Center for Teaching Old Models New Tricks (TOMNET)

A USDOT Tier 1 University Transportation Center

PROJECT PROPOSAL

Title: Grid-aware robust fast-charging station deployment for electric buses under socioeconomic considerations

Principal Investigator: Chaoyue Zhao, Industrial & Systems Engineering, University of Washington

Co-Principal Investigator (if applicable): Cynthia Chen, Industrial & Systems Engineering and Civil & Environmental Engineering, University of Washington

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1. Introduction/Problem Statement

With a 27% contribution to greenhouse gas (GHG) emissions in 2020, the transportation system has already become the biggest economic sector that consume fossil fuels [1]. To reduce the exhaust gas emissions of public transportation, the concept of electromobility is rapidly being embraced by public transportation authorities. When it comes to bus system, electromobility offers substantial advantages in terms of the decreased operating and maintenance costs, increased energy efficiency, improved reliability, and reduced air and noise pollution. The recent developments in battery technology and price reduction of battery have also greatly encouraged the fleet electrification in many cities world widely. For example, in United States, electric bus pilot programs have been implemented in many areas, including New York City [2], Chicago [3], Salt Lake City [4], Los Angeles [5], Washington, D.C. [6] and King County in Washington [7]. Toronto in Canada, London in UK, and Mexico City in Mexico, are committed to a 100% zero-emission bus fleet by 2040 [8] and 2025 [9] respectively.

Despite many advantages compared with conventional diesel buses, electric buses suffer from the disadvantages of limited driving range and slow charging rate. In addition, for many companies, their electric buses have to be charged at their own facilities. That means the buses have to be off route to get charged, which is inefficient and time-consuming. Fortunately, the recent development of fast-charging technology offers a great opportunity to offset aforementioned shortcomings of electric buses. The fast-charging technology enables electric buses to be quickly recharged during trips so that on-route operations can be maintained with modest battery capacity. Potential fast-charging stations for electric buses can be the bus stops of the served routes. Where to place the fast-charging stations and how to ensure the availability, efficacy, and efficiency of charging infrastructure become very important issues and have been studied in recent years [10-13]. However, most of existing literature of this research only focus on the transit system itself and aim to reduce the costs. There are still several critical issues remain to be unsolved for the deployment of electric bus fast-charging stations:

1. Power grid interaction. Fleet electrification will closely connect the transportation and power systems. This system interactions not only bring benefits, such as increasing grid flexibility, enabling load shifting, and facilitation of decarbonization, but also bring significant challenges, such as voltage instability, power quality problems, increased power loss, and transformer

overloading. Therefore, taking local grid impacts into consideration is vital in planning the placement of fast-charging stations of electric buses.

2. Dynamic nature of fleet management. Choosing the location of charging stations involves a lot of uncertain and unforeseen circumstances. For instance, the quantity of passengers may influence battery energy consumption and, consequently, influence how the charging stations are arranged. The modeling process should also take into account the potential effects of traffic and weather on energy use and journey time, and local grid electricity usage on grid stability.
3. Fleet electrification in disadvantaged communities. Disadvantaged communities mostly reside in or near areas of high traffic, which makes them disproportionately impacted by transportation emissions and noises. This could be greatly lessened by fleet electrification. However, low-income and disadvantaged communities usually have a lower concentration of public charging infrastructure than wealthier areas [14]. The fleet electrification should be encouraged in low-income communities and make sure they can also benefit from new fast-charging station investment. The fairness and equity between communities should be considered when making the choice of electric bus charging stations.

2. Project Objectives

The major objective of this project is to develop a comprehensive optimization model to select the optimal location of fast-charging stations of electric buses. It aims at addressing several conceptual and methodological complexities inherited in the interconnected transportation-electricity infrastructure systems and the socioeconomic considerations for installing new charging stations to disadvantaged communities. In order to make the location selection decisions reliable, the optimization will also take into account a variety of uncertainties, such as traffic, local grid conditions, and energy usage between stops. A robust optimization methodology is adapted to guarantee that the selected locations are trustworthy enough to handle any real case scenario of uncertainty without violation of constraints. Benders' decomposition approach is utilized to effectively solve the resulting two-stage robust optimization problem in an iterative way.

