SCOPE: Smart-city Cloud Based Open Platform and Ecosystem

NSF Partnerships for Innovation: Building Innovation Capacity (PFI:BIC) Award #1430145
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2016 Annual Report

Project Abstract

This NSF Partnerships for Innovation: Building Innovation Capacity (PFI:BIC) project from Boston University will research, prototype, and evaluate novel "smart-city" services for the city of Boston and for the Commonwealth of Massachusetts. The centerpiece of the project is a Smart-city Cloud-based Open Platform and Ecosystem (SCOPE), which creates a multisided marketplace for smart-city services based on the Open Cloud eXchange model, in which stakeholders compete and cooperate within the same infrastructure. By harnessing breakthroughs in cyber-physical, mobile, and cloud computing technologies, and by building upon novel data acquisition and mining capabilities to be developed by the investigators and their industrial partners, SCOPE-enabled smart-city services will address challenges faced by twenty-first century cities: connecting people with resources, guiding changes in collective behavior, and supporting innovative transportation, healthcare, energy distribution, and emergency response solutions, as well as business, commerce, and social applications. SCOPE's broader impacts include providing a template for widespread experimentation with and adoption of smart-city services by other cities in Massachusetts and beyond; accelerating technological innovation, commercialization, and business development; breaking technological and institutional silos; facilitating institutional transformations and deep citizen engagement; and development of curricular content and projects that leverage smart-city big-data platforms.

The implementation of SCOPE entails the design and prototyping of new techniques and novel application programming interfaces, adding capabilities that are currently not available in public cloud offerings, including (a) support for predictable operation of cyber-physical systems in support of sense-and-respond real-time applications; (b) management of data quality and provenance attributes in support of applications that fuse potentially noisy data from multiple trusted and untrusted sources; and (c) incorporation of security-enhancing services in support of privacy-preserving analytics. In addition to the design and prototyping of SCOPE, the investigators and their collaborators will work with partners to develop specific SCOPE-enabled smart-city services, including (d) transportation and mobility services to reduce traffic congestion, save time and wasted fuel, and reduce pollution; (e) energy and environmental services that monitor/estimate greenhouse gas emissions for congestion management and coordination of smart-grid energy demand-response solutions; (f) public safety and security services for big-data-driven coordinated scheduling of public works and municipal repairs; and (g) tools for management of city assets through mining of large data sets and crowd-sourced coordination of asset use. Additionally, the investigators will investigate and evaluate various (h) social, institutional and behavioral mechanisms to facilitate adoption of new services, such as incentive programs and community report cards to promote transparency and sustainability.

Through the Hariri Institute for Computing at Boston University, SCOPE will be led by investigators from multiple disciplines including Computer Science, Systems Engineering, Earth and Environment, and Urban Planning. Once developed, SCOPE services will be offered through the Massachusetts Open Cloud, a new public cloud designed and implemented through the Green High-Performance Computing Center (Holyoke, MA) and supported by the Massachusetts Technology Collaborative (Westborough, MA). Industry partners include two large businesses: Schneider Electric (Palatine, IL) and International Data Corporation, an IDG subsidiary (Boston, MA), and three small businesses: Integrated Technical Systems (Wallingford, CT), Connected Bits (Bedford, NH), and CrowdComfort (Beverly, MA). Public sector partners include the Commonwealth of Massachusetts Office of the CIO, City of Boston, Metropolitan Area Planning Council, and the Metropolitan Planning Organization (Boston, MA).

Project Web Site

http://www.bu.edu/hic/research/scope/

Project Activities

Overall Goal

Twenty-first century cities are increasingly being challenged -- to respond to diverse constituent needs, to prepare for major environmental changes, to improve urban quality of life, and to foster economic development. Today's "smart cities" are closing these gaps by leveraging the rapid technology innovations that present potentially transformative opportunities -- for connecting people with resources, guiding changes in collective behavior, and facilitating economic innovation. To address these challenges and opportunities, Boston University SCOPE project is leveraging a unique partnership between researchers, private sector and public sector stakeholders to create a new eco-system -- of stakeholders, technology, organizations and information.

SCOPES's goals are to enable urban stakeholders to harness, learn, innovate and monetize 'big data assets; spur a generation of new public and commercial goods; innovate with state-of-the-art technology, sensor-based information and plug-and-play architectures; and create new spaces for public [data-driven] policy debate, and enhance and innovate quality and equity of services.

Major Thrusts

The research activities undertaken as part of this project focus on the following thrusts:

Development of Applications and Use Cases Informing the Design of SCOPE

These are the applications and services, which will be deployed on (or will leverage) SCOPE as targeted/early use cases, thus informing the design of SCOPE's various interfaces and functions. These use cases could be services intended for use by individuals (city residents and dwellers) or institutions (planners and policy-makers). These use cases leverage prior and on-going research work by the PIs.

SCOPE-Enabled Cross-Cutting Services and Collaborative Governance Applications

In contrast to the "siloed" applications and services discussed above, in this thrust we focus on SCOPE-enabled cross-cutting applications and services that integrate data from multiple sources to enable a new range of capabilities that are impossible to entertain without SCOPE. In addition to implementing these cross-cutting services, we are also studying how data sharing may impact organizational and institutional configurations (and provide a setting that allows related issues to be analyzed). Some of these cross-cutting services have emerged organically based on real opportunities, needs, and experience, (which illustrate the essence of a platform: it is a catalyst for innovation and not a determinant of innovation).

Key Capabilities and Application Programming Interfaces in SCOPE

This thrust is concerned with the development of the key features, attributes, and capabilities in SCOPE, including data quality management services, security and integrity services, provenance services, privacy and anti-piracy services, software stacks for CPS clouds. The motivation for these attributes of the SCOPE platform stems from the various requirements of the smart services discussed in the above thrusts.

The following are specific project activities pursued this past year with direct support from this award. They are grouped within the three research thrusts of the project described above.

A. End-User Services Informing the Design of SCOPE

   A.1 Data Driven Traffic Analysis and Control
   A.2 Smart City Mobile Apps

B. SCOPE-Enabled Cross-Cutting Services and Collaborative Governance

   B.1 Traffic Management for Sustainability
   B.2 Data-driven Public Safety Applications
   B.3 Coordination of Crowdsourced Resources
   B.4 Participatory Planning and Organization

C. SCOPE Capabilities and APIs

   C.1 Mobility Index Analytics
   C.2 Secure Multi-Party Analytics

Activity Descriptions and Findings

For each project listed above, we provide a short synopsis: the co-PIs leading the project, contributors to the project, as well as the start date (and end date, if the project is concluded) and a project description. The current technical results, findings, and conclusions associated with each one of the projects are also detailed.

A.1 End-User: Data Driven Traffic Analysis and Control

Lead: Cassandras (Co-PI)
Status: Started September 2014, ongoing
Participants: Pourazarm, Zhang, Fleck (PhD'16), Khazaeni (PhD'16)

Synopsis

The tasks performed under this activity are all aiming at dynamic and adaptive management and optimization of traffic flows, including the support of new objectives, such as the consideration of constraints imposed by new services (e.g., electric vehicle charging stations and smart parking infrastructures).

The dynamic traffic regulation we are pursuing does not merely control traffic lights but sets more ambitious goals such as avoiding large fluctuations in kinetic energy (across all vehicles in the city) in an attempt to minimize fuel consumption and pollution. Our primary SCOPE industrial partner (Schneider Electric) has considerable expertise in this area and our plan is to pursue this direction in collaboration with the City of Boston.

Subject to any given traffic regulation scheme, the question of what would be the optimal routing for a given objective must be addressed. Along these lines, there are two innovative aspects to our traffic routing approach. First, we incorporate Electric Vehicles (EVs) which face energy constraints and must plan routes that include possible recharging. Second, we seek to optimize a system-centric (socially optimal) objective criterion rather than the usual user-centric (selfish) one.

In order to test our traffic regulation and our route optimization approaches, we use real-traffic data sets (collected by INRIX and made available to us through the City of Boston) to build models that allow us to derive vehicle flows by location and by day and time of day. This information is then fed to a detailed traffic simulator so as to evaluate the effectiveness of traffic light control and traffic routing policies we are developing. At the same time, these data will be incorporated into the SCOPE platform for visualization.

Findings for 2015

For traffic regulation, we developed a number of adaptive traffic light controllers through which red/green light cycles are dynamically adjusted so as to minimize various congestion metrics. Results obtained for simulated urban settings in 2015 show congestion reductions of about 50%.

For our optimal routing work, we obtained system-optimal routing policies for both EV and non-EVs grouped into vehicle “subflows” and developed an approach for determining the desired number of such subflows.

Findings for 2016

For traffic regulation, we extended our traffic light controllers to be quasi-dynamic, i.e., based on partial state information defined by detecting whether vehicle backlogs are above or below certain thresholds. Using infinitesimal perturbation analysis methods, we have derived online gradient estimators of a congestion metric with respect to the controllable light cycles and threshold parameters and used these to iteratively adjust all controllable parameters through an online gradient-based algorithm so as to improve the overall system performance under various traffic conditions, with results tested in simulated urban settings.

For our optimal routing work targeting metropolitan (rather than strictly urban) areas, we turned attention to the 55G dataset of one-year’s worth of traffic data in Eastern Massachusetts roadways provided to us by the Boston Region Metropolitan Planning Organization. Assuming that the observed traffic data correspond to user (Wardrop) equilibria for different times-of-the-day and days-of-the-week, we formulated appropriate inverse optimization problems to recover the per-road cost (congestion) functions determining user route selection for each month and time-of-day period. We then formulated a system-optimum problem in order to find socially optimal flows for the network. We investigated the network performance, in terms of the total latency, under a user-optimal policy versus a system-optimal policy. We have found that the ratio for many road segments and different times of day is often in the 1.3-1.6 range, implying that there is an opportunity to significantly improve traffic conditions by properly managing flows. This can be accomplished using optimal flow methods developed in 2015.

A.2 End-User: Smart City Mobile Apps

Lead: Christos Cassandras (Co-PI)
Status: Started September 2014, ongoing
Participants: Pourazarm, Zhang, Fleck (PhD'16), Khazaeni (PhD'16)

Synopsis

There are three tasks performed under this activity: Sensing and Classifying Roadway Obstacles using Street Bump, Smart Parking, and EV Charging Station Management.

The Street Bump project was initiated by the City of Boston to collect roadway obstacle data from sensors embedded in citizens' commercial cell phones to geo-locate "bumps" to be fixed. The term "bump" is generically used to describe such items as potholes and sunk castings substantial enough to be sensed by a driver and potentially cause damage to a vehicle. The ultimate goal is to distinguish between "actionable obstacles" and less serious or unavoidable ones (*e.g.*, cobblestone, speed bumps), allowing the City to prioritize how to allocate its resources for both short-term and long-term planning purposes. We exploit the ubiquity of cell phones and the sensors (accelerometers and GPS) embedded in them. "Street Bump" is a free iPhone app developed by our partner Connected Bits which enables the collection of roadway data while a vehicle with the phone in it is in motion. These data are collected and processed so as to achieve the goals mentioned above.

We have developed and implemented a prototype Smart Parking system currently operational in a Boston University facility. This system determines the best parking space for a driver in an urban environment for any given destination entered through a smartphone app. It then reserves the space for the driver. Standard GPS technology is used to guide the vehicle to it. The "best" space is based on criteria specified by the driver that combine proximity to destination with parking cost, while also ensuring that the overall parking capacity is efficiently utilized. Thus, besides the obvious convenience to drivers, the system reduces traffic, as well as fuel consumption and pollution. SCOPE will enable its broader use through extensive data from the City and collaboration with our partners Schneider Electric and ITS (through its subsidiary mPay2Park) for citywide deployment.

The principles of the Smart Parking system discussed above can be used for an optimal allocation and reservation system for Electric Vehicles (EVs) at charging stations distributed in an urban environment. The system assigns and reserves an optimal space at a charging station based on the user's cost function and then guides the user to that station (or a better station if a space there becomes available). We note that the limited range of EVs, coupled with the low density of charging stations in most urban areas, makes prompt and accurate directions to charging stations critically important. SCOPE, in this case, will not only provide the charging station data necessary, but also grid data to develop the coordination and scheduling required for a truly "smart" interaction between EVs and the grid.

Findings for 2015

We developed algorithms for processing Street Bump data, classifying roadway obstacles into predefined categories and identifying actionable ones in need of immediate attention based on a proposed "anomaly index." The novel "anomaly index" allows us to prioritize among actionable obstacles. Results on an actual data set provided by the City of Boston illustrate the feasibility and effectiveness of this system in practice.

We completed a pilot test at a Boston University parking facility using sensors located at individual parking spaces. We are also studying how to upload data from the Street Bump iPhone app to the SCOPE platform.

We also completed a simulation study of a charging station management system.

Findings for 2016

We extended some of the data analytics previously developed for the Street Bump system and developed new algorithms. We have also launched a new task inspired by our analysis of the 55G dataset described under A.1. to create a Smart City app which allows for contrasting actual traffic flows to the "best possible" achievable ones. As data become available for subsequent years, the same app can be used on a by-year basis and on a per day and time-of-day basis for any desired road segment and path that a user may be interested in.

B.1 Cross-Cutting: Traffic Management for Sustainability

Lead: Lucy Hutyra (Co-PI)
Collaborators: Scott Peterson, Boston Metropolitan Planning Organization
Status: Started September 2014, ongoing
Participants: Gately (PhD'15, Postdoctoral Fellow)

Synopsis

On-road transportation accounts for 28% of total U.S. CO_2 emissions and is the most uncertain source of CO_2, as vehicle activity is constantly changing across time and space. In addition to greenhouse gas emissions, the transportation sector is responsible for 75% of CO and 60% of NO_x emissions, two important criteria air pollutants that contribute to low-level ozone formation and increase the risk of respiratory disease and other negative health outcomes. We integrate multiple large, heterogeneous datasets to dramatically improve the characterization of transportation sector emissions at both national, regional and local scales.

Findings for 2015

We completed the development of a new national emissions inventory, the Database of Road Transportation Emissions (DARTE), which estimates CO_2 emitted by US road transport at a resolution of 1 km annually for 1980–2012. DARTE reveals that urban areas are responsible for 80% of on-road emissions growth since 1980 (63% of total 2012 emissions). This analysis (Gately et al. 2015) garnered national press coverage, including The Atlantic and Scientific American (September 2015) and has been downloaded over 1,000 times for additional analysis. The DARTE dataset is one of the most highly downloaded datasets held at the Oak Ridge National Laboratories Data Active Archive Center (ORNL DAAC).

Findings for 2016

In parallel with the completion of the national analysis we developed a roadway-scale model of vehicle emissions of both CO_2 and five additional air pollutant species (CO, NO_2, NO_x, SO_2, $PM_{2.5}$), for the greater Boston metropolitan area in close collaboration with the Boston Metropolitan Planning Organizations (Boston MPO). Our model integrated EPA and Boston MPO vehicle and travel models, road sensor measurements of traffic, and a very high resolution dataset of actual vehicle travel speeds at 5-minute intervals derived from mobile phone and vehicle GPS data provided by the traffic consultancy INRIX. The final high-resolution inventory quantifies pollutant emissions at hourly time scales for every road in eastern Massachusetts. We used the inventory to identify spatial and temporal "emissions hot spots" where combinations of vehicle activity and traffic congestion produce large amounts of pollutant emissions. We also identified key traffic corridors where traffic congestion is responsible for localized pollution enhancements of over 75% above normal traffic levels.

Illustrations and additional details of this work can be found in the Appendix.

