 2035 (energy impacts of lower speed limits?)
- Reduce commuter drive-alone rate from 84% to 78% by 2035 (shared mobility)
- Increase the percent of population within ¾ mile from bus stop from 69% to 80% by 2035 (maximizing transit accessibility for energy savings)
- Increase the percent of population within ¾ mile from bikeways from 62% to 80% by 2035 (maximizing mobility/accessibility for energy savings)
- Increase density of population and jobs within ¾ miles of arterials from 4.1 to 6.0 people and jobs per acre (maximizing density for energy savings).

Mapping data and models: Table 3, as initial comparisons of urban transportation models, evolved into the initial creation of model "profiles" (Figure 14), as a consistent template for model leads in each city to input consistent information. This exploration helps to compare changes in models over time. A next step in this analysis will be to compare and perhaps harmonize urban model scenarios considered.

Table 3 Subset of U.S. DOT Smart City Challenge finalists models: MORPC & METRO

Smart City Finalists: Travel Models	Key Features of Transportation Models
Mid-Ohio Regional Planning Commission (MORPC) Travel Demand Model for Columbus More at: https://drcog.org/documents/MORPC.pdf	**Activity-based platform** – daily activities undertaken by households/ persons (Note: this is typically missing in conventional travel models).
	Tour-based structure of travel where the tour is used as the base unit of modeling travel instead of the elemental trip; this structure preserves a consistency across trips included into the same tour, by such travel dimensions as destination, mode, and time of day.
	Microsimulation modeling techniques applied at the fully disaggregate level of persons and households
	Data inputs: Travel Survey database includes 1999 Household Interview Survey; On-board Transit Surveys; Parking Surveys; Land Use and Demographic/Socio-economic data
	Units of analysis: 1807 Traffic Analysis Zones (TAZs); 3 transit accessibility zones
Portland METRO Activity Based Model (ABM) More at: https://drcog.org/documents/portland_tour-based.pdf	**Activity-based platform –** One of first MPOs in U.S. to experiment with, and implement tour-based models
	Tour-based structure as three versions- V1) Developed for Travel Model Improvement Program (TMIP); used for regional congestion pricing study (identified as computationally burdensome / memory-intensive; V2) ABM with full synthetic population and Monte Carlo simulation of discrete choices; V3) Tour and Trip ABM using same zonal system for LOS data; more spatially detailed/inclusive of transit access (still being calibrated/validated).
	Modeling platform: resembling TRANSIMS modeling system
	Data inputs: Two-day activity diary survey in which respondents reported every activity with a duration of at least 30 minutes;
	Units of analysis: ~10,000 zones

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Figure 14 Characterizing regional travel models: a sample profile for City of Denver

City-based literature review on research / reports: Table 4 offers an example showing how this effort will include knowledge developed to date studying Smart Cities, mobility, and energy impacts with focus in each of the case study cities. The available papers and reports will also help to identify new data sets and explore data-driven responses by cities. New literature is emerging rapidly, e.g., a paper by Liu et al. (2017) focused on agent-based simulation of shared autonomous vehicles across the Austin, Texas, network. A web repository of available research and reports could help advance city efforts or technical analyses by other researchers interested in smart cities, mobility, and energy.

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Table 4 Summary table for city-based literature review (research and practice-oriented)

	Authors	Year	Title	Peer-Reviewed Research Publication	City and Region-Led Report Publication
Denver	Hillman and Ramaswami	2010	Greenhouse Gas Emission Footprints and Energy Use Benchmarks for 8 U.S. Cities	✔	
Columbus	MORPC	2016	2016-2040 Metro Region Plan		✔
Portland	Tufte and Kothuri	2008	Assessment and Refinement of Real-Time Travel Algorithms for Use in Practice		✔
Austin	Nichols and Kockelman	2015	Urban Form and Life-Cycle Energy Considerations: Case Studies at the City Scale	✔	

Discussion

The next steps in this effort will focus on further developing this study on additional curation of key data and models to understand energy impacts of changing urban environments and diffusion of key smart city "revolutions." The co-design of an online web platform and knowledge management system/process is a future anticipated effort for engaging and maturing data and model environments for use by and inputs from key Smart City stakeholders (allowing cities to volunteer information and data consistent with the model). The comparability of access to available open data, city indicator analytics, mapping data models, and available literature as an open-source resource has been validated as a useful "niche" resource to Columbus and the other Smart City finalists.

Future data integration, visualizations, and technical analyses addressing each of these tabs or boxes will be presented in an online web portal, in order to make knowledge management efforts easily available within across cities, for researchers and the U.S. DOE to accelerate planning and decisions on energy-efficient and sustainable urban mobility.

Conclusions

While this paper focuses primarily on examples from four of the U.S., DOT Smart City Challenge finalists, this effort will expand beyond Denver, Columbus, Austin and Portland to also develop analyses and comparisons with Pittsburgh, San Francisco, and Kansas City. Foundational research, analyses, and benchmarking across these cities can inform future smart mobility efforts and networks, e.g., the recently announced Aspen Institute/Bloomberg automated vehicle global initiative in 10 cities, with four U.S. cities: Austin, Texas; Los Angeles, California; Nashville, Tennessee; and Washington, DC (Decker, 2017). One shortcoming to informing city networks is the insufficient data available on the impacts of TNCs; with this data critically important to Smart City performance measurement, modeling the effectiveness of techno-economic interventions (e.g., shifts from ride-hailing to ride-sharing), and data-driven governance.

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