3. Proposed Methodology and Data

This paper aims to study a location selection problem of fast-charging stations of electric buses, for achieving the integrated optimization of traffic efficiency, safety of power grid, economic interests of transit sector and fairness among communities. A two-stage robust mixed-integer problem (MIP) is developed, as shown in Figure 1. As for the model setting, we assume that every route has a distinct route cycle that is made up of a depot, a series of intermediate (en route) stations, and a terminal station. Any electric bus is supposed to charge either at the depot or during the cycle of its route. The initial candidate locations are assumed to be given prior solving the model (If not, then all the stations in the routes can be served as the initial candidate locations).

With the aim of minimizing the installation/investment cost, which takes into consideration the expenses of land use, charging infrastructure construction, and other fixed costs for establishing charging stations, a set of locations (characterized as binary variables) are chosen in the first stage. The locations should be selected subject to current traffic route requirements or the policy of land use. It should also assess the state of the grid network. For example, in some locations, existing power grids may not be efficient enough to provide additional and sufficient power for electric vehicles. When choosing the sites of charging stations, the requirements for battery capacity and state of charge (SOC) are also crucial. Otherwise, the buses may not have enough time to recharge or may run out of battery before arriving at the charging stations. To promote the fairness among the communities, we utilize the Rawlsian maximin criterion, with the objective of maximizing the least utility generated by the location plan among all the communities. It worth noting that all the first-stage decision are made “here and now”, before observing any realization of uncertainties like traffic information and grid load scenario.

The second stage will involve obtaining the charging schedule/amount (characterized as general continuous variables) for each route using the first stage's selection of charging stations. The objective is to minimize the total operational cost and the power loss cost while maintaining the power system security, battery state of charge balance, and energy usage balance as constraints. The solutions obtained in this stage are referred to as "wait-and-see". That is, the solution is depending on different realization of uncertain variables. More specifically, for each revealed scenario of traffic and grid condition, the corresponding charging schedule should be able to sustain adequate energy to complete trips and not cause any violation of power grid balance requirement. The second stage will give a recourse to the first stage to rule out any infeasible or suboptimal selection of charging locations.

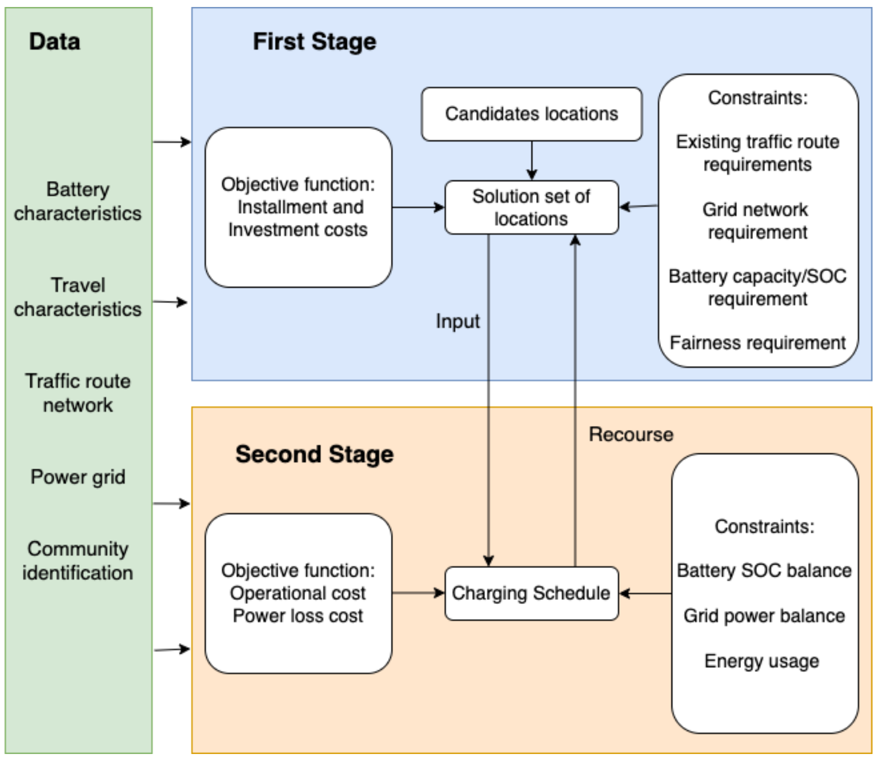

Figure 1: Two-stage optimization model structure

In addition, we intend to incorporate the idea of robust optimization [15-17] into the model's formulation. It is typically in a min-max or a max-min format. In this problem, we will derive the optimal location solutions based on the worst-case realization of uncertainty. That is, the choice of locations should be robust and trustworthy enough to handle any real case scenario without violation of constraints. We will use Benders' decomposition approach [18] to tackle this two-stage robust MIP formulation.