B.2 Cross-Cutting: Data-driven Public Safety Applications

Lead: Evimaria Terzi (Co-PI)
Status: Started January 2015
Participants: Frederick Joossens (Software Engineer)

Synopsis

Online and mobile apps are used extensively for routing from one point in the city to another. Such applications (e.g., google maps) allow the users to set many of their preferences, including information about what means of transportation they are willing to use. In many settings, solving the shortest path problem is not adequate. For example, consider a user interested in a bike route that avoids dangerous intersections, avoids roads where competition with vehicular traffic at rush hours may be hazardous, or avoids streets that are not well-lit at night, or with poor drainage in rainy conditions, etc. Clearly, the consideration of such objectives goes well beyond shortest-path routing. By combining information about the characteristics of different paths, it is possible for routing applications to recommend routes that balance these characteristics, using bi-criteria shortest-path optimization techniques. We note that the same mechanisms and algorithms developed for safe routing could also be adapted for use by police patrols to map out optimal coverage of city streets (whether by foot, on bikes, or in cars). Here the objective would be reversed: rather than choosing the safest routes, police assets would be directed to locations and routes where police presence is most influential.

Findings for 2015

PI Terzi has worked on the implementation and the transferring of route-recommendation algorithms within the context of a platform that users can use. The main idea behind this effort is to create a platform for route recommendations to users so that people can insert different datasets (e.g., datasets that incorporate different features such as distance, crime rates etc.) and the system will adapt its recommendations to the input data. At the same time, the platform will be flexible so that different developers can incorporate and test their different routing algorithms. As a first step towards generating this platform, we have focused on providing alternative route recommendations to users so that the suggested routes take into account two objectives: (a) the distance between the source and the destination and (b) the safety of the route as computed using crime data from the city of Boston website (available here: https://data.cityofboston.gov/). Illustrations of the platform are provided in the Appendix. A first prototype of this work is now available in the BU network at: http://sail.bu.edu/safenav. Steps are underway to make it available to the public.

Findings for 2016

We have worked on speeding up the route-recommendation algorithm with the goal of improving the user experience of our platform. Elements of our work that were incorporated into the SCOPE platform were instrumental in the student projects developed during the first iteration of the Data Mechanics course on urban data science. These projects addressed questions of public safety, including an application that characterized bike routes by safety according to pot hole data, analyses that aimed to determine whether there are correlations between urban lighting and crime incidence, and neighborhood classification and scoring systems that aimed to incorporate data on availability of healthcare facilities, crime incidence, and other factors.

B.3 Cross-Cutting: Coordination of Crowdsourced Resources

Lead: Azer Bestavros (Project PI)
Status: Started March 2015 and Completed May 2016
Participants: Christine Bassem (PhD'16)

Synopsis

Exemplified by the StreetBump application, crowdsourcing – i.e., using capabilities and resources of crowds of end users – has significant potential for many smart-city applications that can leverage the location in space and time of users to achieve specific tasks, which can range from taking a picture, passively sensing their environments, delivering a package, or sharing a commute. In all such applications, the key resource being offered is the "Geo Presence" of a participant in a particular location at a particular time. As such, a key envisioned capability of SCOPE is to allow the management of this resource – namely how to coordinate the geo-presence of crowdsourced mobile resources in order to satisfy some required functionality (e.g., efficient package delivery or uniform sampling of city streets) subject to constraints imposed by owners of these resources (e.g., preexisting planned routes). To support Geo Presence as a Service (GPaaS) requires the development of APIs for route coordination and management which can be readily used by applications built on top of SCOPE. More importantly, this capability also requires the development of economically-sound, incentive-compatible mechanisms that allows participants to monetize (or otherwise derive value from) their Geo-Presence. While the coordination of crowdsourced resources is a general problem, in this project, and given the emphasis on mobility in a smart-city setting, we are focusing our attention to route coordination problems as instances that leverage GPaaS.

Findings for 2015

We have developed an incentive compatible route coordination mechanism, in which participating mobile agents satisfy geo-temporal requests in return for monetary rewards. We define the Flexible Route Coordination (FRC) problem, in which an agent's flexibility is exploited to maximize the coverage of a mobility field, with an objective to maximize the revenue collected from satisfied paying requests. While we have shown that the FRC problem is NP-hard, we were able to define a variant of the problem – namely, route planning for a single agent in a graph with evolving labels -- for which an optimal algorithm can be applied. We used this optimal algorithm to obtain a 0.5-approximation of the solution to the general FRC problem (with multiple agents). More importantly, we defined an incentive compatible, rational, and cash-positive payment mechanism, which guarantees (in a game theoretic sense) that an agent's truthfulness about its flexibility is an ex-post Nash equilibrium strategy.

In addition to developing the mechanism and analyzing it theoretically, we have also implemented it and evaluated its performance and scalability experimentally using historical mobility traces from urban environments in San Francisco, which we plan on repeating using traces obtained from the city of Boston, and eventually deploying as a feature of the SCOPE platform for in vivo use by applications that seek to leverage GPaaS while providing incentives (payment, credit, or otherwise) to participating end users.

Findings for 2016

The generality of the mechanisms we have developed allows us to also apply them in very different settings, including for cloud workload brokerage applications which require the coordination and pricing of data center resources. We have extended our work in that direction resulting in a number of novel algorithms for scheduling and coordination of crowd-sourced resources both in urban settings (e.g., for vehicular routing and for geotagging) as well as for brokered cloud workload management.

B.4 Cross-Cutting: Participatory Planning and Organization

Leads: Katherine Lusk (Senior Personnel) and Paul McManus (Senior Personnel)
Status: Started September 2014, ongoing
Participants: Andrei Lapets (Collaborator), Frederick Joossens (Software Engineer)

Synopsis

The City of Boston, a key stakeholder in SCOPE, and Boston University, represent two distinct sectors with their own functions, cultures, with their own languages, incentive structures and organizational processes. For the SCOPE eco-system and platform, Sr. Personnel Lusk is building a 'bridge' connecting the two, ensuring that to identify and remove barriers to engagement and implementation, work with and motivate the right stakeholders and keep each side attune to the others' needs. This is especially needed as the City lacks the resources for any kind of dedicated participant (e.g. project manager or gatekeeper responsible for managing the relationship between the University and the City in relation to SCOPE.) In addition, this activity is to help to advocate for the institutional change necessary within the City to effectively receive and implement the innovations and tools that emerge from SCOPE. The ultimate goal is to ensure a sustainable life for the services and products of SCOPE at the completion of the project.

More broadly, the organization of the SCOPE project is by design a unique, multi-stakeholder and cross-sector collection of participants. Thus, the development of guidelines for the design, governance structure and economics of the platform form an organizational standpoint is an important activity of the overall project.

Findings for 2015

Ongoing discussions and meetings to facilitate numerous City of Boston participants is enabling development of SCOPE work involving the City of Boston. In conjunction with an evaluation to participate in the Metro Lab Network convened by the White House Office of Science & Technology, developing new methods of collaboration between area universities and the City of Boston. Consolidated feedback provided from ten BU faculty who work in close partnership with the City on ways in which to improve partnership between the City and the University.

Based on an analysis of the outcomes of a brainstorming workshop, we were able to validate that SCOPE has naturally structured itself as multi-sided, cross-stakeholder platform where its member have critical development questions to be centered in the areas, organizational architecture, organization governance and the intra-community issues of financial and information economics. The Appendix provides a mapping of the comments and keys issues raised during the workshops and is a key outcome of the workshop.

Findings for 2016

Senior Personnel Lusk and Collaborator Lapets worked to identify and engage several City of Boston department and Mass DOT stakeholders to identify opportunities to "unlock" City data. Students from the Data Mechanics course, supervised by Lapets, worked with these data sets from the City to answer questions, perform analyses, and solve problems related to the organization and characterization or urban resources in Boston. A key outcome was incorporating these projects into the unifying SCOPE prototype platform.

Planning is underway for a broad SCOPE stakeholder meeting for an update on project outputs, including the City Data Mechanics student projects, and brainstorming and prioritization around new potential opportunities based on new tools and platform that have emerged. Further, with the recent arrival of the

City of Boston's first Chief Data Officer Therriault, it is on the horizon to position BU SCOPE as a key engagement tool with his Citywide Analytics Team.

C.1 SCOPE Capabilities: Mobility Index Analytics

Lead: Azer Bestavros (Project PI)
Status: On-going (started September 2015)
Participants: Evimaria Terzi (Co-PI), Dora Erdos (PhD'15), Nisreen Dahod (MS'15), Benjamin Lawson (CAS'17), Frederick Joossens (Software Engineer), and Katharine Lusk (Senior Personnel).

Synopsis

The genesis of this project was from the first SCOPE workshop in Oct 2014. At the time, the Director of Planning, in the City of Boston, explained his goal to "enable the City of Boston to transparently assess its performance over time in sustainably improving the mobility of its residents across three key dimensions: equity of access, economic impact and climate impact." Since that time, it has become evident that a singular or universal definition for such an index is elusive. Rather, any working definition for such an index must flexibly allow a range of attributes along multiple dimensions (e.g., climate attributes, sustainability attributes, affordability attributes) to be specified and appropriately weighted relative to one another. Towards that goal, this project aims to create a flexible framework for a mobility index to be expressed and visualized, allowing multiple definitions and calculation of a host of metrics (not just one) that can change over time. These metrics, when combined, allow us to assign score to an objective criterion stated in plain English for a resident, planner, or policy maker – for example "a high mobility index score reflects a neighborhood with clean air and access to multiple, affordable, efficient, safe transportation options which can convey residents to a multitude of high-paying job opportunities and are not vulnerable to catastrophic weather events." Thus, one has to map such statements to a set of concrete metrics – a score for clean air, a score for efficiency and/or cost of multiple forms of transportation (walking, biking, driving, buses, public, …), a way to represent distance to where the jobs are (or where entertainment, schools, etc. are). This suggests a framework that offers an "API" that allows any (or at least a very large number of) definitions to apply. More importantly, such an API should allow such metrics to be computable at different levels of aggregation, whether spatial (street address vs neighborhood vs city) or temporal (weekday, month, season).

Findings for 2015

We have developed the blueprints of a computational model upon which mobility indices could be defined and efficiently evaluated. The model represents any locale as a graph, with nodes representing points of interest (e.g., intersections) and edges representing "distances" between these nodes where distance could specify a variety of attributes (depending on purpose of model). For example, one can attach a dollar figure to an edge (suggesting cost of transportation between nodes) and to a node (suggesting the average pay for jobs at the nodes). As another example, one can attach to an edge an amount of time (suggesting average travel times between nodes) or a capacity metric (suggesting maximum number of people per unit time that can move between nodes). With that in mind, there are many powerful graph algorithms that one can leverage to enable the calculation of very expressive and informative mobility indices. For example, looking at such graphs as "flow graphs" allows us to use algorithms such as max flow or min cut to assign cores to subgraphs and/or to express very powerful notions (e.g., evacuation capacity).

During the 2014/2015 reporting period, we have developed a number of algorithms that allow for new mobility index analytics to be defined and evaluated. In particular, we focused on the efficient evaluation of "group centrality" metrics. The notion of centrality of the nodes in a network has been key in analyzing different types of network. Typically, high-centrality nodes are those that impact/shape most of the observed traffic. Measures for quantifying the centrality of a node in a network date back to the 1950s. The common characteristic of these measures is that they quantify a node's centrality by computing the number (or the fraction) of (shortest) paths that go through that node. For example, in a navigational network, a node with high centrality is one that "sees" (and potentially controls) most of the traffic. In many applications, the centrality of a single node is not as important as the centrality of a group of nodes. For example, in a smart-city setting, one might want to measure the combined centrality of a particular group of street locations as candidates for Hubway parking stations, or the combined centrality of a group of intersections as candidates for installing security surveillance. For such applications, the notion of centrality needs to be generalized to measure the centrality of groups rather than single nodes. The technical difficulty of such generalization comes from the fact that the centrality of a group is not simply the sum of the centralities of its members; two nodes that lie on the same set of shortest paths have the same centrality as the centrality of a group consisting of one of these nodes. Along these lines we have developed new efficient techniques to compute these types of mobility analytics. The generality of the algorithms we have developed allows us to also apply them in very different settings, including for social networks and for cloud and Internet applications.

Starting in May 2015, we have also embarked on the development of a data collection platform that allow us to measure in real-time the mobility of individuals in the City of Boston as reflected through geotagged content and/or media they share through the blogosphere and through social networks. This source of data (along with APIs to facilitate its use for mobility index analytics) complements nicely the more static data sets available from other sources (such as traffic loop counts and/or aggregate volume of passengers on various subway/bus routes, etc.) In particular, a key advantage of using social media as a source of mobility information is that it allows for the consideration of individual (as opposed to aggregate) patterns, flows, and statistics.

Findings for 2016

This year we have expanded the data collection process and plan to use this data to develop new algorithms for route recommendation and the development of the mobility index. The data collection process has resulted in rich datasets from main social-networking websites like Twitter and Instagram; in addition to Boston we expanded our data-collection effort to other cities, for example, Austin and San Francisco. First, using the history of users we classified the content produced into two classes: content that was produced by locals and content that was produced by tourists of a city. In order to get accurate classification results we looked at the history of the geotagged content produced by users and we classified as locals to city X all users that have been consistently posting from city X for a long period of time (more than 6 months). This classification of the geotagged content allows us to measure the activity (in terms of produced content) associated with different locations in a city. This also allows us to identify hotspots for both locals and tourists. Although such hotspots are visually evident, we are currently working on the development of an algorithm that will automatically find them. Using this information, we can improve recommendations for both local citizens and tourists visiting a city (This is also related to Activity B.2). In addition, this knowledge will enable us to integrate this information into our mobility-index definition.

Several student projects developed during the first iteration of the Data Mechanics course on urban data science also represent a contribution towards the data collection process and the instantiation of mobility indices. The projects themselves, dealing with issues such as accessibility, bicycle route safety, and public transport resource allocation, represent not only possible instantiations but also possible real-world uses of mobility indices. Each project involved the creation of reusable scripts that can retrieve the latest data sets from sources such as the City of Boston Data Portal and the MBTA Developer Portal. In particular, data can be obtained from 311 service call records, public work zone listings, filtered police department records (e.g., to identify those dealing with bicycle collisions), street light locations, and many others. All the projects conform to a uniform framework, allowing all the retrieved data sets to be queried collectively and processed using optimization and statistical analysis algorithms.

C.2 SCOPE Capabilities: Secure Multi-Party Analytics

Lead: Azer Bestavros (Project PI)
Status: On-going (started November 2014)
Participants: Nikolaj Volgushev (PhD Student), Andrei Lapets (Postdoctoral Collaborator), Kyle Holzinger (CAS’16), Eric Dunton (CAS’15), Frederick Joossens (Software Engineer), and Katharine Lusk (Senior Personnel).

Synopsis

To facilitate the development of applications that leverage data assets from multiple organizations or agencies, there is a need to extend popular, scalable data analytics platforms to allow for computation to be done without requiring constituent organizations or agencies to “share” or “release” their data assets. Towards that goal, secure Multi-Party Computation (MPC) is a promising approach that allows a group of organizations (or parties) to jointly perform a desirable computation without having to release any of the privately held data assets on which the computation is to be performed. More specifically, secure MPC allows a set of parties to compute a function over data they individually hold (the private inputs) while ensuring that the only information that can be gleaned is the result of the function evaluation as opposed to the private inputs to this function (unless such function “leaks” these inputs). Secure MPC has been an active area of cryptography research for over 30 years. While incredibly powerful (and elegant), secure MPC has remained mostly a subject of academic interest, with significant advances made in the last few years to bridge the theoretical underpinnings of MPC (how to compute universal functions) to the applied aspects of MPC (how to efficiently compute specific functions or algorithms). The goal of this project is to take these advances to production scale by extending a highly popular programming paradigm – Hadoop MapReduce. Our Secure Multi-Party MapReduce platform will enable seamless MPC across multiple organizations using their virtualized cloud resources and data assets by extending Hadoop/Map-Reduce AWS platform to instantiate an architecture that leverages MPC libraries such as VIFF and Sharemind.

