University Transportation Research Center - Region 2

# Final Report

## Broadband Hybrid Electromagnetic and Piezoelectric Energy Harvesting from Ambient Vibrations and Pneumatic Vortices Induced by Running Subway Trains

Performing Organization: State University of New York (SUNY)

May 2017

**Sponsor:**
**University Transportation Research Center - Region 2**

## University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

**Education and Workforce Development**

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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**Principal Investigator(s):**
**Ya Wang**
Assistant Professor
Stony Brook University
Stony Brook, NY 11794
Tel: (631) 632- 8322
Email: ya.s.wang@stonybrook.edu

**Performing Organization(s):**
State Univesity of New York (SUNY)

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**Mailing Address:**

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

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**Bahman Moghimi***: Research Assistant;*
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16. Abstract

The airfoil-based electromagnetic energy harvester containing parallel array motion between moving coil and trajectory matching multi-pole magnets was investigated. The magnets were aligned in an alternatively magnetized formation of 6 magnets to explore enhanced power density. In particular, the magnet array was positioned in parallel to the trajectory of the tip coil within its tip deflection span. The finite element simulations of the magnetic flux density and induced voltages at an open circuit condition were studied to find the maximum number of alternatively magnetized magnets that was required for the proposed energy harvester. Experimental results showed that the energy harvester with a pair of 6 alternatively magnetized linear magnet arrays was able to generate an induced voltage (Vo ) of 20 V, with an open circuit condition, and 475 mW, under a 30 Ω optimal resistance load operating with the wind speed (U ) at 7 m/ s and a natural bending frequency of 3.54 Hz.

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## Executive Summary

The airfoil-based electromagnetic energy harvester containing parallel array motion between moving coil and trajectory matching multi-pole magnets was investigated. The magnets were aligned in an alternatively magnetized formation of 6 magnets to explore enhanced power density. In particular, the magnet array was positioned in parallel to the trajectory of the tip coil within its tip deflection span. The finite element simulations of the magnetic flux density and induced voltages at an open circuit condition were studied to find the maximum number of alternatively magnetized magnets that was required for the proposed energy harvester. Experimental results showed that the energy harvester with a pair of 6 alternatively magnetized linear magnet arrays was able to generate an induced voltage (Vo ) of 20 V, with an open circuit condition, and 475 mW, under a 30 Ω optimal resistance load operating with the wind speed (U ) at 7 m/ s and a natural bending frequency of 3.54 Hz.

## Background

Energy Harvesting (EH) is the process of capturing residual energy from one or several sources, which can then be harvested, stored, and conditioned for many low voltage/power electronic and sensor devices that required power supplies or batteries.[1-2] Currently, electrochemical batteries (zinc–carbon batteries, lithium-ion, etc.) are the main energy source for low-power application, especially portable/remote electronic devices. However, the size, cost, and maintenance, such as the burden of replacement or recharging of batteries limited its use in remote electronic application. [1-4] Therefore, the need of alternative power sources or EH that overcome these limitations are highly desirable.

Nowadays, most of the existing energy harvesting research has focused on the electromagnetic and piezoelectric transformation mechanism.[5] In the past, scientists had placed much of their efforts in harvesting the mechanical vibrations from humans[6] or moving vehicles. Recently, the focus on harvesting aeroelastic vibration to electrical energy has received a lot of attention over the last few years.[7-8] The goal is to convert airflow energy into electricity for powering small electronic components employed in remote applications, specifically those that are located in an environment with critical access to the electronic equipment in question.

## Objectives

In this project, a unique inductive mechanism was proposed to explore an airfoil-based wind energy harvesting mechanism, by means of a parallel array motion between multi-pole magnets and a flexible coil. In order to promote maximum magnetic flux density, the multi-pole magnets were positioned along the trajectory of the tip of moving coil and its deflection span. Compared to a traditional electromagnetic energy harvester using a single magnet and moving coil, our suggested harvester is able to harvest more energy in each period which is more suitable to power a high power electronic device.