4. Work Plan (Project Tasks)

The following five tasks will be undertaken in this project.

<u>Task 1: Literature review</u>

In comparison to the extensive literature on the routing component of electric bus management, the selection of fast-charging stations for electric vehicles has received less attention, among which the studies on grid interactions and impact are even less. However, the strategic plan for managing charging infrastructure with grid stability could greatly facilitate the integration of fleet electrification in good distribution schemes. The project will conduct a comprehensive review of the literature on the studies of general fleet charging infrastructure management to gain insights and tackle transit-power interdependency in Task 2.

Although, as far as we are aware, the fairness concern surrounding the selection of charging stations for electric buses has not been covered in literature before, the fairness through general social welfare optimization has been researched. We have already studied some of this literature, but a more thorough literature review on this topic will be needed in order to effectively complete this project.

<u>Task 2: Two-stage mixed integer model development</u>
In this task, we will develop a two-stage mixed integer model to describe the optimal strategy of charging station selection of electric bus. Candidate locations modeled as integer variables are determined in the first stage for minimizing installment cost of charging stations, while charging schedule and amount modeled as continuous variables are decided in the second stage for minimizing the total operational cost and power loss cost. In particular, we will focus on the interdependency of transit and power distribution networks and model the impact of the selection decisions on the stability of local power grid. To ensure that the utility of constructing additional charging stations for underserved neighborhoods does not differ from that in wealthy places, we will also include the fairness aspect in the model. Several fairness metrics such as Rawlsian criteria [19], leximax criteria [20], and McLoone index [21] will also be discussed in this task.

<u>Task 3: Robust optimization counterpart and solution approach</u>
In this task, uncertainties such as energy usage and grid load will be incorporated into the model. First, we construct an ambiguity set of these uncertain parameters in order to characterize their random behavior. These uncertain parameters are allowed running adversely within the ambiguity set. In our approach, the ambiguity set considers that the uncertain parameter for each operating hour is between a lower bound and an upper bound, which can be inferred from the historical data. Besides, an overall budget constraint will be added to the ambiguity set to make the summation of all uncertainties within the planning horizon bounded below. With the constructed ambiguity set, we can derive the two-stage robust optimization counterpart of the model. That is, in the first stage, we include the charging location decisions with unknown energy usage and grid load patterns. After realizing the worst-case scenario of energy usage and grid load, we decide in the second stage the charging schedule for each electric bus to minimize the total cost with the consideration of the worst-case scenario of uncertainty. As a result, the obtained solution will be robust enough to handle any realization of uncertainties. To solve the problem, we will use Benders' decomposition. By adding feasibility and optimality cuts, we can solve this problem iteratively.

<u>Task 4: Report results and publish in a peer-reviewed journal</u>
Final report will be completed encompassing Tasks 1 to 3. The project findings will be disseminated via a peer review journal publication and presented at Transportation Research Board conference.

5. Project Schedule

The timeline of this project is described in Figure 2:

Task name	Timeline											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Task 1: Literature review												
Task 2: Model development												
Task 3: Solution approach												
Task 4: Final report												

Figure 2: Timeline of the project

6. Relevance to the Center Theme/Mission

Electromobility is expanding globally due to its substantial environmental, operational and energy-related advantages. Since buses account for more than 80% of all public transit trips worldwide, the transition from currently deployed conventional diesel buses to greener electric buses can greatly reduce the exhaust greenhouse gas (GHG) emissions and directly impact the quality of life in cities. The study of charging infrastructure of electric buses is highly relevant to the mission of TOMNET to understand the impact of technology changes on transportation and reflect the new mobility choice of transit system.

Meanwhile, due to the rising adoption of electric buses, the transportation and electricity sectors are becoming more connected and interdependent. Though the electric bus charging can introduce significant technical issues to the power grid, such as voltage drop and grid fault, the power grid stability is the most crucial yet least explored aspect for electric buses. Understanding the interactions and impacts between transportation and electricity sector is of great importance to enhance and improve the resilience and reliability of each system, which is also aligned with TOMNET's mission.

Last but not least, the applications to important topics like equity are greatly encouraged by TOMNET research. This project strikes to improve electric bus penetration in disadvantaged and underserved communities and make sure those in disadvantaged communities could benefit from transportation electrification.