Findings for 2015

Starting in Fall 2014, we joined forces with the Boston Women’s Workforce Council to use SCOPE’s secure MPC as a platform for supporting the “Boston Women’s Compact” (BWC) – a voluntary agreement in which businesses pledge to take concrete, measurable steps to eliminate the wage gap and to report their progress anonymously every two years. Over 60 businesses have signed on to BWC, including key Fortune 500 companies such as EMC, State Street, Raytheon, and Mass Mutual. The key technical challenge for the compact was to enable the calculation of pay gap analytics (at the aggregate level) without revealing the presence or extent of such gaps in any of the participating businesses: companies’ payrolls are proprietary, because their disclosure could be a boon to competitors, a black eye for the firms, and ammo for disgruntled employees who could sue over pay inequities. Even if firms could trust a third party to look at their numbers and calculate industry averages, hackers might breach that party’s online security and steal these precious informational nuggets. This particular application provided the initial motivation for the development of the MOC capability in SCOPE, which is envisioned as a capability to be used in many other similar settings where “social good” can be derived from the use of MPC over privately-held and highly-sensitive data assets.

An initial implementation of SCOPE secure MPC capability was started in January 2015 and completed in March 2015. The design and implementation was discussed and subjected to significant scrutiny and eventually approved by various city and state agencies, and most importantly by the legal and IT leadership in all participating businesses. A prototype application developed using this initial platform capability has been implemented and tested in May 2015. The application was deployed and used by over 40 of BWC signatories on June 8th 2015 to compute the BWC major pay equity aggregate statistics, the results of which are expected to be published in a report the Boston Women’s Workforce Council in August 2015. There was significant coverage of this successful use of the platform to enable BWC in local and national newspapers, which was hailed as a “the game changer” by Boston’s Mayor Marty Walsh and by Evelyn Murphy, the former lieutenant governor and member of the Boston Women’s Workforce Council.

Recognizing the value of secure MPC for SCOPE, starting in June 2015, we are embarking on a more ambitious goal of integrating SCOPE’s MPC capabilities into a staple of data analytics – the Hadoop MapReduce platform. This will enable the platform to be used on much larger data sets from a larger set of parties, and using a highly popular computational platform that is widely adopted in industry.

Please find an illustration of this work in Appendix 3.

Findings for 2016

In Fall of 2015, we began work on a more general MPC platform that could scale to very large data sets that are spread across multiple organizations. A prototype of a distributed computational infrastructure and associated high-level programming language were implemented. This infrastructure allows multiple parties to leverage their own computational resources capable of supporting MapReduce operations in combination with MPC (implemented using Viff in the prototype, but compatible with other systems such as Sharemind). The infrastructure allows a programmer to author and compile a protocol using a uniform collection of standard constructs, even when that protocol involves computations that take place locally within each participant’s MapReduce cluster as well as across all the participants using an MPC protocol.

Defining algorithms that use MPC is a challenge for analysts who wish to perform data analyses. Further, releasing data for analysis (even using MPC) can be a challenge for data contributors. We have begun investigating the possibility of supporting policy-agnostic analysis algorithms that can later be automatically parameterized with the particular privacy requirements associated with their input data. This requires the development of a static analysis inference algorithm that can be used to determine possible policies that can be supported by a given policy-agnostic analysis algorithm definition.

In Spring of 2016, the earlier implementation of a lightweight, web-based MPC application for computing aggregate analytics was improved to address usability and compatibility issues. After these improvements were implemented, the application was successfully deployed and used by about 70 BWC signatories on May 20th, 2016 to compute the BWC major pay equity aggregate statistics. Alternative prototypes of the application (that could support more general analytics algorithms) were also constructed using underlying systems such as Viff, in order to investigate how off-the-shelf tools can be used to extend the power of the web-based MPC application.

Broader Impacts

Overview

SCOPE is not only breaking down technical and institutional silos across the public, private and academic sectors, it is also a data and curriculum-sharing platform that is breaking down disciplinary silos in the academic setting. At BU, there is a diverse range of programs that are involved in the project focusing on smart-city applications: the College of Engineering (ENG) Systems Engineering program, the Questrom School of Business, and the College of Arts and Science (CAS) Computer Science and Earth & Environment programs. In the private sector, we have a major partner, Schneider Electric along with smaller company participants. In the public sector, we have myriad stakeholders from the city, region and state, all contributing to the eco-system.

At the curricular level, there are tremendous opportunities for integrating our smart-city work into existing and new courses. For example, a new graduate-level computer science course on urban data science entitled “Data Mechanics for Pervasive Systems and Urban Applications” was developed and taught in Spring 2016. This course’s focus was on how data can move through institutions and computational infrastructures to inform decisions and operations within large systems such as cities. The course taught students to apply some of the tools and methods that facilitate data collection, retrieval, provenance tracking, integration, interpretation, and visualization with a particular focus on urban informatics. Another example, the Cloud Computing course was taught for a second year in Spring 2016 due to it’s strong reviews. It was also expanded to a joint Boston University/Northeastern University offering. Initially offered in 2015, the course has been developing significant new skills in cloud computing application development, critical technology that will enable the SCOPE platform. Within BU, this course was cross-listed with the College of Engineering (Electrical and Computer Engineering) and College of Arts and Sciences (Computer Science) department and involved 17 industry mentors. The last example is the Questrom School of Business course, IT Strategies for a Networked Economy, which is introducing the use of smart-city services into new business strategies and models (and our Smart Parking system is used as a case study).

Exposing students to SCOPE and its services is providing training through a balanced mix of relevant theory and practice. To do so, we have leveraged our collaboration with partners. The City of Boston, providing both people and data assets this past year, has created opportunities to expose students to the intersection of policy and technology of smart cities via the November 2015 Transportation Nudges Conference and the Spring 2016 Data Mechanics course as two examples. In Summer 2015, Schneider Electric funded a student internship focused on understanding and creating value from transportation data that will leverage the SCOPE platform, supporting the project activity A.1 Data Driven Traffic Analysis and Control. SCOPE has also provided opportunities for undergraduate student involvement, through data collection and processing, as for example, in the project described in Activity B.2 Data-driven Public Safety Applications.

Another approach we are following is to engage a broad community of innovators and software developers. In Spring 2015, the BU Hariri Institute for Computing launched the Software and Application Innovation Lab (SAIL) as the umbrella organization for this activity. SAIL consists of a small team of professional software architects and developers who are assigned to work directly with faculty members (and their research teams) on specific software and application development projects. SCOPE’s activities are among SAIL’s first “clients”. SAIL provides the much-needed professional training to students under their direct supervision, for example, the project activity described in C.2 Secure Multi-Party MapReduce. As of July 2016, SAIL has provided internships for 14 students many of whom derived from the Data

Mechanics course mentioned above which provided 18 projects with 30 data sets from the City of Boston, some SCOPE project samples of which are included in Appendix 3.

SCOPE reflects a consensus within and across public and private sector agencies that today's urban problems require collaboration and new spaces to deliberate and improve upon existing public policies and planning practice. As described in activities B.4 Participatory Planning and Organization, participants from city, regional and state agencies are working to deliberate and improve these practices through the SCOPE platform. Further, the project described in Activity C.1 Mobility Index Analytics is a prime example of how SCOPE has begun purposeful and transparent data-sharing on smart-city issues related to mobility: transportation, equity of citizen services, and economic development. These are issues that transcend agency boundaries (multiple City of Boston agents with interest in mobility), as well as require new rules and protocols on data use and applications.

Outreach Activities

While the first year's outreach efforts associated with this project have been primarily in promoting the research agenda, the second year has focused substantively on data science and mechanics of the platform. The PIs have been active in delivering lectures and colloquia at various universities, research laboratories and government agencies. In addition, there has been substantial coverage of various aspects of the project in both popular and scientific media.

Meeting Organization

The following are examples of meetings organized and/or hosted by various SCOPE personnel:

- Senior Personnel Lusk hosted the Initiative on Cities Urban Seminar Series: "Urban Energy Systems" (December 2015) and the "The Resilient City", Boston, MA (November 2014).
- Senior Personnel Lusk with the support of PI Azer Bestavros organized a multi-discipline conference on "Transportation Nudges: Experiments in Improving Urban Mobility." Co-hosted by BU Initiative on Cities, BU Hariri Institute, and the City of Boston, the conference was examined technological and behavioral interventions to reduce congestion and improve safety. PI Bestavros and Co-PI Christos Cassandras presented in panel discussions. A student poster session included posters by a number of SCOPE-affiliated students: C. Bassem, Wellesley College, C. Gately, BU, Y. Khazaeni, BU, S. Pourazarm, BU, Y. Zhang, BU. Designed to promote cross-disciplinary conversation, the diverse audience of 120 attendees consisted of 29% government officials, 33% academic researchers, 23% members of the private sector and 12% think tanks or nonprofit institutions.
- Co-PI Cassandras chaired the December 3-4, 2015 NSF Workshop on Smart Cities in Arlington VA. The workshop focused on areas including transportation, energy distribution, environmental monitoring, as well as data management, social engagement, urban planning, and policy. Participants included SCOPE PI Bestavros, as well as SCOPE partners from the City of Boston and Schneider Electric among many others.
- Senior Personnel Lusk served as the co-organizer and led the Urban Environment Roundtable discussion on policy/research collaboration at the conference "Understanding and Improving Cities: Policy Research Partnerships in the Digital Age", Boston, MA (December 2014).

Invited talks and plenary addresses

The following are examples of invited talks and plenary addresses:

- PI Bestavros gave a number of invited and keynote presentations at a number of venues focusing on the technologies and applications of the SCOPE platform, including at Dataverse Workshop on Privacy of Urban Analytics (July 2016); Columbia University Inaugural Meeting of the Data Science Institute (December 2015), Harvard University IQSS Seminar (October 2015); Symposium on Data-Driven Innovation and Value Creation: Establishing Thought Leadership Networks, Bentley University (June 2015); The Inaugural Meeting of the "100% Talent: The Boston Women's Compact" organized by the City of Boston's Women Workforce Council (May 2015); CELAR EU Project Plenary Meeting at PlayGen, London, UK (October 2014); ACM SIGAPP International Conference on Management of computational and collective IntElligence in Digital EcoSystems (MEDES), Qassim, KSA (September 2014).
- Co-PI Cassandras gave a number of plenary lectures, invited talks, and keynotes at a number of venues to promote systems engineering research related to smart-city and CPS applications, including the Workshop on Smart Cities, Hiroshima, Japan; the Workshop on Traffic Control, IPAM, Los Angeles, CA; Institute of Transportation Studies, GaTech; and 5th IFAC Conference on Analysis and Design of Hybrid Systems, Atlanta, GA (October 2015); the MathWorks, Inc, Research Faculty Summit, Newton, MA (June 2015); the National University of Singapore and Nanyang Technological University (June 2016 and June 2015); Peking University, the Chinese Academy of Science, and Tsinghua University, Beijing, China (May 2016 and May 2015); ACM/IEEE Conference on Cyber-Physical Systems, Seattle, WA (April 2015); UTC Institute for Advanced Systems Engineering, Storrs, CT (October 2014).
- Co-PI Hutyra gave a number of invited and plenary presentation at a number of forums focusing on "The urban carbon cycle" and on the general topic of urban sustainability, including: Boston University Conference on Sustainability Research, Boston, MA (May, 2016); Annual Meeting of the American Geophysical Union, San Francisco, CA (December, 2015); the Boston Metropolitan Planning Organization, Boston, MA (October, 2015); PBS NOVA Series, Cambridge, MA (May 2015); The Department of Energy, Oak Ridge National Laboratory Seminar (May 2015).
- Co-PI Terzi has given a number of invited talks in university colloquia and in industry. These include talks on "Recommender Systems in a Complex World" given in LinkedIn Corp and Quora.com as well as a talk on "Entity Selection and Ranking for Data Mining Applications" given at La Sapeinza University of Rome, 2nd workshop on Semantic Web Research, Northeastern University, and Alto University (2016); and at the Max Planck Institute for Informatics and the University of Minnesota (2015).
- Senior Personnel Lusk delivered a number of keynote speeches and invited presentations at a number of forums focusing on various aspects of urban life and innovation, especially as it relates to the intersection of technology and public policy, including: the Living Cities City Accelerator Cohort on "Building City/University Connections" attended by representatives from Philadelphia, and Louisville (November, 2015); Boston Smart Cities Learning Collaborative, Boston, MA, which was attended by myriad City of Boston departments and private sector companies including Schneider Electric, SCOPE's primary partner as well as others (October 2014); City of Boston's conference on Building Productive City/University Partnerships, Boston, MA (June 2015).
- Senior Personnel Krieger gave a keynote address at the National Science Foundation Workshop on Software-defined Infrastructure and Software-defined Exchanges (2016) and invited talks at Intel Cloud Day and Intel Chip Chat (2016); and the OpenStack Summit (April 2015).

Panel Discussions

The Following are examples of participation in panels related to SCOPE technology and applications:

- PI Bestavros was on a panel evaluating best practices for deploying practical privacy-preserving protections for big-data analytics using the Dataverse platform, which was organized by Harvard IQSS and hosted by Harvard Medical School (July 2016).
- Co-PI Cassandras was on a panel on Urban Mobility in Clean, Green Cities, Institute for Sustainable Energy, Boston University (April 2016); and at the Federal Highway Administration Workshop on Next Generation Traffic Control Systems, Washington, DC (February 2015).
- Collaborator Lapets participated in "Convening on Urban Data Science" at University of Chicago, a panel entitled "Problem Properties, Segregation, Wage Equity, and Public Innovation: Advancing Urban Informatics in Boston" (April 2016).
- Co-PI Hutyra was featured in the panel discussion of the seminar Initiative on Cities Urban Seminar Series: "The Resilient City", Boston, MA (November 2014).

Technical Presentations

The following are examples of technical presentations on SCOPE-related research themes:

- PI Bestavros gave an extended talk on cloud platforms for scalable and elastic computing at the Joint IEEE CAC Conferences, Cambridge, MA (September 2015), and at the Army Research Labs, Washington, DC (September 2015).
- Co-PI Hutyra, and collaborators Sue Wing and Gately gave scientific conference presentations on Emissions of CO_2 and Criteria Air Pollutants from Mobile Sources: Insights from Integrating Real-time Traffic Data into Local Air Quality Models at the European Geophysical Union General Assembly (April 2016) and at the American Geophysical Union, San Francisco, CA, (December, 2015); and "Quantifying Diurnal and Seasonal Variation in On-road CO2 Emissions Across the Northeastern US" American Geophysical Union Fall Meeting, San Francisco, CA, December 2014
- Co-PI Cassandras gave a number of technical talks, including at the ORNL Workshop on "Connected and Automated Vehicles: The Road to the Future Urban Mobility", Knoxville, TN (November 2015); International Conference on Event-Based Control, Communication and Signal Processing, Krakow, Poland (June 2015); the 54th IEEE Conference on Decision and Control, Osaka, Japan (December 2015); and at the IEEE Conf. on Decision and Control, Los Angeles, CA (December 2014); the Symposium on the Control of Network Systems, Boston, MA (October 2014).
- Senior Personnel Lusk and PhD student Gately presented at the poster session during the conference "Understanding and Improving Cities: Policy Research Partnerships in the Digital Age", Boston, MA, (December 2014).
- Senior Personnel Krieger gave a presentation at MIT Cloud Workshop (September 2014).