## Introduction

Therefore, the inductive mechanism has been utilized in the airfoil-based wind energy harvester, due to the fact that the maximum power of the electromagnetic energy harvester can be reached when the low region of the ambient frequency matches the resonance frequency of the energy harvester device. Dias *et al.* proposed to attach a single magnet to the tip of the airfoil, so that the relative translating motion could also be captured by the electromagnetic induction. This would then allow the piezoelectric-inductive transduction to be incorporated into a fully coupled three-DOF electroaeroelastic model. However, both of them did not consider any design aspects of the inductive mechanisms in array magnets nor were any experimental investigations performed. [13,17,18]

## Summary of the Literature Review

In recent years, a number of studies have focused on the use of aeroelastic vibrations to harvest energy from the wind. Erturk *et al.* showed theoretically and experimentally that the energy can be harvested from aeroelastic vibrations, by using an airfoil attached to the cantilever beams with piezoelectric materials fixed onto the beams.[9] Abdelkefi *et al.* investigated the level of harvested power from aeroelastic vibrations for an elastically mounted wing supported by nonlinear springs.[10] Later, Yang *el al.* studied different tip cross-sections profiles of the piezoelectric cantilever for small scale wind energy harvesting based on the galloping phenomenon.[11] Magnets have since been introduced to exploit the nonlinear piezoelectric region for broadband energy harvesting, however, the energy levels that can be harvested from a piezoaeroelastic energy harvester was limited due to the low operational natural frequency.[11-16]

## Summary of the Work Performed

The proposed wind energy harvester was assembled by an airfoil supported by two aluminum beams, 2 flexible moving coils, and 12 NdFeB magnets [Fig. 1]. The airfoil was printed by the 3D System CubePro, a printer that uses a PLA filament according to NACA 0012 type dimension ratio (weighing 242 g, a span length of 20 cm, and half cord length of 5 cm). An aluminum rod was placed through the axis hole of the airfoil and then supported by two 6061-type aluminum cantilever beams (300 mm × 35 mm × 1.6 mm). Additionally, two-music wire torsional springs (spring coefficient of 0.2442) were installed between the beams and airfoil to provide the restoring rotation force. The two flexible coils (inner diameter of 10 mm, outer diameter of 25mm, height of 10mm, and 900 turns) made of copper wire were attached on the upper and lower axis hole of the cantilever beams. By considering the winding gap inside the coil, the internal resistance

($R$) of a flexible coil can be written as[19]

$$R = \frac{NM}{14250W^2} \quad (1)$$

where $N$ is the no. of turns of the coil; $M$ is the mean of the diameter of the coil; and $W$ is the diameter of the copper wires. Finally, the airfoil was attached to the free end of the cantilever beams by aluminum blots. The multi-pole magnetic array, supplied by the K&J magnetic, was assembled by 6 same-size N52 NdFeB magnets (25.4 mm × 25.4 mm × 9.5 mm and 1.43 T of residual induction), in the position of the trajectory, which was determined by deflection range of the tip. The relative bigger magnets comparing with the coils were chosen to prevent magnetic flux density created in coil. The two-magnet-arrays were installed respectively using the two upper and lower aluminum bolts to provide the alternative magnetic flux for the moving coil. In the meantime, two piezoelectric (MFC) patches (M-8528-P1 103 mm × 35 mm × 0.2 mm), supplied from Smart Material Corporation, were attached onto the two aluminum cantilever beams for a power output comparison.