7. Anticipated Outcomes and Deliverables

The proposed project will result in the development of comprehensive robust optimization modeling framework on the selection scheme of fast-charging stations of electric buses, for achieving the integrated optimization of traffic efficiency, safety of power grid, economic interests of transit sector and fairness among communities. The main deliverables of this project will be a final report, peer-reviewed paper documenting the work and findings, and a presentation at Transportation Research Board conference.

8. Research Team and Management Plan

Chaoyue Zhao is an Assistant Professor in the Department of Industrial & Systems Engineering at the University of Washington (Seattle). She works on data-driven optimization methodologies to support strategic and operational planning in power systems management. She developed innovative distributionally robust optimization approaches to enable effective decision-making under uncertainty for power system operations and planning, flexibility, resilience, renewable energy integration and risk assessment. Her work has been published in top-tier journals such as IEEE Transactions on Power Systems, IEEE Transactions on Reliability with about 2000 citations. She has received multiple grants from the federal agencies such as the National Science Foundation, Department of Transportation and Argonne National Laboratory. She is an associate editor of IISE Transactions.

Cynthia Chen is the interim chair in the Department of Industrial & Systems Engineering and a professor in the Department of Civil & Environmental Engineering at the University of Washington (Seattle). She is an internationally renowned scholar in transportation science and directs the THINK (Transportation-Human Interaction and Network Knowledge) lab at the UW. The work at THINK lab is at the intersection of human behavior and the system within which individuals and businesses operate. More specifically, THINK lab research unpacks complexities found at different scales of an urban system from micro-level individual behaviors, to meso-scale interactions formed as the result of individual behaviors, and to macro-scale system behaviors that propagate through a single network or multiple networks. Cynthia has published over 60 peer-reviewed publications in leading journals in transportation and systems engineering including Transportation Research Part A-F and Omega, as well as interdisciplinary journals such as PNAS. Her research has been supported by federal agencies such as NSF, NIH, APAR-E, NIST, USDOT, and FHWA as well as state and regional agencies. Cynthia served a two-year assignment from 2017-19 as the Program Director of Civil Infrastructure Systems, CMMI (Civil, Mechanical, and Manufacturing Innovation) division with the National Science Foundation. She is an associate director of TOMNET (Center for Teaching Old Models New Tricks), a USDOT-funded Tier 1 University Transportation Center led by ASU. She is also an associate editor of two leading journals: Transportation Science, and Service Science and is on the editorial board of Sustainability Analytics and Modeling.

Xinyi Zhao is a PhD student in the Department of Industrial & Systems Engineering at the University of Washington (Seattle). She got her MSc in electrical engineering, from Tsinghua University with Tsinghua Comprehensive Scholarship. She has great research experience in operations research, especially its application of power systems area. She has two journal papers published, including the first-author paper published in Applied Energy, a flagship journal in energy area. She also has three conference proceedings including two first authored ones, and one patent. She has participated in several National Key R&D Programs of China and cooperated with China Southern Power Grid, State Grid Corporation, China Resource Power Holdings, and so forth. She was proficient with power system modeling, optimization methods, and algorithm implementation.

9. Technology Transfer Plan

The results of this project will be disseminated through peer-reviewed publications and conference presentations, as well as collaborations with various industries and local communities. The team plans to implement the proposed framework in open-source software and provide tutorials for researchers and practitioners who can benefit from it. All data (after suitable anonymization if necessary), results and code will be documented and made publicly available through the project website, research seminars, conference presentations, and scientific journals.

10. Workforce Development and Outreach Plan

The proposed project will involve one research assistant. The research effort will allow this student to gain valuable training experiences via conducting research activities, attending academic conferences, and collaborating with other researchers. The project will provide new course materials for the undergraduate- and graduate-level courses the PIs are teaching at UW. More specifically, Dr. Zhao is teaching both a graduate level and an undergraduate level integer programming courses. The content of this research will be utilized as optional course projects to broaden students' vision on industrial application and deepen their understanding on mixed integer programming. Finally, the research team is strongly committed to diversity, and will strive to include underrepresented minorities, including all three female researchers for this project, in all aspects of this research effort.