Media Coverage

The following are examples of media coverage related to achievements directly related to SCOPE:

- WBUR On Point Coverage of Bestavros and team's work on cloud platforms for private analytics: http://www.wbur.org/onpoint/2016/03/30/gender-gap-pay-gap-boston-amazon
- Boston Globe coverage of impact of SCOPE platform on feasibility of pay-equity analytics: https://www.bostonglobe.com/business/2016/03/27/more-boston-businesses-join-drive-end-gender-wage-gap/MTgBGKMgxMfhHvseVYukUI/story.html
- Boston Globe coverage of impact of SCOPE platform on feasibility of pay-equity analytics: https://www.bostonglobe.com/business/2015/04/07/walsh-women-venture-capital-summit-says-female-staff-members-underpaid/nKlivDh1VtOCV8hwVJ5XNM/story.html

- Government Technology: http://www.govtech.com/fs/7-Smart-City-Projects-Emerge-from-MetroLab-Network.html
- Coverage of research by Hutyra in Scientific American in September 2015: http://www.scientificamerican.com/aug2012/graphic-science
- Showcase of SCOPE Big-Data student projects at the Cisco Live event in San Diego, CA: http://www.newswire.com/press-release/boston-university-students-showcased-novel-open-source-internet
- BU Today on emission tracking work: http://www.bu.edu/today/2015/a-new-map-for-greenhouse-gas
- Futurity on emission tracking work: http://www.futurity.org/cars-cities-emissions-maps-898772
- Daily Free Press on emission tracking work: http://dailyfreepress.com/2015/04/10/researchers-find-correlation-between-population-density-carbon-dioxide-emissions
- Boston Globe: http://www.boston.com/cars/news-and-reviews/2015/04/08/boston-one-the-few-cities-where-per-driver-has-decreased-since/FR1JM5nO0hy5Sr9kd5uhrO/story.html
- The Atlantic, City Lab: http://www.citylab.com/commute/2015/04/how-suburban-cars-are-clouding-up-cities/389832
- Climate Central: http://www.climatecentral.org/news/city-tailpipe-emissions-18861
- Phys.org: http://phys.org/news/2015-04-vehicle-emissons-aid-urban-sustainability.html
- AccuWeather.com: http://www.accuweather.com/en/features/trend/northeast-cities-spend-millions-repaire-potholes-roads/44510208
- Boston Globe: http://www.bostonglobe.com/business/2015/03/16/the-van-that-goes-looking-for-potholes/b9q6eD3Wv8wf8SfM1rYfmJ/story.html
- BU Today: http://www.bu.edu/today/2015/computational-thinking-breaks-a-logjam
- Boston Globe: http://www.bostonglobe.com/business/2015/04/07/walsh-women-venture-capital-summit-says-female-staff-members-underpaid/nKlivDh1VtOCV8hwVJ5XNM/story.html
- Campus Technology: https://campustechnology.com/Articles/2014/09/24/Boston-U-NSF-Grant-Will-Turn-Boston-into-Smart-City.aspx

Accolades

The following are examples of accolades by personnel involved in SCOPE-sponsored activities:

- Mark Barrasso won the Top Hacker Award at the 2015 Cisco Live! San Diego, for his Smart Cities projects (developed as a course project in Orran Krieger's Cloud Computing course).
- Students Kyle Holzinger (BU CAS'16) and Eric Dunton (BU CAS'15) won a $5K award from Emerson College (matched with $5K from BU's IoC) for their work on SCOPE's multi-party-computation platform used in the "100% Talent: The Boston Women's Compact" application by developed for the City of Boston's Women Workforce Council.

- Theodora Brisimi won the 2014 IBM/IEEE Smarter Planet Challenge competition prize for her work on the Street Bump system.
- Senior Personnel Lusk was elected to the Boston Area Research Initiative Advisory Board as well as being selected among 40 urban leaders from across the U.S to participate in the Next City Vanguard class of 2016. https://nextcity.org/vanguard

Development of Human Resources

The following are examples of students (graduate and undergraduates) who have either graduated or secured internships as a result of their direct involvement in activities supported by this grant.

- PhD student Julia Lima Fleck (supervised by Co-PI Cassandras) graduated in May 2016, subsequently returning to her native Brazil.
- PhD student Yasaman Khazaeni (supervised by co-PI Cassandras) graduated in May 2016 and became employed by IBM Research, Boston, MA, having secured an internship at the Xerox Research Center, Webster, NY, Summer 2015.
- PhD student Conor Gately (supervised by Co-PI Hutyra) defended his PHD dissertation in October 2015 and subsequently worked as a post doctoral fellow, on the transportation and air quality modeling as well as interning at the MPO to gain more familiarity with the scientific needs and data opportunities.
- Lusk provided support for BU graduate students who obtained summer internships with the City of Boston and Providence as well as supporting students and faculty with projects related to smart cities via our Early Stage Urban Research Fund for both 2015 and 2016.
- Undergraduate software engineering interns Chang Gao, CAS ’17 and Jacqueline You CAS ’16 (supervised by Collaborator Lapets) contributed to the ongoing maintenance and development of the SCOPE platform built during the first iteration of the Data Mechanics course.
- PhD Andrew Trlica (supervised by Co-Pi Hutyra) obtained funding from BARI for his research on urban heat islands in 2015/16.
- PhD student Christine Bassem (supervised by PI Bestavros) obtained her PhD in July 2015 and started as an assistant Professor at Wellesley College in August 2015.
- Ben Lawson, an undergraduate (supervised by Co-PI Terzi) had an internship from the Department of Homeland Security in Washington DC in Summer 2015. He had been supported by this project in Spring 2015 to implement the infrastructure for collecting location data from social media in order to identify the moving patterns of people within the city of Boston.
- PhD student Kristin Mead (supervised by PI Bestavros) had an internship for Summer 2015 from Lincoln Laboratory, Cambridge, MA to investigate cybersecurity problems related to IoT applications.
- PhD student Yue Zhang (supervised by co-PI Cassandras) had an internship at the Oak Ridge National Laboratory, Knoxville, TN, Summer 2015.
- PhD student Sepideh Pourazarm (supervised by Co-PI Cassandras) had an internship from Schneider Electric (partner in this project), Summer 2015.

Development of Curricular Materials

(1) A new computer science course on urban data science entitled “Data Mechanics for Pervasive Systems and Urban Applications” was developed and taught in Spring 2016. This course’s focus was on how data can move through institutions and computational infrastructures to inform decisions and operations within large systems such as cities. The course taught students to apply some of the tools and methods

that facilitate data collection, retrieval, provenance tracking, integration, interpretation, and visualization with a particular focus on urban informatics. The course concluded with a poster session, attended by the BU and City of Boston community.

Students learned how to use the relational and MapReduce paradigms to assemble analysis, optimization, and decision-making algorithms using real-world data obtained from the City of Boston Data Portal, MassDOT Developers' Data Sources, and other resources. Over the course of the semester, about 30 students assembled about 20 individual projects using these data sources and the techniques learned during lectures. These projects focused on aspects of urban environments such as mobility and transportation, employment, gentrification, traffic safety, accessibility and health, public safety, and others. They were all developed within a single, unifying framework that allows any of the projects to be interoperable and interdependent, e.g., data generated by one project could be used by another project. Together, the framework and the student projects constitute a platform upon which future course projects, as well other urban data science research efforts can be built.

A number of the students from this course have secured internships with the SAIL group at https://www.bu.edu/hic/about-hic/sail/

For the course posters and project reports, please visit the website http://datamechanics.org

(2) The Massachusetts Open Cloud, SCOPE's enabling technology platform, has been training a host of undergraduate students, both as interns on the project as well as students who have participated in a new Cloud Computing course. Over 70 undergraduates developed agile development and cloud computing skills in the second run Spring 2016 course and over 60 in the first iteration offered in Spring 2015. This course was developed and co-taught by Orran Krieger, Boston University and Peter Desnoyers, Northeastern University. We surveyed the students after the course, and collected valuable information about skills they learned that are directly applicable to industry. Students reported much improved preparation to enter the workforce in general, and to apply for cloud computing positions specifically. In 2016, 23 students reported that the course directly led to interviews and/or employment offers.

The course involved industry mentors leading teams of 3-5 students developing cloud computing and Big Data projects. In 2016, two SCOPE smart city projects were supported by the course. One, mentored by Google, analyzed MBTA performance and developed a new UI for users to help them plan their commute. Another, mentored by the MBTA, analyzed alerts from the MBTA, the correlation to subsequent impact on delays, and developed a new tool for the MBTA itself. In 2015, three SCOPE smart city projects where supported by the course. Two Internet of Things (IoT) applications provided visualizations of mobile device positions on interactive maps of both indoor facilities and aerial/satellite imagery by combining signals acquired from disparate "things" including Bluetooth low energy (BLE) beacons, Internet routers, and GPS. Another smart city Big Data application obtained, cleaned, and then analyzed a large data set of bus transit information from the Commonwealth of Massachusetts, providing valuable feedback to the Mass Department of Transit on the impact of a major bus route changes.

In 2016, students involved in the two course projects where Pranay Singh, Ang Li, Siwan Yang, Ho Tan, Alex Casella, John Ben Snyder, Edwin Fitzpatrick, Daniel Gorelick, Eddy Luo. A full list of students/interns on the project can be found under the list of current and alumni team members. In 2015, students involved in the IoT applications were: Mark Barrasso, Jose Bautista, Justina Choi, Sean Liu, Nehal Odedra, Niklas Kunkel, Qingqing Li, and Yingchao Zhu. Students involved in the Big Data application were: Yue Zhang, Hua Li, Huy Le, Xin Peng, Arlyn Rodrigues, Reva Scharf, A full list of students/interns on the project can be found here https://github.com/CCI-MOC/moc-public/wiki/People

Contributions to the Discipline of the Proposed Work

We provide a brief summary of how the outcomes of the research pursued as part of this project have contributed to the state-of-the-art in computer science and systems engineering

Scalable and Efficient Multi-Party Computation in the Cloud: Our work on extending Hadoop MapReduce to allow for multi-party Computation will enable the SCOPE to be used on much larger data sets from a much larger set of parties, and using a highly popular computational platform that is widely adopted in industry. Our work on this project involves the development of innovative techniques in many Computer Science sub-disciplines, including Programming Languages, Applied Cryptography, and Distributed Systems.

Infrastructure for Big Data Analytics: We have architected and started implementing an Infrastructure for Big Data that was in part motivated by the SCOPE use cases. This will allow tenants to spin up their own isolated elastic Big Data environments while providing very efficient access to public data sets. More information is available at http://info.massopencloud.org/blog/bigdata-research-at-moc/.

Optimal routing for Energy-aware Vehicles: The increasing presence of Battery-Powered Vehicles (BPVs), such as Electric Vehicles (EVs), in traffic networks has created new challenges for integrating BPVs into such networks while also maintaining high overall traffic performance levels. More generally, when the entities in a network are characterized by physical attributes exhibiting a dynamic behavior, this behavior can play an important role in the routing decisions, thus giving rise to novel issues in classical network routing problems. Our work in this area has expanded the scope of classical optimal routing problems to incorporate these energy-aware features.

Dynamic resource allocation in Smart Cities: The framework we have developed based on stochastic hybrid systems contains a unique aspect in that resources are continuously re-assigned, enabling resource reservation improvements as the state of the system changes. Our results adopting this approach for Smart Parking have led to a prototype system deployed in a parking facility at Boston University. The gradient-based methodologies we have used in solving the Traffic Light Control (TLC) problem not only provide a unique real-time data-driven approach for dynamically adjusting traffic light cycles, but have also established a broader setting for solving complex stochastic optimization problems in a quasi-dynamic fashion, by defining "aggregate states" which are easier to observe and allow solutions to otherwise intractable Dynamic Programming problems.

Contributions to other related Science and Engineering Disciplines

Many of the concepts and methods developed in this project are applicable to broader disciplines in engineering and computer science. Several techniques we are specifically studying are generic in nature and may be translated to various application scenarios, e.g., civil and mechanical structure monitoring, surveillance system design, manufacturing equipment and process monitoring. The following are some examples:

- Our work on dynamic resource allocation in urban settings, our work on novel services such as Geo-Presence as a Service, and our work on the mobility index platform provide general frameworks for solving problems for a very broad range of applications and establish connections to disciplines such as economics (for pricing and policy making), cloud computing, public health, among others.
- Our work also involves the development of mathematical frameworks for distributed optimization, event-driven control, and anomaly detection all of which impact disciplines relying on such mathematical methodologies.

More broadly, as described in SCOPE Activity B.1 Traffic Management for Sustainability, tracking and managing air-polluting emissions is important for the nation's efforts to control greenhouse gases in order to mitigate the negative impacts from climate change. Recognizing that this challenge must be tackled regionally by various stakeholders, this SCOPE activity led to an Institute-led proposal in to connect smaller and mid-sized resource-constrained communities with their larger counterparts, thus empowering them to become active change-makers and innovators. The proposal, entitled "PETALS NSF Northeast Big-Data Spoke: Partnership for Emission Tracking and Analytics at Locally-relevant Scales", provides the blueprints for a sustainable data management and stakeholder integration model focusing on the inherently multi-faceted problem of managing emissions in the Northeast; a model that can be replicated by other regions across the country. PETALS will also advance other national priorities, most notably mitigating effects of air pollution, climate change, and the built environment on public health, and using transportation and energy data/analytics as catalysts for K-20 STEM education and outreach to the general public, whose engagement is essential to support climate mitigation policies. PETALS's approach to sustaining its computational infrastructure, one that can also be leveraged by the SCOPE platform, is a pilot that could be developed further within NSF's Hub & Spoke ecosystem for wider adoption as a best practice. Discussions about this and other aspects of PETALS have already engaged the Northeast Hub Executive Director, including a May 2016 Roundtable hosted at the Institute with regional stakeholders, some of whom are also SCOPE partners, to actively engage and develop ways to launch PETALS in advance of any proposal award.

Impact on Society at Large

We provide a brief summary of how the outcomes of the research pursued as part of this project have contributed to society at large with a focus on challenges in urban environments delivering improved smart-city services in a major metropolitan area.

Impact on Social Justice: Our work on the SCOPE MPC platform has proved critical in advancing a major social justice issue, not only for the city of Boston and the State of Massachusetts, but indeed nationally and internationally. The impact on society from this work is best summarized by the words of the executive director of the Women's Workforce Council, Christina Knowles: *"[We] spent more than a year brainstorming with global experts in fruitless pursuit of a data-gathering method that would ensure employers' confidentiality. It proved impossible to find a solution—until we were introduced to Professor Bestavros [and the SCOPE platform which was] absolutely vital to our work. We owe our progress on this innovative and groundbreaking project [to them]. The project is the first of its kind in the country."*

Impact on Economic Development: The SCOPE project helped motivate millions of dollars of investment by companies in the Massachusetts Open Cloud (MOC) Big Data platform, by companies like Red Hat, Intel, Brocade, Cisco, Lenovo, Two Sigma, Dell, Fujistu and others. The software development for this platform is being developed jointly by the MOC, Intel and Red Hat, and involves changes to Open Stack, the Ceph file system, and the Apache BigTop distribution of Hadoop. Further, to date, over 30 students from the Cloud Computing course have said that the course directly led to employment opportunities. We have described SCOPE as a motivational example for the MOC in many forums and many industry talks.

Impact on City Planning: Our work on smart-city applications had several direct implications to the daily operation of a city and the lives of its dwellers. The Smart Parking system demonstrated that changing policies regarding the use of public resources (in this case, parking spaces) can improve overall resource utilization, reduce fuel consumption and emissions, reduce traffic congestion, and improve overall quality of life. Our work with the City of Boston in classifying "bumps" on the road recorded through crowd-sourcing by citizen drivers allowed the City to prioritize emergency repairs (pothole filling, repairing castings, etc.)

Impact on Sustainability and Environment: Our work on transportation and emissions modeling provides a level of detailed insight never seen before through the fusion of novel cell phone data set, state-of-the-art air quality models, travel demand models, and big data fusion. These methodological advancements provide vital tools for policy assessment, identification of intervention opportunities, and greenhouse gas monitoring for assessment of sustainability goals.

Impact on Policy: Our inventory data product provides local and regional policymakers with valuable information on the timing and location of severe pollution emissions, and serves as a benchmark for the development and testing of mitigation strategies to reduce vehicle emissions in key corridors. Even more importantly, the analytical framework that we developed paves the way for similar future analyses across other regions.

Impact on Better Quality of Life in Cities: Our work on the SCOPE Mobility Index Analytics will enable the City of Boston to transparently assess its performance over time in sustainably improving the mobility of its residents across three key dimensions: equity of access, economic impact and climate impact. This connection of mobility and city planning will enable a better quality of life in cities. As a tool for city planners, the Mobility Index Analytics platform is creating a flexible framework for a mobility index that can be expressed and visualized, allowing multiple definitions and calculation of a host of metrics (not just one) that can change over time, e.g., travel options and access to jobs in various neighborhoods or the city at large. As described earlier, the Institute's February 2016 PETALS Big Data Spoke proposal has already had immediate impact to Cities. As a result, the City of Providence approached Boston University Initiative on Cities seeking a collaboration to aid in the development of Providence's first greenhouse gas inventory. Associate Professor Lucy Hutyra and Postdoctoral Researcher Conor Gately of the BU Earth and Environment Department have extensive experience in developing high resolution emissions inventories at urban scales, had recently completed a complete inventory of carbon dioxide emissions for the northeastern U.S., and were excited to share their existing datasets and methodologies with the City of Providence.