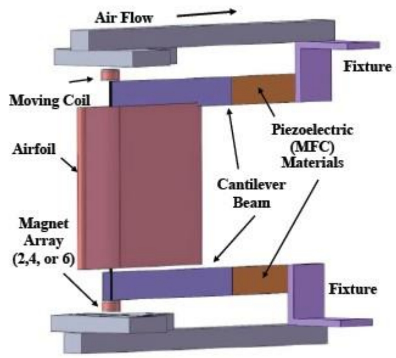


**Figure 1**

The operational principle of the EH presented here was based on the bending oscillations of an airfoil supported by a pair of cantilever beams that faces the direction of the wind. When the air flowed towards the front of the airfoil, an initial force was applied onto the beam causing the cantilever beam to operate and spring back, thus causing the cantilever beams to oscillate. This allows the energy harvester to sustain the necessary oscillations under uniform and steady flow conditions. When our energy harvester operated at a lower wind speed, the amplitude of the moving coil was able to reach 2 or 4 magnets. However, when the wind speed was increased, the bending amplitude of the moving coils and the cantilever beams also increased, which enables the coil to acquire stronger magnetic flux at a 6 magnet-array. Based on Eq. 1, the 6-magnet linear array configuration was able to harvest more energy. In addition, the linear electromagnetically coupled with the airfoil electroelastic equation can be written as follow[20]

$$(m + m_e)\ddot{h} + mbx\ddot{\ } + d_h\dot{h} + k_h h \quad \frac{B_l}{l} I = \quad L \quad (2)$$

$$mbx\ddot{\ }h + I\ddot{\ } \quad + d\dot{\ } \quad + k \quad = M \quad (3)$$

.

(4)

$$L_c I + (R_c + R_l)I + B_l h = 0$$

where $m$ is the airfoil mass per length (in the span direction); $m_e$ is the fixture mass (connecting the airfoil to the plunge springs) per length; $M$ is the aerodynamic moment; $L$ is the aerodynamic lift; and the over-dot represents differentiation with respect to time ($t$); $l$ is the span length; $R_l$ is the load resistance in the electrical domain; $R_c$ is the internal resistance of the inductor coil; $I$ is the induced electrical current; $L_c$ is the coil inductance, and $B_l$ is the electromagnetic coupling. By transforming the governing equations to a state-space form, the flutter speed can be obtained by monitoring the location of the eigenvalues of state-space form and used for the experiment.[20] All the experiments are operated above the predicted flutter speed to capture the most dynamic motions.

The wind tunnel with controllable wind speeds was used in this test to apply the airflow for the electromagnetic airfoil-type energy harvester. The induced voltage ($V$o) of the harvester was found by the waveforms that were obtained by the digital oscilloscope (Tektronix DPO2014). The power output was calculated by applying the induced voltages through the resistance load connected to the energy harvester. The wind speed was controlled by the voltage-mode controlled wind turbine, and the speed of the airflow inside the wind tunnel was measured by a hot-wire anemometer (Dwyer Instruments). In order to test the piezoelectric material, two resistance boxes were used as a voltage divider due to the fact that a high voltage output is produced by the direct piezoelectric bending effect, under an open circuit condition. The corresponding power was, then, determined by applying the resistance load to the output of the piezoelectric materials.

Figure 2 shows the measured induced voltage of our proposed energy harvester. For the 2-magnet array, a peak voltage of 8.3 V was obtained at the low wind speed ($U$) of 4.61 m/s and was increased to 23 V at 7.19 m/s. Under the 4-magnet array, a peak voltage of 7.9 V of peak voltage was found at the wind speed of 4.46 m/s and reached to 20.5 V when the wind speed was increased to 6.98 m/s. And finally, for the 6-magnet array, a peak voltage of 8.1 V was measured at 4.49 m/s and raised to a peak voltage of 18 V at 7.18 m/s. All time durations (respecting to frequencies) of each peak voltages in all magnet arrays configuration were nearly the same because of the natural frequency ( $_h^2 = k_h / m$, where $k_h$ is the stiffness per length in the plunge DOF and $m$ is the airfoil mass per length) of the unchanged flexible coils and airfoil.[20]