11. References

[1] United States Environment Protection Agency, 2022. *Sources of Greenhouse Gas Emissions*, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
[2] New York Power Authority, 2018. *Governor Cuomo Announces All-Electric Bus Pilot Program to Reduce Emissions and Modernize Public Transit Fleet*. https://electricenergyonline.com/article/energy/category/energy-storage/143/675861/governor-cuomo-announces-all-electric-bus-pilot-program-to-reduce-emissions-and-modernize-public-transit-fleet-.html
[3] Chicago Transit Authority, 2014. *CTA Announces First Electric-Powered Buses Added to its Fleet*. https://www.transitchicago.com/cta-announces-first-electric-powered-buses-added-to-its-fleet/.
[4] Utah Transit Authority, 2016. *UTA Announces Plans to Add First All-Electric Buses to Fleet*. https://www.rideuta.com/news/2016/04/UTA-Announces-Plans-for-All-Electric-Buses.

[5] Kinman, M., 2017. *DASHing to a Clean Electric Bus Future for Los Angeles.* https://environmentcalifornia.org/blogs/blog/cae/dashing-clean-electric-bus-future-los-angeles.
[6] DDOT, 2018. *Mayor Bowser Celebrates Arrival of New Electric Circulator Buses*. https://ddot.dc.gov/release/mayor-bowser-celebrates-arrival-new-electric-circulator-buses.
[7] King County Executive, 2017. *King County Executive announces purchases of battery buses, challenges industry to build next-generation transit*. https://www.kingcounty.gov/elected/executive/constantine/news/release/2017/January/10-battery-buses.aspx.
[8] Toronto Transit Commission, 2019. *TTC Green Initiatives*. https://www.ttc.ca/riding-the-ttc/TTC-Green-Initiatives
[9] Bloomberg New Energy Finance, 2018. *Electric buses in cities: Driving towards cleaner air and lower CO2*. On behalf of: Financing Sustainable Cities Initiative, C40 Cities, World Resources Institute, Citi Foundation. https://data.bloomberglp.com/professional/sites/24/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf.
[10] Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., & Silveira, S. (2017). *Locating charging infrastructure for electric buses in Stockholm*. Transportation Research Part C: Emerging Technologies, 78, 183–200. https://doi.org/10.1016/j.trc.2017.03.005.
[11] He, Y., Song, Z., & Liu, Z. (2019). *Fast-charging station deployment for battery electric bus systems considering electricity demand charges*. Sustainable Cities and Society, 48, 101530. https://doi.org/10.1016/j.scs.2019.101530.
[12] Chen, Z., Yin, Y., & Song, Z. (2018). *A cost-competitiveness analysis of charging in- frastructure for electric bus operations*. Transportation Research Part C: Emerging Technologies, 93, 351–366. https://doi.org/10.1016/j.trc.2018.06.006.
[13] Iliopoulou, C., & Kepaptsoglou, K. (2019). Integrated transit route network design and infrastructure planning for on-line electric vehicles. Transportation Research Part D: Transport and Environment, 77, 178–197. https://doi.org/10.1016/j.trd. 2019.10.016.
[14] Hsu, C. W. & Fingerman, K. *Public electric vehicle charger access disparities across race and income in California*. Transport Policy 100, 59–67 (2021). https://doi.org/10.1016/j.tranpol.2020.10.003.
[15] Bertsimas, D., Brown, D. B., & Caramanis, C. (2011). *Theory and applications of robust optimization*. SIAM review, 53(3), 464-501.
[16] Zhao, C., & Guan, Y. (2013). *Unified stochastic and robust unit commitment*. IEEE Transactions on Power Systems, 28(3), 3353-3361.
[17] Zhao, C., Wang, J., Watson, J. P., & Guan, Y. (2013). *Multi-stage robust unit commitment considering wind and demand response uncertainties*. IEEE Transactions on Power Systems, 28(3), 2708-2717.
[18] Benders, J. F., 1962, *Partitioning procedures for solving mixed-variables programming problems*, Numerische Mathematik 4(3): 238–252.
[19] Ogryczak W, S´liwin´ski T (2002) *On equitable approaches to resource allocation problems: The conditional minimax solutions*. Journal of Telecommunications and Information Technology pp 40–48
[20] Ogryczak W, Sliwinski T (2006) *On direct methods for lexicographic min-max optimization*. In: Gervasi O, Kumar V, Tan C, et al (eds) Computational Science and Its Applications (ICCSA). Springer, LNCS 3982, pp 802–811
[21] Verstegen, D. A. (1996). *Concepts and measures of fiscal inequality: A new approach and effects for five states*. Journal of Education Finance, 22(2), 145-160.