Postlude

Impact of the NSF Partnerships for Innovation Program

It is befitting to conclude this report with an acknowledgment of the value of the NSF Partnership for Innovation: Building Innovation Capacity (NSF PFI:BIC) program on catalyzing much of the progress made under this project.

The emphasis of NSF PFI:BIC on connecting applied and translational research activities with implementation and integration in functional and usable services steered our work in a direction that we found to be highly rewarding.

First and foremost, individually, the investigators supported through this award (who come from very different backgrounds) have a long history of successful sponsored projects and accomplishments under various NSF directorates and programs. Yet, the success of this past track record was measured in terms of traditional metrics of publications, citations, and graduate student training, etc. Whether or not this track record ended up informing real services was seen as a byproduct and at best an indicator of broader impact. In contrast, making this goal the central focus of NSF PFI:BIC projects served the SCOPE team very well not only in terms of setting priorities and of identifying the right opportunities to pursue, but more importantly in attracting non-academic partners to a project that promised (from day one) to be different. Quoting PI Bestavros from the inaugural workshop for SCOPE held in early 2015: *"SCOPE is not business as usual with respect to outcomes from sponsored research: It is not the number of published papers that matter, but rather the number of user clicks!"* Indeed, this focus on making a difference resulted in the identification and pursuit of an unplanned (but highly rewarding) connection with the City of Boston – namely our work with the Boston Women Workforce Council. The reason this group was directed to us in the first place was precisely because of our interest in taking on translational research activities that lead to implementation and integration in functional and usable services.

Second, the emphasis of NSF PFI:BIC on the importance of a multi-disciplinary approach to tackling human-centered service systems has led to new collaborations and new opportunities for basic research in all of the disciplines represented by member of the SCOPE team (in computer science, systems and control engineering, environmental sciences, and management). For example, our need to develop a single platform for visualizing mapping information in support of multi-objective routing (co-PI Terzi), CO_2 emissions (co-PI Hutyra), and traffic flow modeling (co-PI Cassandras) resulted in the need for these three research thrusts to "agree" on the platform requirements. The availability of a professional software developer, funded through this project to flesh out this capability using available open-source, production quality software architectures has changed the best practices in developing GIS solutions in these disciplines (emphasizing the importance of usability and scalability and robustness). This was also very valuable for graduate students who (perhaps for the first time) developed an appreciation for what it takes to develop software artifacts that have a lifetime (and purpose) that goes beyond the submission and publication of a research article.

Third, the nature of the feedback loop – informing translational research by experiences learned through deploying a real service – has had a significant impact on our collective appreciation of the subtleties of deploying new services (e.g., the degree to which public sector agencies are risk averse in terms of trying out new solutions and the importance of "optics").

Appendices

Appendix 1: Participants

Below is the list Principal Investigators (PIs) and senior personnel, as well as anybody who collaborated on activities supported by the grant even if not paid from the grant (namely, faculty, students, and postdocs). Additional information is entered on Research.gov, including demographic info as well as a few lines describing the role and the duration of work (and if graduated, then when).

Principal Investigators and Senior Personnel

- Azer Bestavros, PI
- Christos G. Cassandras, Co-PI
- Lucy Hutyra, Co-PI
- Evimaria Terzi, Co-PI
- Orran Krieger, Senior Personnel
- Katharine Lusk, Senior Personnel
- Paul McManus, Senior Personnel

Participants supported by the grant

- Conor Gately, Postdoc collaborator, previously a Grad Student
- Sepideh Pourazarm, Grad Student
- Frederick Joossens, Software Engineer
- Chang Gao, Undergraduate Student

Participants supported by other sources

- Esther Galbrun, Postdoc collaborator
- Andrei Lapets, Postdoc collaborator
- Ata Turk, Postdoc collaborator
- Christine Bassem, Grad Student
- Nisreen Dahod, Grad Student
- Dora Erdos, Grad Student
- Julia Lima Fleck, Grad Student
- Yasaman Khazaeni, Grad Student
- Nikolaj Volgushev, Grad Student
- Yue Zhang, Grad Student
- Eric Dunton, Undergraduate Student
- Kyle Holzinger, Undergraduate Student
- Ben Lawson, Undergraduate Student

Other collaborators and contacts

- Carl Spector, City of Boston, Energy and Environment Services
- Brad Swing, City of Boston, Energy and Environment Services
- Charles Zhu, City of Boston, Energy and Environment Services
- Kris Carter, City of Boston, Mayor’s Office of New Urban Mechanics
- Nigel Jacob, City of Boston, Mayor’s Office of Urban Mechanics

- Megan Costello, City of Boston, Mayor's Office of Women's Advancement
- Chris Osgood, City of Boston, Office of Urban Mechanics
- Alice Brown, City of Boston, Department of Transportation
- Gina Fiandaca, City of Boston, Department of Transportation
- Vineet Gupta, City of Boston, Department of Transportation
- Christine Dennehy, City of Boston, Department of Innovation and Technology
- Jascha Franklin-Hodge, City of Boston, Department of Innovation and Technology
- Alex Heimann, City of Boston, Department of Public Works
- Agnieszka Ilnicka, City of Boston, Department of Public Works
- Matthew Mayrl, City of Boston, Department of Public Works
- James Soloman, City of Boston, Department of Public Works
- Katie Johnston, Boston Women's Workforce Council
- Christina M. Knowles, Boston Women's Workforce Council
- MaryRose Mazzola, Boston Women's Workforce Council
- Dave Mitchell, Connected Bits
- Ruthbea Yesner Clarke, IDC Government Insights
- Wei Li, Mathworks
- Ben Levine, Metro Lab Network
- Scott Peterson, Metropolitan Planning Organization
- Jen Curtis, Schneider Electric
- David Markt, Schneider Electric
- Alistair Pim, Schneider Electric
- Farhad Pooran, Schneider Electric
- Cary Vick, Schneider Electric

Collaborating organizations

Boston Women's Workforce Council: PI Bestavros, starting in Fall 2014 in conjunction with the research activity Secure Multi-Party MapReduce, began a collaboration with the Boston Women's Workforce Council to use SCOPE's secure MPC application as a platform for supporting the "100% Talent: The Boston Women's Compact" (BWC). In addition to the Council, we had design and implementation collaboration from various city agencies and employer organizations who had to provide approval. About 70 employers participated in the second data collection round in 2016 using the latest version of the secure MPC service.

City of Boston and Massachusetts Departments: PI Bestavros, Co-PIs Hutyra and Cassandras, Senior Personnel Lusk, and Collaborator Lapets are working with various departments within the City of Boston including Energy and Environment Services, Office of Urban Mechanics, the Department of Transportation, the Department of Public Works, and the Department of Innovation and Technology. Collaborator Lapets has also been in contact with the Massachusetts Department of Transportation (MassDOT) Office of Performance Management & Innovation. Collaborations are in progress focused in identifying needs and priorities for City services, data sharing, analysis, and dissemination of results as well as in designing partnership and eco-system process, identifying inhibitors and solutions. Our collaborators in these departments are providing data, software, and personnel as well as offering a critical lens on the social/institutional behaviors of the SCOPE ecosystem.

Connected Bits: Co-PIs Cassandras is collaborating with Connected Bits, an enterprise mobile services developer, who has been critical to the integration of the Street Bump project into SCOPE, bringing extensive mobile app implementation and market knowledge. Our collaborator has provided data and explanations of data from the Street Bump app that were used to determine roadway obstacle classifications and regularity indices.

IDC Government Insights: Senior Personnel Paul McManus is working with IDC, an IDG subsidiary, who brings dedicated research resources on smart cities and market opportunity expertise covering the breadth of SCOPE activities including cloud computing, big data analytics, social media and mobility, furthering the market development and commercialization of SCOPE's smart-city services and connecting it to potential adopters. Their personnel have provided collaboration in developing platform eco-system workshops and collaborative process development.

The Massachusetts Green High-Performance Computing Center: Working with Senior Personnel Orran Krieger, the MGHPCC is providing critical infrastructure support to the SCOPE platform and it's enabling technology of the Massachusetts Open Cloud. The MGHPCC is jointly operated by BU, Harvard, UMass, MIT, and Northeastern, and is a world-class, green data center housed in facilities in Holyoke, MA in support of R&D enabled through the use HPC and big-data, with SCOPE's smart-cities related application services being a key user.

Mathworks: Co-PI Cassandras has received a gift grant from MathWorks to study the use of control, optimization, and automated sensitivity analysis tools in smart service apps. One of the problems his research group will be studying is the development of Advanced Driver Assistance Systems (ADAS) for vehicles in Smart Cities using simulation software tools from MathWorks.

Metro Lab Network: Senior Personnel Lusk is collaborating with this national network of cities and their university partners conducting research on Smart Cities. Included in their efforts are plans to convene Network member cities in Boston around topics related to SCOPE and smart cities.

Metropolitan Planning Organization: Co-PIs Hutyra and Cassandras are working with Boston's MPO transportation planning group on traffic analysis, smart signaling and routing, and improving emissions estimates. This group within the MPO brings customers' views with a focus on the regional transportation planning process, working with massive data sets and analytics. MPO's assets align with the cross-cutting SCOPE activities that connect transportation with environmental policy. Together with Co-PIs Hutyra and Cassandras, the MPO is helping to scope the project, provide data sharing, analysis, and dissemination of results. In addition, Scott Peterson, Director of Technical Services, served on the PhD dissertation committee for Conor Gately and co-authored one of the papers from Gately's dissertation (Gately et al. in review).

Schneider Electric: Co-PI Cassandras has been working closely with Schneider Electric (SE) our key industry partner. SE brings global experience building collaborative smart-city solutions, integrating multiple data streams from city infrastructure to create meaningful information and services for policy makers, researchers and citizens. Collaborations with SE include interactions on developing traffic monitoring and control tools for Boston as well as input regarding traffic signaling devices and emulation laboratory facilities used by Schneider where we can test algorithms we are developing. Schneider has provided funds for a Summer Research Assistant working with Co-PI Cassandras.

Appendix 2: Products

Below is a highlights list of products from the Principal Investigators (PIs) and senior personnel, as well as anybody who collaborated on activities supported by the grant even if not paid from the grant (namely, faculty, students, and postdocs). These are organized by published journal publications followed by conference proceedings and other. Where available, hyperlinks are provided.

Journal publications and conference proceedings

- Bassem, C., and Bestavros, A. Multi-Capacity Bin Packing with Dependent Items and its Application to the Packing of Brokered Workloads in Virtualized Environments. Future Generation Computer Systems, 2016.
- Brisimi, T.S., Cassandras, C.G., Osgood, C., Paschalidis, I.C., and Zhang, Y. Sensing and Classifying Roadway Obstacles: The *Street Bump* System. In *IEEE Access*. 2016.
- Fleck, J.L., Cassandras, C.G., and Geng, Y. Adaptive Quasi-Dynamic Traffic Light Control. In *IEEE Trans. on Control Systems Technology*, Vol. 24, pp.830-842. 2016.
- Pourazarm, S., Wang, T., and Cassandras, C.G. Optimal Routing and Charging of Energy-Limited Vehicles in Traffic Networks. *Intl. J. of Robust and Nonlinear Control*, Vol. 26, 6, pp.1325-1350. 2016.
- Zhang, J., Pourazarm, S., Cassandras, C.G., and Paschalidis, I.C. The Price of Anarchy in Transportation Networks by Estimating User Cost Functions from Actual Traffic Data. Refereed Conference Paper. In *55^{th} IEEE Conference on Decision and Control*. 2016.
- Galbrun, E., Pelechrinis, K., Terzi, E.: ``Urban Navigation Beyond Shortest Route: The Case of Safe Paths", Inf. Syst. 57: 160-171. 2016.
- Hutyra, L. R., Gately, C. K. The U.S. Second State of the Carbon Cycle Report (SOCCR-2), The Urban Carbon Cycle (Chapter contributors). September 2016 [U.S. Special Assessment Report]
- Decina, S. M., Hutyra, L. R., Gately, C. K., Getson, J. M., Reinmann, A. B., Short Gianotti, A. G., Templer, P. H. Soil Respiration Contributes Substantially to Urban Carbon Fluxes in the Greater Boston Area. *Environmental Pollution* 2016, *212*, 433–439.
- Volgushev, N., Lapets, A., and Bestavros, A. Programming Support for an Integrated Multi-party Computation and MapReduce Infrastructure. In *Proceedings of IEEE HotWeb 2015: The Third IEEE Workshop on Hot Topics in Web Systems and Technologies*, Washington DC, November 2015.
- Bassem, C. and Bestavros, A. Rational Coordination of Crowdsourced Resources for Geo-temporal Request Satisfaction. In *Proceedings of IOT-SOS'15: The IEEE Workshop on Internet of Things Smart Objects and Services*, Boston, MA, June 2015.
- Gately, C., Hutyra, L.R., Sue Wing, I. Cities, traffic, and CO2: A multi-decadal assessment of trends, drivers, and scaling relationships. *Proceedings of the National Academy of Sciences of the United States of America,* 112 (16): 4999-5004, 2015.
- Gately, C.K. Greenhouse Gas Emissions from Mobile Sources: Improved Understanding of the Drivers of Emissions and Spatial Patterns, Boston University PhD Dissertation, 2015.
- Bassem, C. and Bestavros, A. Network-Constrained Packing of Brokered Workloads in Virtualized Environments. In *Proceedings of CCGrid'15: The IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing*, Shenzhen, Guangdong, China, May 2015.
- Teixeira, M. and Bestavros, A. End-to-End Informed VM Selection in Compute Clouds. In *Proceedings of ICC'15: The IEEE International Workshop on Cloud Computing Systems, Networks, and Applications*, London, UK, June 2015.

- Erdos, D., Ishakian, V., Bestavros, A., and Terzi, E. A Divide-and-Conquer Algorithm for Betweenness Centrality. In *Proceedings of SDM'15: The SIAM International Conference on Data Mining*, Vancouver, Canada, May 2015.
- Brisimi, T.S., Ariafar, S., Zhang, Y., Cassandras, C.G., and Paschalidis, I.C. Sensing and Classifying Roadway Obstacles: The Street Bump Anomaly Detection and Decision Support System. In *Proceedings of 2015 IEEE Conf. on Automation Science and Engineering*. 2015.
- Fleck, J.L., and Cassandras, C.G. Infinitesimal Perturbation Analysis for Personalized Cancer Therapy Design. Refereed Conference Paper. In *Proceedings of 5th Conference on Analysis and Design of Hybrid Systems*. 2015.
- Wang, T, Cassandras, C.G., and Pourazarm, S. Optimal Motion Control for Energy-aware Electric Vehicles. Refereed Journal Paper. Control Engineering Practice, Vol. 38, pp. 37-45. 2015.
- Pourazarm, S., and Cassandras, C.G. System-Centric Minimum-Time Paths for Battery-Powered Vehicles in Networks with Charging Nodes. Refereed Conference Paper. *In proceedings of 5th Conference on Analysis and Design of Hybrid Systems*. 2015.
- Gately, C.K., Hutyra, L.R., Sue Wing, I. Cities, traffic, and CO_2: A multidecadal assessment of trends, drivers, and scaling relationships. Refereed Paper. In *proceedings of the National Academy of the United States Proceedings of the National Academy of the United States 112 (16): 4999-2004 (doi: 10.1073/pnas.1421723112)*. April 6, 2015.
- Galbrun, E., Pelechrinis, K., Terzi, E. Safe Navigation in Urban Environments. UrbComp Workshop. *Urban Computing, KDD 2014*. August 2014.