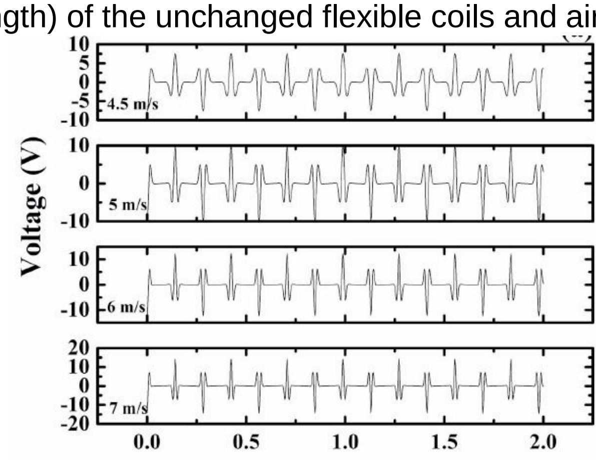

**Figure 2**

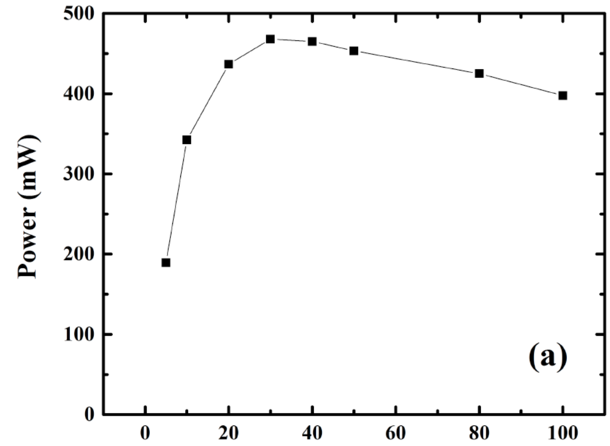


**Figure 3**

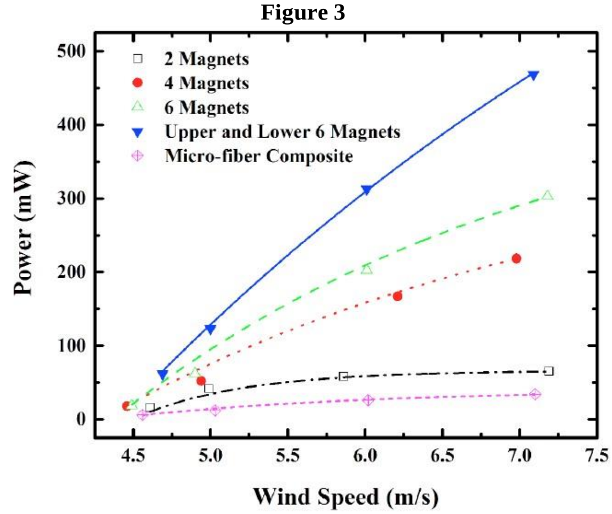


**Figure 4**

## Conclusions

an electromagnetic airfoil-typed energy harvester based on the parallel array motion between the trajectory matching multi-pole magnets and flexible coil was investigated. The magnetic flux density and the induced voltages of the moving coil that operated under 2, 4, and 6-magnet array were studied. From the experimental results the number of pulses displaying the induced voltages in each period increased significantly with respect to the number of magnets utilized in the magnet array. Based on the simulation results, the number of magnets can be determined. Compared with a piezoelectric-based airfoil energy harvester the power output significantly increased which makes the parallel motion of the linear magnet array and coil more suitable for energy harvesting under the condition of a low natural frequency that can be expected in air flow.

## Implementation and Training

Compared to the traditional electromagnetic energy harvester with a single magnet moving through a coil, the proposed energy harvester, containing multi-pole magnets and parallel array motion, enables the moving coil to accumulate a stronger magnetic flux in each period of the swinging motion. In addition to the comparison made with the airfoil-based piezoelectric energy harvester of the same size, our proposed electromagnetic energy harvester generates 11 times more power output, which is more suitable for high-power-density energy harvesting applications at regions with low environmental frequency.