12. Qualifications of Investigators

CHAOYUE ZHAO

Curriculum Vitæ

Industrial and Systems Engineering
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I. Professional Preparation
University of Florida, Gainesville, FL
Ph.D., Industrial and Systems Engineering, 2014
Dissertation title: Data-Driven Risk-Averse Stochastic Program and Renewable Energy Integration

Fudan University, Shanghai, China
B.S., Information and Computing Sciences, 2010

II. Key Appointments
University of Washington at Seattle, Seattle, WA, USA
Assistant Professor (Sep. 2019-present)

Oklahoma State University, Stillwater, OK, USA
Jim and Lynne Williams Assistant Professor (Aug. 2014 - Aug. 2019)

Pacific Gas & Electric Company, San Francisco, CA, USA
Contractor (Aug. 2012 - May 2013)

III. Products Most Closely Related to the Proposed Project
[1] Bagheri A, Zhao C. Distributionally Robust Reliability Assessment for Transmission System Hardening Plan Under N-k Security Criterion. IEEE Transactions on Reliability. 2019; 68(2):653- 662. Available from: https://ieeexplore.ieee.org/document/8694016/
[2] Sadra Babaei, Chaoyue Zhao, Lei Fan, Tieming Liu. Incentive-Based Coordination Mechanism for Renewable and Conventional Energy Suppliers. IEEE Transactions on Power Systems. 2019 May; :1--1. Available from: https://doi.org/10.1109/TPWRS.2018.2879657
[3] Zhao C, Guan Y. Data-driven risk-averse stochastic optimization with Wasserstein metric. Operations Research Letters. 2018; 46(2):262-267.
[4] Ali Bagheri, Jianhui Wang, Chaoyue Zhao. Data-Driven Stochastic Transmission Expansion Planning. IEEE Transactions on Power Systems. 2016; DOI: 10.1109/TPWRS.2016.2635098
[5] Zhao C, Guan Y. Unified stochastic and robust unit commitment. IEEE Transactions on Power Systems. 2013 April 04; 28(3):3353-3361. Available from: https://ieeexplore.ieee.org/abstract/document/6494360

IV. Synergistic Activities
1. Associate Editor for IISE Transactions and Reviewer for 20+ Journals
2. 30+ Presentations for 10+ conferences and universities.
3. Membership to The Institute for Operations Research and Management Science (INFORMS), 2011 - present; Institute of Electrical and Electronics Engineers (IEEE), 2011 - present; Institute of Industrial and Systems Engineering (IISE), 2011 – present
4. IISE Energy Systems Division Board member: 2019-present
5. Session & Track Chair of ISERC and Informs

12.Budget Including Non-Federal Matching Funds

[Provide itemized budget showing federal and non-federal matching funds. Please use the tabular format shown below. Projects should be of one-year duration. Multi-year projects should be proposed each year as a separate phase.]

Institution: University of Washington

Project Title: ZHAO TOMNET

Principal Investigator: Chaoyue Zhao

Budget Period: 9/16/2022 - 09/15/2023

CATEGORY	Budgeted Amount from Federal Share	Budgeted Amount from Matching Funds	Explanatory Notes; Identify Source of Matching Funds
Faculty Salaries	2,981	16,876	0.25 summer month from federal share for Chaoyue Zhao. 1.4 academic month from cost share for Chaoyue Zhao.
Other Staff Salaries			
Student Salaries	33,515		12 months student support from federal share
Fringe Benefits	7,857	4,067	Faculty benefits @ 24.1%
Total Salaries & Benefits	44,353	20,943	
Student Tuition Remission	25,392	14,615	Res/Non-Res tuition difference from cost share
Operating Services and Supplies			
Domestic Travel			
Other Direct Costs (specify)			
Other Direct Costs (specify)			
Total Direct Costs	69,745	35,558	
F&A (Indirect) Costs	24,616	11,623	MTDC 55.5%

TOTAL COSTS	94,361	47,181	

Grant Deliverables and Reporting Requirements for UTC Grants (November 2016)

Exhibit F

UTC Project Information	
Project Title	
University	
Principal Investigator	
PI Contact Information	
Funding Source(s) and Amounts Provided (by each agency or organization)	
Total Project Cost	
Agency ID or Contract Number	
Start and End Dates	
Brief Description of Research Project	
Describe Implementation of Research Outcomes (or why not implemented) Place Any Photos Here	

Impacts/Benefits of Implementation (actual, not anticipated)	
Web Links • Reports • Project Website	