Software and Data Sets

- Web site: http://metrolab.heinz.cmu.edu/projects/boston-ma/. This web site contains SCOPE affiliated work featured as part of the showcase of projects affiliated with Metro Lab Network, a national network of cities and their university partners conducting research on Smart Cities (Lead: Lusk) 2016.
- Web site: Data Mechanics. This web site contains a course description of the new urban data science course offered within the Boston University Computer Science Department, and a list of student projects (reports, posters, and code repositories). Spring 2016.
- Software: Link to Boston Women's Compact Salary Equity software developed as part of the Secure Multi-party MapReduce work. (Lead: Bestavros) 2015
- Dataset: Cities, traffic, and CO_2: A multidecadal assessment of trends, drivers, and scaling relationships. *http://dx.doi.org/10.7910/DVN/28999* (Lead: Hutyra) 2015
- Software: Interactive Simulation Environments for Testing Distributed Control and Optimization Algorithms. (Lead: Cassandras) 2015

Appendix 3: Demonstratives

In the following pages of this section, we have included several examples of demonstratives used to overview activities that we have pursued, artifacts that we have developed as part of SCOPE over the last year, as well as clippings from highly-visible media coverage.

- SCOPE Overview Poster
- A.2 End User: Smart Cities Mobile Apps [new in 2016]
- B.1 Cross-Cutting: Traffic Management for Sustainability [updated in 2016]
- B.2 Cross-Cutting: Data-driven Public Safety Application [updated in 2016]
- B.4 Cross-Cutting: Participatory Planning and Organization
- C.1 Mobility Index Analytics [new in 2016]
- C.2 Capabilities: Secure Multi-Party MapReduce Salary Equity Software
- Media coverage of impact of SCOPE capabilities on a City of Boston priority

NSF Award IIP #01430145 – Duration: 3 Years Award – Start Date: August 1, 2014

SCOPE: A Smart-city Cloud-based Open Platform and Ecosystem

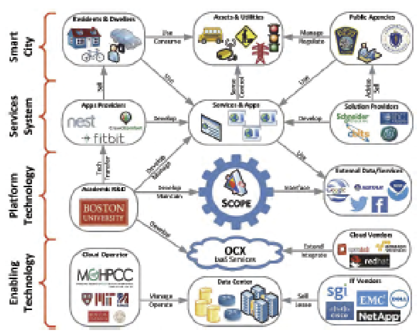
Boston University, Hariri Institute for Computing

Azer Bestavros (PI, CS), Christos Cassandras (Co-PI, ECE), Lucy Hutyra (Co-PI, Earth/Environment), Evimaria Terzi (Co-PI, CS)
Orran Krieger (CS/ECE), Katharine Lusk (Initiative on Cities), Paul McManus (Management), Vinit Nijhawan (Tech Development)

Project Overview

SCOPE is a cloud computing platform that exposes the digital pulse of the City of Boston, allowing innovators to develop smart services that leverage a unique ecosystem of technology, organizations, and big-data assets. SCOPE integrates cyber-physical and data management/mining capabilities into an open cloud architecture, targeting services and applications in transportation and mobility, energy and environmental sustainability, public safety, and urban planning.

SCOPE Socio-Technical Ecosystem



Research Areas/Tasks

		Systems Eng.			Computer Science				Sustainability			
	Activities	Decision & Control	Optimization	Cyber-physical	Networked Systems	Software Systems	Data Mining	Security & Privacy	Environmental Sci.	Urban Sustainability	Urban Policy	Business/Econ Dev
Platform Development	OCX Integration			✔	✔	✔		✔				✔
	CPS Cloud Support			✔	✔	✔						
	Data Quality Mgmt	✔	✔				✔					
	Data Privacy Mgmt						✔	✔				
	Integrity & Provenance			✔		✔	✔	✔				
End-user Services	Smart Parking		✔	✔		✔	✔	✔	✔	✔	✔	✔
	EV Charge Mgmt	✔	✔	✔						✔	✔	✔
	Tour Navigation					✔		✔		✔	✔	✔
	Hubway Mgmt					✔		✔	✔	✔	✔	✔
Planning Services	Street Bump	✔		✔			✔	✔				
	Traffic Light Control	✔	✔	✔		✔		✔	✔	✔	✔	✔
	Transport Planning		✔			✔	✔					
	Monitor Environment		✔			✔	✔		✔	✔	✔	
	Community Energy						✔	✔		✔	✔	
Crosscutting Services	Traffic & Environment		✔				✔		✔	✔	✔	
	Big Data & Pub Safety		✔			✔	✔	✔		✔	✔	
	Behavior & Incentives		✔				✔	✔		✔	✔	✔
	Participatory Gov't									✔	✔	✔
	Transparent Gov't								✔	✔	✔	✔

Partners

Private Sector
Schneider Electric
International Data Corporation
Connected Bits
CrowdComfort
Integrated Technical Systems

Public Sector
City of Boston
Commonwealth of Massachusetts
Metro Area Planning Council
Metro Planning Organization
Massachusetts Green HPC Center

Contributions

1. Spur the generation of new commercial products and public goods.
2. Create new spaces for public data-driven policy debate.
3. Enable urban stakeholders to collectively harness, learn from, and monetize unused big-data assets.
4. Improve quality of life by promoting environmental sustainability.

Challenges

1. Changing established institutional cultures that resist open data and open-source design.
2. Aligning incentives across the triple-helix: academia, industry and the public sector.
3. Integrating proprietary, legacy systems into the OCX open-stack, open-source design.

Innovative Attributes

Underlying Smart Technology

SCOPE leverages the Open Cloud eXchange (OCX) – a plug-and-play architecture that integrates key capabilities, including data quality management services; security and integrity services; provenance services; privacy and anti-piracy services; and software stacks in support of CPS infrastructures. OCX is well suited to deal with the defining characteristics of big-data: volume (sheer amount of data), velocity (rate of data streams), variety (diversity of data sources and formats), and veracity (uncertainty associated with data provenance and quality).

Targeted Service System

SCOPE will enable the development and deployment of smart-city services targeting city dwellers, urban planners, and pubic servants. SCOPE's stakeholders will collectively harness, learn and innovate from "big data" by monetizing unused assets, facilitating cross-agency collaboration, enhancing quality/equity of services, and developing new ones.

Sustaining Smart Service Innovation

SCOPE's OCX architecture allows many partners to compete and cooperate on the same cloud platform, effectively creating a multi-sided marketplace where innovation can flourish, providing businesses and entrepreneurs with new opportunities for deriving value from existing data assets by combining them in new ways for even smarter city services.

Interdisciplinary Collaborations

SCOPE brings together a team of PIs and Senior Personnel with a diverse and complementary set of expertise in systems engineering, computer science, and social and management sciences – as illustrated in the breakdown of research activities and major project tasks across various types of expertise and disciplines.

New Environments/Playgrounds for Partners

SCOPE offers a new ecosystem in which partners have an opportunity to connect with new stakeholders, including technology innovators, public and private organizations, data service providers, integrators and solution providers, among others. Partners from each stakeholder group will be able to tap into a unique holistic environment with bridges between academia, the private sector, and the public sector.

New Educational & Training Opportunities

SCOPE offers unique experiences for students at all levels, including integration of smart-city work into curricula of courses offered in all cognate disciplines, undergraduate research opportunities, internships at private sector partner organizations, rotation and residence in living labs at various City of Boston departments, STEM education through inner-city related initiatives, and K12 outreach through MGHPCC activities offered to underrepresented minorities in Holyoke, MA.

B.1 Cross-Cutting: Traffic Management for Sustainability

Lucy Hutyra (Co-PI)

The United States, with 5% of the world's population and 30% of the world's automobiles, emits 45% of global transportation CO_2 emissions. Nationally, the on-road sector represented 28% of total fossil fuel CO_2 emissions in 2012 and is responsible for almost half of the growth in total US emissions since 1990. Despite being a substantial component of US emissions, on-road CO_2 remains poorly quantified at sub-state and urban scales.

As the first nationally consistent inventory of US on-road CO_2 emissions built from bottom-up source activity data, DARTE not only establishes a national benchmark for the monitoring, reporting, and verification of emissions that are vital to regulating GHGs but provides previously unidentified insights into how key features of urban areas contribute to climate change. DARTE can provide valuable information to local and regional climate change mitigation initiatives (e.g., state and city climate action plans) whose success turns on the ability to assess both city-scale GHG emissions and their responsiveness to policy accurately.

In the Gately et al. (2015) paper we developed a new emissions inventory, the Database of Road Transportation Emissions (DARTE; Figure 1 below), which estimates CO_2 emitted by US road transport at a resolution of 1 km annually for 1980– 2012. DARTE reveals that urban areas are responsible for 80% of on-road emissions growth since 1980 and for 63% of total 2012 emissions.

We observe nonlinearities between CO_2 emissions and population density at broad spatial/temporal scales, with total on-road CO_2 increasing nonlinearly with population density, rapidly up to 1,650 persons per square kilometer and slowly thereafter (Figure 2 below). Per capita emissions decline as density rises, but at markedly varying rates depending on existing densities. This cross-sectional analysis highlights key changing dynamics over time and thresholds.

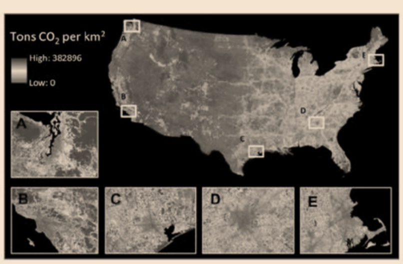


Figure 1. Map of 2012 on-road CO2 emissions for the coterminous United States and selected urban areas at a resolution of 1 km. (Insets) Maps show details of metro areas surrounding Seattle (A), Los Angeles (B), Houston (C), Atlanta (D), and Boston (E). (Gately et al. 2015)

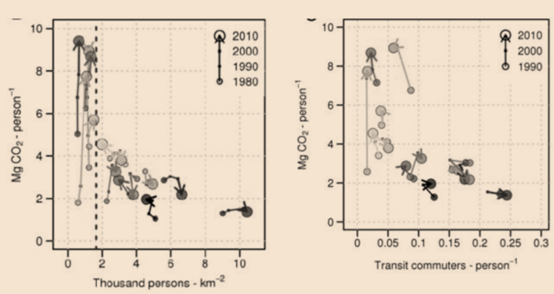


Figure 2. Left: Decadal per capita emissions vs. density for 14 US cities. Movement in time is denoted by point size and arrows. Right: Per capita on-road CO2 plotted vs. the share of residents who commute using public transit. (Gately et al. 2015)

Building on insights from the work of Gately et al. (2015) on patterns in vehicle emissions across urban/suburban domains, we worked in collaboration with the City of Boston and the Boston Metropolitan Planning Organization's Central Transportation Planning Staff (CTPS) to characterize and analyze vehicle emissions at the scale of individual roads and intersections.

As patterns in on-road emissions are highly variable on scales of only minutes and 10s of meters, urban air quality models require detailed data on emissions at these scales in order to accurately quantify ambient pollution and identify hotspots of human exposure.

To achieve an emissions inventory at this necessary level of detail, we harmonized open-data streams from the Massachusetts Highway Department Traffic Count Database and Road Inventory with customized model outputs from the CTPS Travel Demand Model.

The Travel Demand Model uses detailed data on land use patterns and road capacity, combined with household-level data on trip patterns and travel modes, obtained from a statewide household travel survey, to predict roadway-scale travel patterns across eastern Massachusetts for different vehicle types (passenger cars, SUVs, medium and heavy trucks, transit vehicles) at different times of day.

We used the EPA's Motor Vehicle Emissions Simulator (MOVES) in combination with the INRIX vehicle speed database to quantify hourly emissions of CO, NO_2, NO_x, SO_2, $PM_{2.5}$ and CO_2 from road vehicles for each of the 280,000 individual road segments in eastern Massachusetts (Figure 3).

- We quantified the impact of traffic congestion on emissions, and found that at regional scales the congestion enhancement is relatively modest (3-6%), but that local hotspots induce annual emissions enhancements of 75% or higher for individual roadways in key corridors.
- We calculate that traffic congestion was responsible for wasting over 113 million gallons of fuel in 2012, worth ~ $415M. However, this accounted for only 3.5% of the total fuel consumed in Massachusetts, as over 80% of vehicle travel does not experience any congestion.
- Emissions in the region are highly concentrated, with over 70% of emissions originating from only 10% of the roads. Notably, we found that the 2011 EPA National Emissions Inventory (NEI) estimates of NO_x, $PM_{2.5}$, and CO_2 are 46%, 38%, and 18% lower, respectively, than our bottom-up estimates for the counties in our study area.
- Emissions of CO and SO_2 agreed within 5% for the two inventories, suggesting that the large biases in NO_x and $PM_{2.5}$ emissions arise from differences in model estimates of diesel vehicle activity.

Our inventory framework utilizing mobile phone and GPS data provides fine-scale information on local emission hotspots and regional emissions patterns to support targeted traffic interventions, transparent benchmarking, and improvements in overall urban air quality.

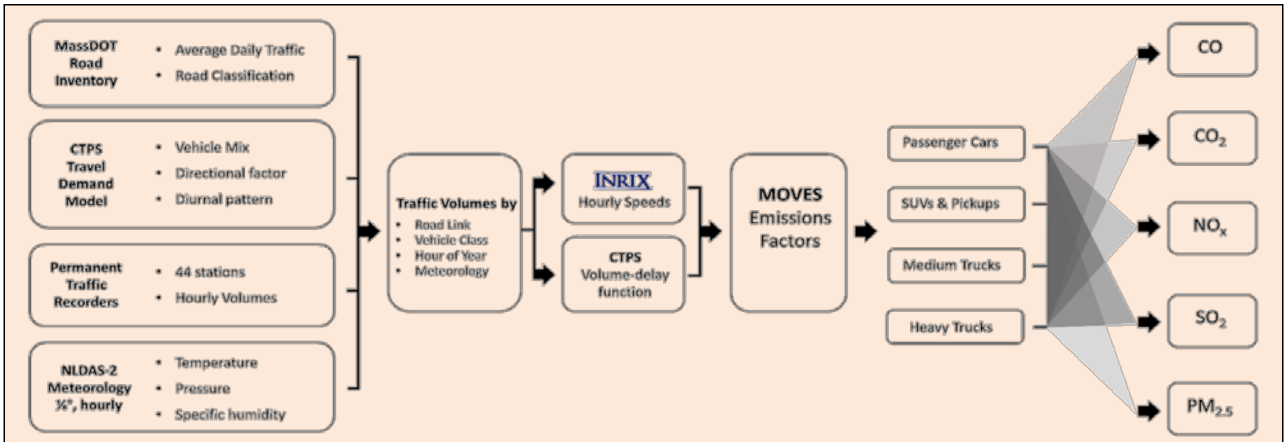


Figure 3. Data fusion methodology. The four major input datasets are spatially merged to generate hourly traffic volumes for 4 vehicle types for each of the 280,424 road segments in the domain, coupled to the hourly ambient meteorology for each road. Traffic flow speeds are assigned to segments using INRIX data where available, or else imputed using a delay function relating speed to road volume and capacity. Emissions of CO, CO_2, NO_2, NO_x, SO_2, and $PM_{2.5}$ are calculated using MOVES2014a for all combinations of vehicle types, speed intervals, and temperature and humidity regimes.