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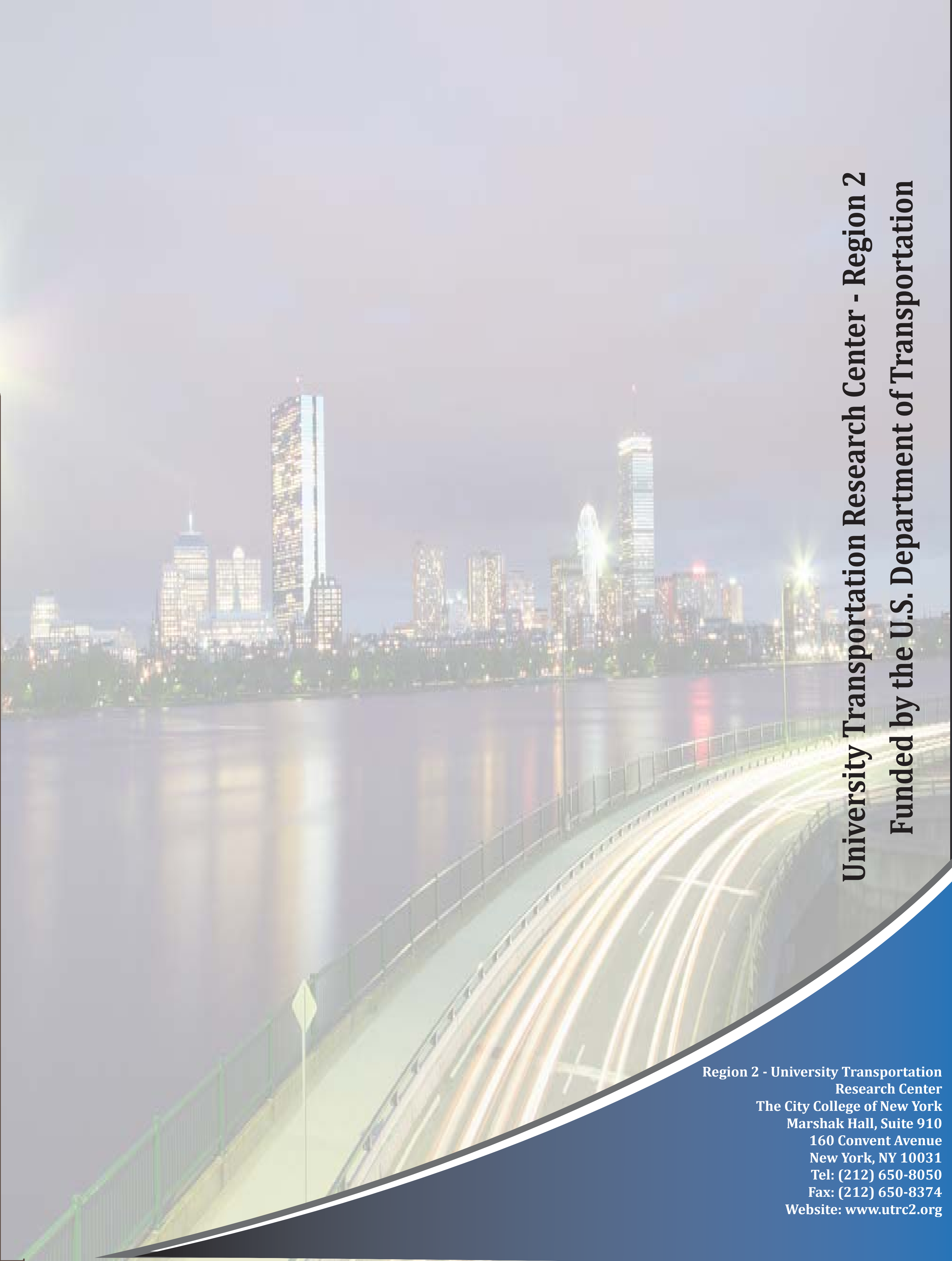

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**The City College of New York**
**Marshak Hall, Suite 910**
**160 Convent Avenue**
**New York, NY 10031**
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