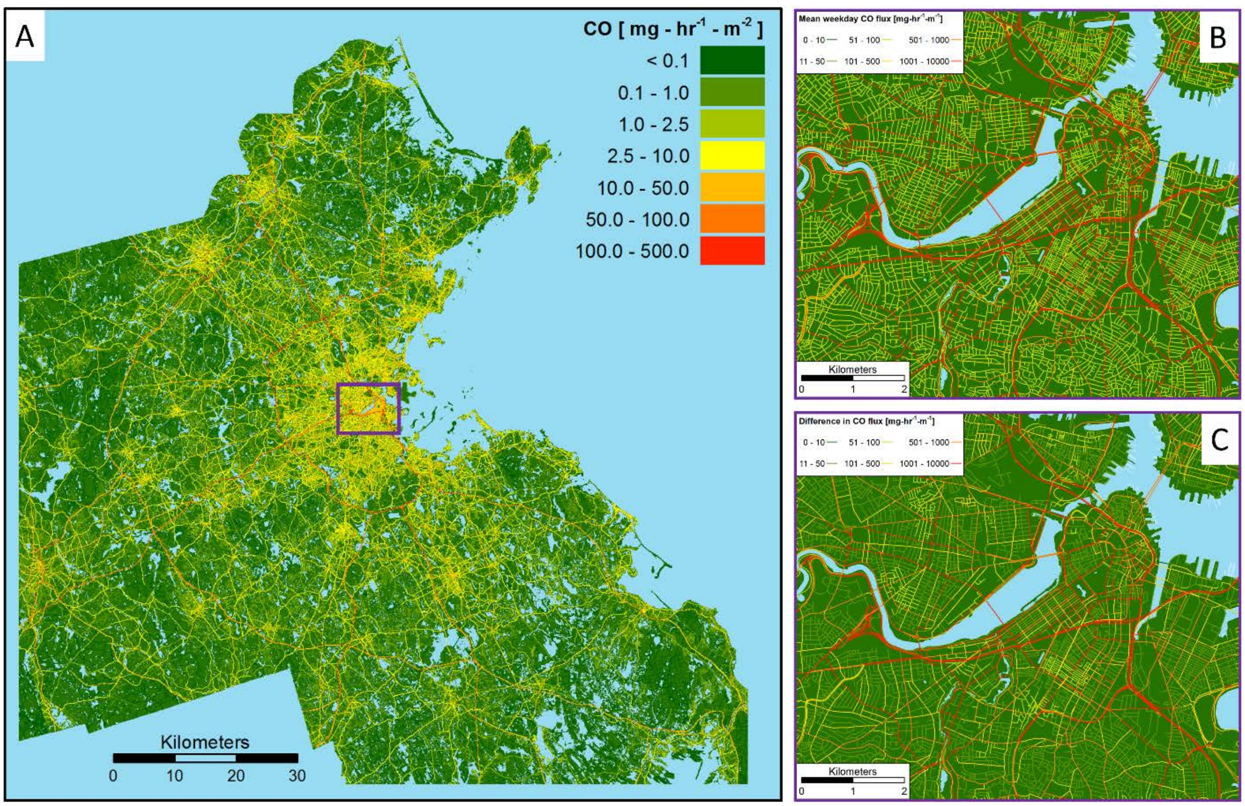


Figure 4. Annual mean hourly CO flux for study domain (Panel A). Panels B and C show a 65 km^2 area surrounding downtown Boston described by the purple box in Panel A. The mean hourly CO flux during weekday evening peak periods (3pm – 7pm) is shown in Panel B, while Panel C shows the difference between the weekday evening CO flux and the overall mean weekday flux (same color scale). Freeway and major arterial emissions are 25-50% higher during evening peak compared to mean daytime.

emissions.

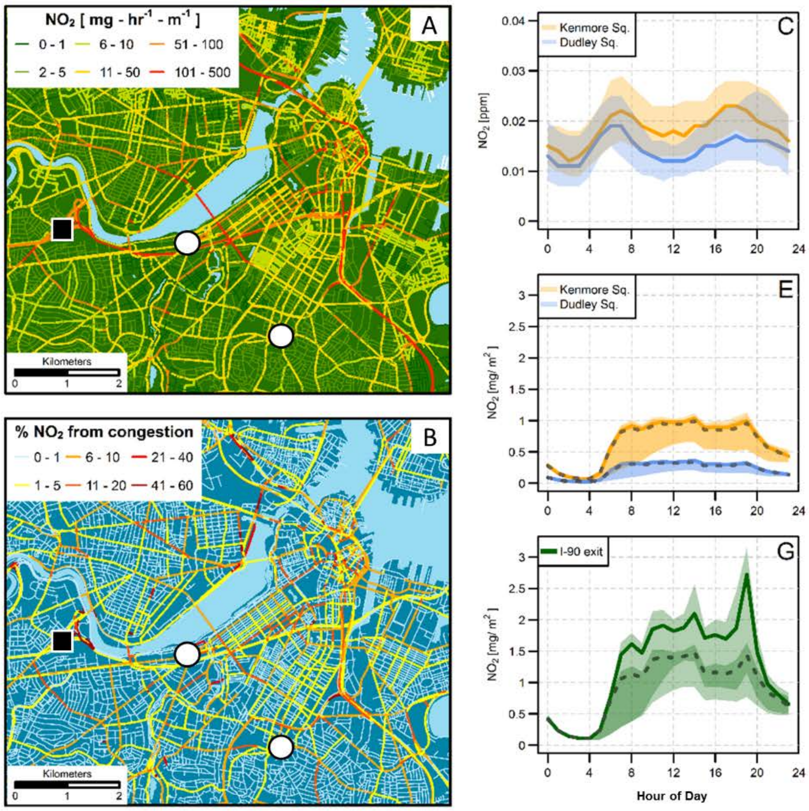
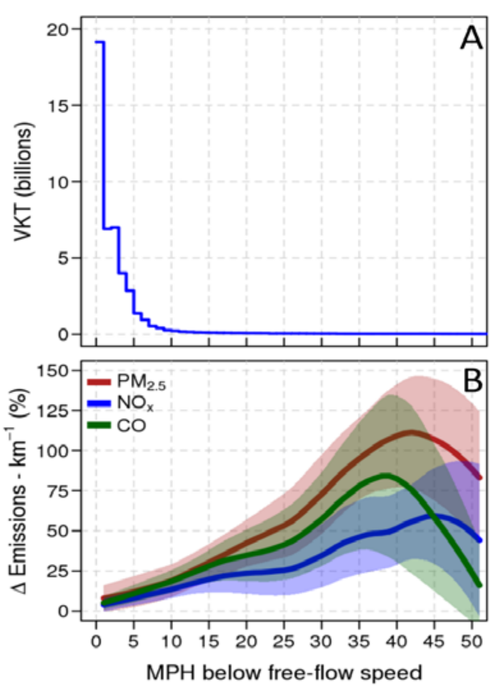


Figure 5. Panel A shows mean weekday daytime NO_2 fluxes in the metro Boston urban core. Panel B shows the percent of total weekday daytime NO_2 emissions that occur solely due to congested traffic conditions. Panels C-D show median and interquartile range of ambient NO_2 and CO concentrations measured at the EPA Air Quality System (AQS) stations in Kenmore and Dudley Squares, (upper and lower white circles in panel A, respectively). Panels E-F show median diurnal weekday NO_2 and CO fluxes for grid cells within 500 meters of the AQS stations. Panels G-H shows equivalent fluxes at an emissions 'hotspot': Interstate-90 near a major exit ramp (black box). Solid lines show 2012 estimates, grey dashed lines show estimated fluxes if traffic congestion was eliminated. Shaded areas represent interquartile ranges.

Figure 6. Distribution of annual VKT by congestion intensity (Panel A). Congestion intensity is expressed as the difference between free-flow and observed speeds. Panel B shows the percent change in emission rates of $PM_{2.5}$, NO_x, and CO as a domain is uncongested (ΔMPH < 5), and of the VKT that is congested, over 50% experiences only moderate speed reductions of 5-25 MPH.



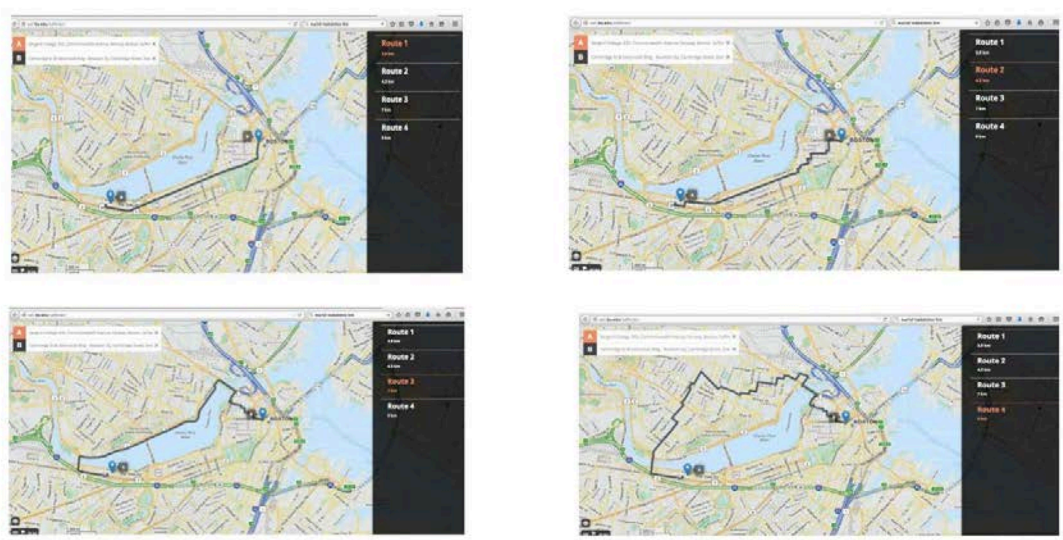
B.2 Cross Cutting: Data-driven Public Safety Applications

Evimaria Terzi (Co-PI)

A first prototype of the implementation and the transferring of route-recommendation algorithms within the context of a platform that users can use is now available at: http://sail.bu.edu/safenav . The main idea behind this effort is to create a platform for route recommendations to users so that people can insert different datasets (e.g., datasets that incorporate different features such as distance, crime rates etc) and the system will adapt its recommendations to the input data. At the same time, the platform will be flexible so that different developers can incorporate and test their different routing algorithms.

As a first step towards generating this platform, we have focused on providing alternative route recommendations to users so that take into account two objectives: (a) the distance between the source and the destination and (b) the safety of the route as computed using crime data from the city of Boston website (available here: https://data.cityofboston.gov/).

An instance of how the current service operates is shown in the screenshots below: here the user gives as input a starting and an ending point (Boston University and a location near the Boston town hall) and the user is given back 4 alternatives as shown below.

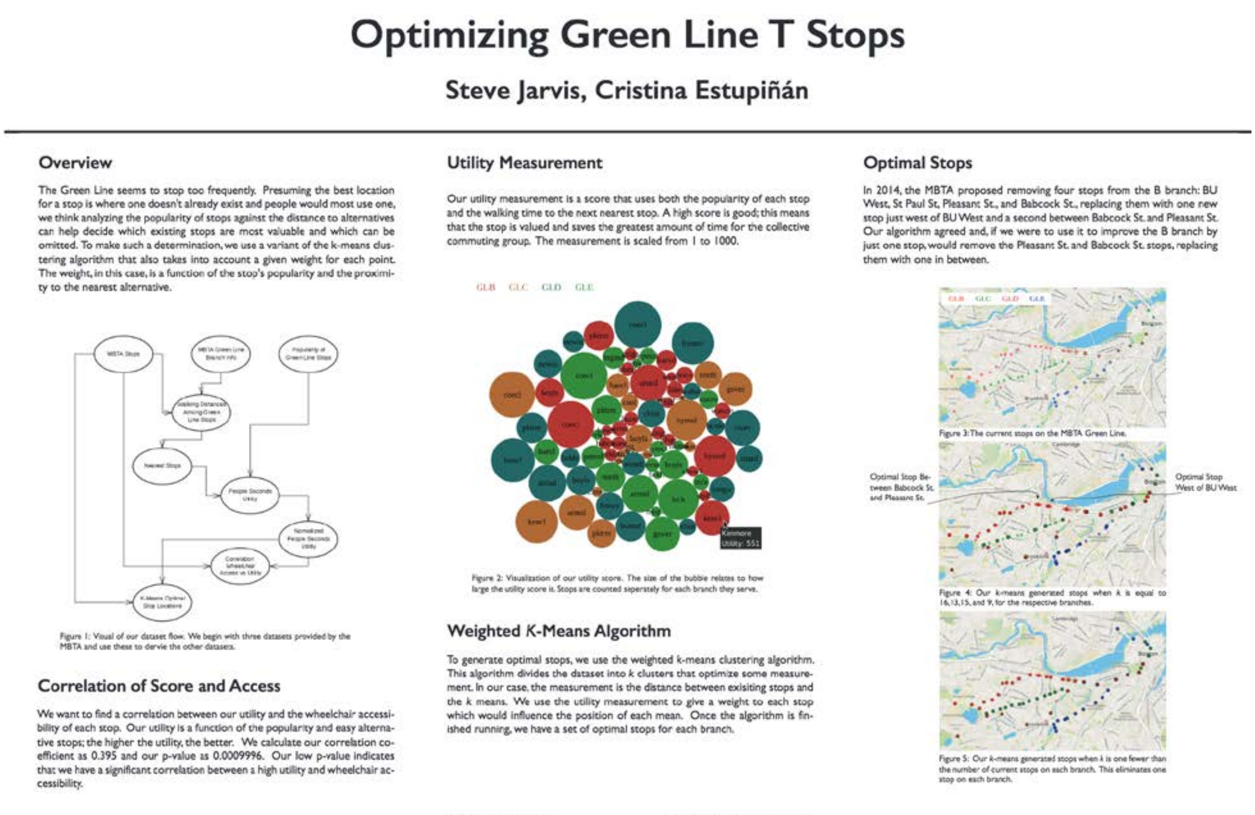


B.2 Data-driven Public Safety Applications & C.1 Mobility Index Analytics

Azer Bestavros (PI) and Evimaria Terzi (Co-PI)

As part of the coursework for the first iteration of a course on urban data science ("Data Mechanics"), students assembled projects that utilized real-world data from the City of Boston and other sources, applied optimization and analysis algorithms to that data, and produced interactive visualizations of the results. The projects were implemented as part of a unified platform in which all the data sets stored within the platform (both the source data sets obtained from third parties as well as data sets derived using algorithms chosen and implemented by students) were interoperable.

The student projects addressed subjects like public safety, transportation planning, urban accessibility and quality of life, and others. As such, some of the projects contributed to one or more activities (in particular, projects that dealt with public safety issues such as the prevalence of crime with relation to other factors such as lighting or neighborhood classification addressed B.2, while projects that dealt with public transit systems and bicycle safety addressed C.1). Some projects could also act as back-end components for potential mobile applications. Posters from a few of the 18 students projects are provided as illustrative examples.



ComputerScience — BOSTON UNIVERSITY

BOSTON BIKES

Expanding Select Bicycle Lanes to Improve Bike Safety in Boston

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CS 512 & CS 591 L1

INTRODUCTION

- **2007** – *Boston Bicycle Program* launched: doubled ridership.
- **2012** – 5 fatal bicycle incidents.
- **2013** – *Boston Bike Network Plan* : decreasing bicycle crashes by 50 percent by 2020.
- This project: *identifying a comprehensive network of bicycle routes* through the city of Boston based on the Bikes Crash Data.

DATA

- **Bikes Crash Data Sets** (2009 – 2012):
  - Boston Bikes Crash Data (by BPD)
  - EMS Crash Data (by City of Boston)
  - Bike Collision Database (by Harvard Dataverse)
- **Existing Bike Network** (by BostonGIS)
- **Boston OpenStreetMap** (by Metro Extracts)
  - to get groups of connected streets
  - to acquire the length of each street

Figure 1. Existing Bike Lane & Bikes Collisions in Boston

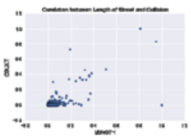

Figure 2a.

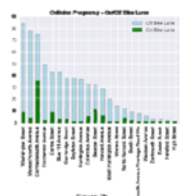

Figure 2b.

DATA VISUALIZATION

- **Figure 2a**: no strong evidence suggests the covariance between the length of the street versus the amount of bike collisions.
- **Figure 2b**: there are significantly less collisions occurred in the bike lane, compared to the streets without bike lane.

DATA ANALYSIS

- **Goal:**
  - To build a better *connected* bike lane network
    - What are the main streets that need a bike lane (if it hasn't) in order to achieve connective routes?
- **Modeling:**
  - 3 states for each pair of streets (x_i,x_j) that connect/intersect:
    - S_1 = both streets have bike lanes.
    - S_2 = only 1 of the 2 streets has a bike lane.
    - S_3 = neither of the streets have bike lanes.
  - Binary representation:
    - S_1 = (1, 1)
    - S_2 = (1, 0) or (0, 1)
    - S_3 = (0, 0)
  - State Transformation (Figure 3.)

Figure 3. States Transformation

- **Optimization:**
  - *Maximize* S_1 where most bike lanes are connected.
  - non-linear model:
  - $argmax_{i,j \in N} \sum(-1)^{x_i * x_j}$
    - *constraint set*: $x_{i,j} \in \{0,1\}$ where 0 represents no bike lane, 1 means there is a bike lane.
    - Solver: **dReal**
  - *Minimize* S_2 where single bike lanes are left alone.
  - linear model:
  - $argmin_{i,j \in N} \sum |xi - xj|$
    - *constraint set*: $x_{i,j} \in \{0,1\}$ where 0 represents no bike lane, 1 means there is a bike lane.
    - Solver: **Z3Opt**
  - Both models need constraint on how many bike lanes *K* would like to be added:
    - $x_1 + x_2 + \cdots + xN \leq K$

FUTURE WORK

- Linear Programming vs. Integer Programming
- Statistical analysis on the impact of adding bike lanes.
- Updated Bike Collision Data.
- More information on when (date) each bike lane was installed in order to match with the bike collision on bike lane.

REFERENCES

- Boston Bikes, http://www.cityofboston.gov/bikes
- Figure 1., https://public.tableau.com/profile/asross#!/
- http://www.cs.bu.edu/faculty/kfoury/UNI-Teaching/CS512-Spring16
- http://cs-people.bu.edu/lapets/591/

"AGE-FRIENDLY" SCORING IN BOSTON

BOSTON UNIVERSITY

Jacqueline You

Introduction

Projections from the City of Boston's 2014 report on "Aging in Boston" indicate that by 2030, about 20% of Bostonian residents will be age 60 or older.

Boston is a member of the World Health Organization's Age Friendly Cities Network. The Milken Institute, an economic think tank, ranked Boston fourth on its 2013 list of "Best Cities for Successful Aging" in the US.

Factors that are considered important to older adults, professionals who work with them, and other community leaders include:

- Physical health
- Housing costs
- Mental wellbeing
- Cost of healthcare
- Transportation access
- Access to social services

Some metrics developed by private and public entities measure factors like transportation access, retail access, and general walkability. These are usually general measures for either the general public or consumers, without a specific target audience/population. They include the Greater London Authority's Public Transport Accessibility Levels (PTAL), Walk Scores' "walkability" service, and the Location Affordability Index's Retail Access Index.

Project

This project attempts to create a distance-based score for a given location in Boston to quantify its "age-friendliness." At this point, the score does not include other information such as healthcare/housing expenses or population composition.

Location data, including longitude/latitude and address, of resources including hospitals, MBTA stops, and community centers (Figure 1), are collected and processed. A particular (potentially arbitrary) input location's geocoded location is then used to compute distances between a given resource and the input location. The distance measures used are either walking distance between the input and destination locations (via the MapQuest API) or approximate absolute distance using Vincenty's formulae.

Currently, the distance to the nearest location or the median value in a restricted set of locations is calculated to represent a subscore for that resource. These subscores are then weighted and summed to produce an overall distance-based score.

Figure 1. Some of the major data sets used in this project.

Figure 2. A map showing a selection of the locations of interest used in this project, namely hospitals (in red) and community centers providing senior services (in blue), in the City of Boston.

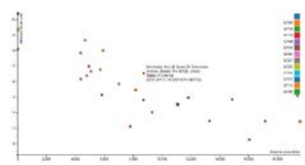

Figure 3. Interactive plot comparing weighted distance score against Retail Access Index from the Housing Affordability Index .

Visualizations

Two visualizations are produced in relation to this project:

a. Scored locations, along with certain categories of sites, are mapped using Leaflet to qualitatively show the distribution of sites in different neighborhoods of Boston (Figure 2).

b. For a given location, its score is plotted against information from the Housing and Urban Development and Department of Transportation's Housing Affordability Index for the location's Census Block Group (Figure 3).

Conclusion

This project presents a basic weighted distance scoring system to measure accessibility to major resources; this scoring could be made more sophisticated with measures such as taking into account inpatient bed count at each hospital, etc., incorporating more statistical methods, and using less arbitrary weights.

This scoring system could be used to randomly select points in a particular neighborhood and calculate an average score for the region. Point selection could occur by using geojson polygon data. The scores by neighborhood/region could then be compared to the current distribution of adults age 60 and older throughout different neighborhoods in Boston.

Selected References

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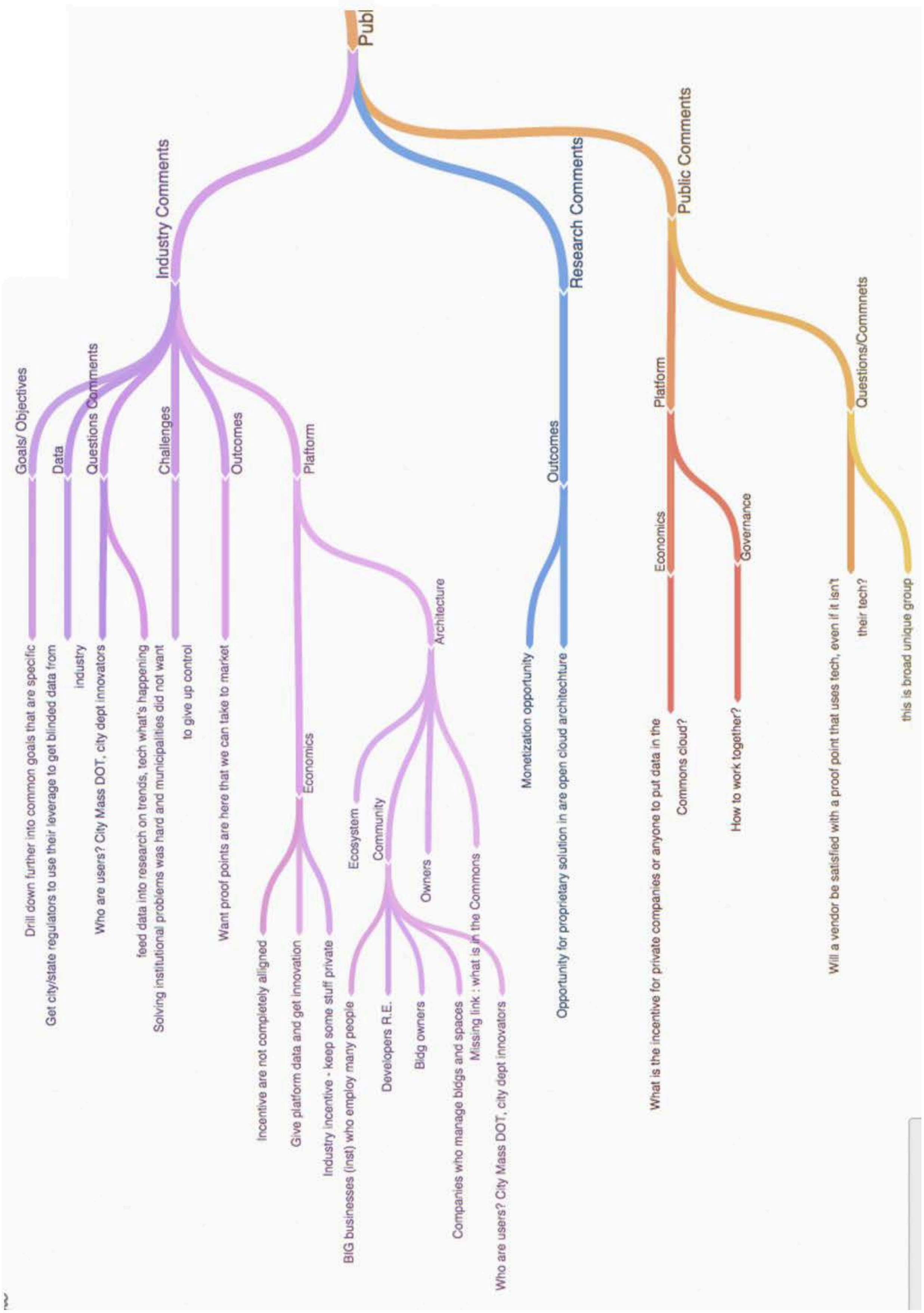
SCOPE Workshop Mind Map



C.2 SCOPE Capabilities: Secure Multi-Party MapReduce Salary Equity Software

Azer Bestavros (Project PI)

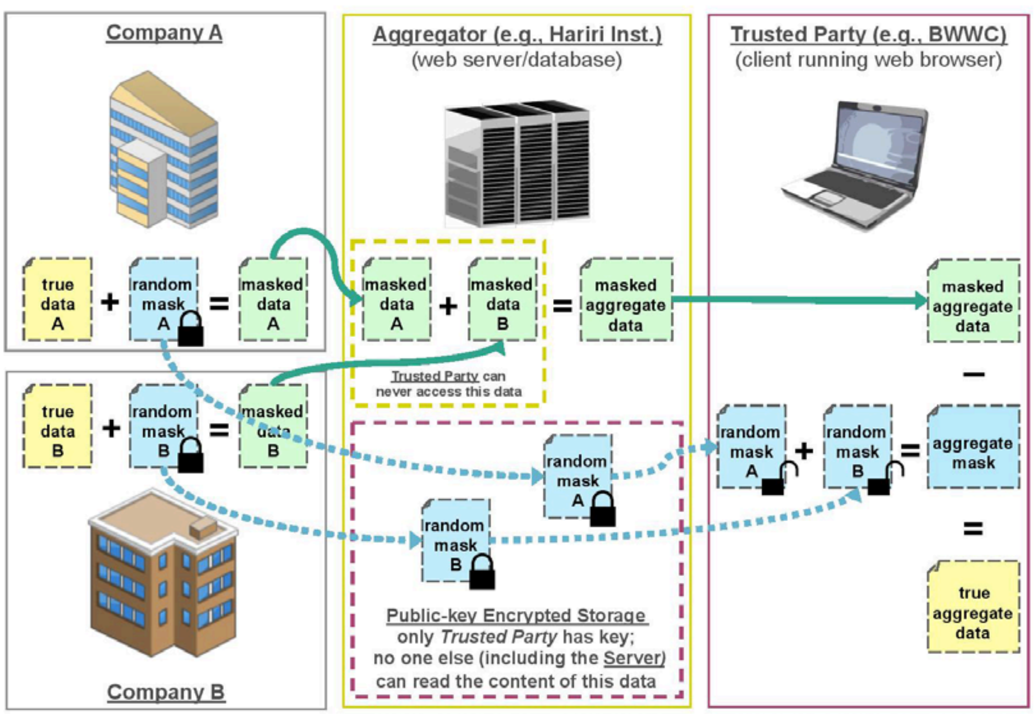
The Salary Equity software allows a group of companies to calculate compensation analytics at the aggregate level without revealing compensation information about any of the participating companies. This platform is an example of multi-party computation in which a group of organizations jointly performs a computation without releasing any of the privately held data assets on which the computation is performed. The prototype application was developed in May 2015 and deployed and used by over 40 of Boston Womens Council (BWC) signatories on June 8th 2015 to compute the BWC major pay equity aggregate statistics.

The first diagram illustrates the logical design of the application, as well as the process that all parties involved follow to perform a computation session collectively and securely. Three parties are involved: the participating **companies** that want to participate in the data collection process, an **aggregator** that stores the data, and the **trusted party** that starts the session and computes the final result. A computation session proceeds as follows:

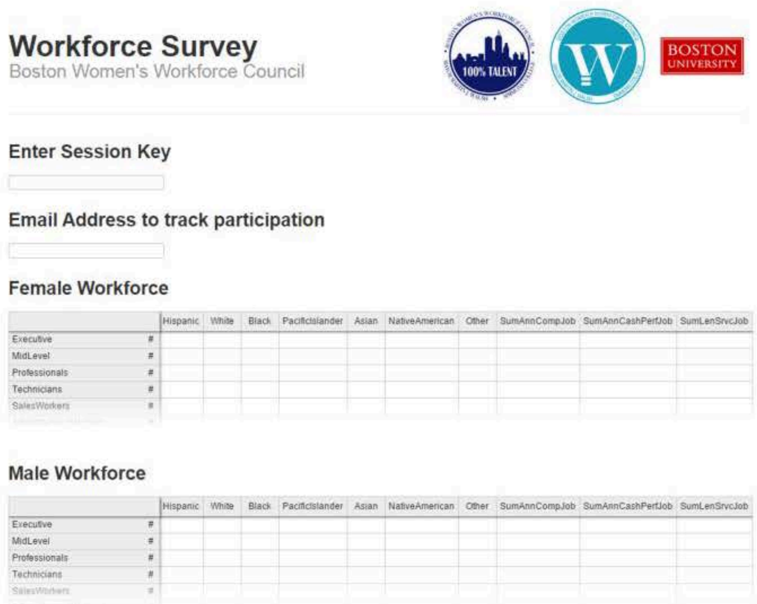
- each company masks its true data using randomly generated masks;
- each company then sends its masked data to an aggregating server, and also stores the masks securely on that server by ensuring that they are encrypted and can only be retrieved by the trusted party;
- the aggregator then computes the aggregate of the masked data;
- finally, the trusted party then retrieves the masks and the aggregate of the masked data, decrypts the masks, and subtracts the total from the masked aggregate to retrieve the true aggregate.

The second diagram illustrates the interfaces of the application as they appear within a standard web browser. The companies enter their data in a spreadsheet, and the trusted party coordinates the process of a dashboard.

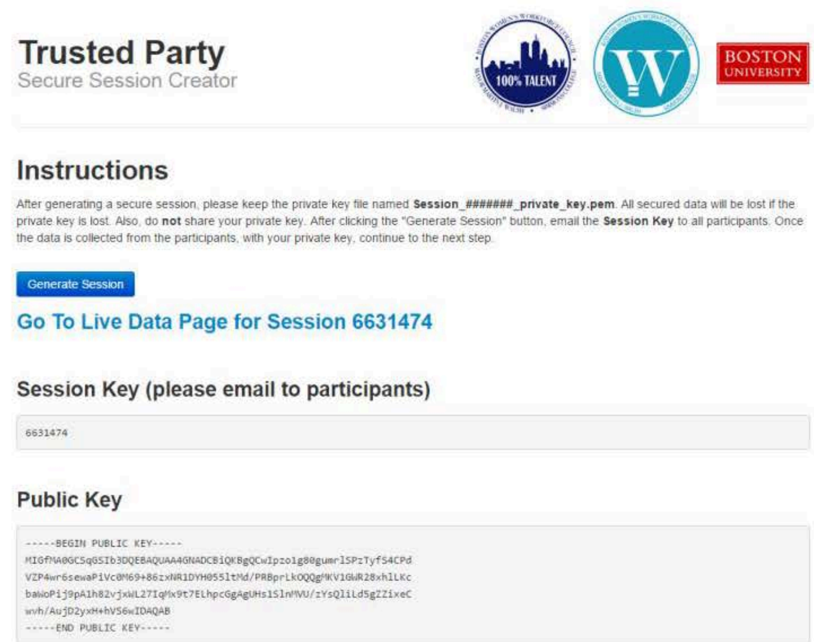
Salary Equity Project – Aggregation Application Data Flows



Salary Equity Project – Aggregation Application Interfaces



Company Interface



Trusted Party Interface

Boston Globe, City of Boston, and BU Today web sites related to the use of SCOPE Multi-Party Computation platform for supporting gender wage gap. Paper describing the platform as well as picture of PI Bestavros with Mayor Marty Walsh at the unveiling of the software which was used by over 50 major employers in a first-of-its-kind exercise.