University Transportation Research Center - Region 2

Final Report

On-Road Energy Harvesting from Running Vehicles

Performing Organizations: State University of New York (SUNY)
Rensselaer Polytechnic Institute

November 2014

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University Transportation Research Center - Region 2

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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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16. Abstract

A new type of large-scale on-road energy harvester to harness the energy on the road when traffic passes by is developed. When vehicles pass over the energy harvesting device, the electrical energy can be produced by the mechanical motion even after the vehicle passed by, which solves the difficulty in regeneration energy from impulse vibration. Design approach and dynamics modeling are presented to reveal the working mechanism of the energy conversion. In-field test with a sedan car is carried out and the regenerated power up about 24 Watts can be produced, which is much larger than the existing highway energy harvester in the published literature. This large-scale energy harvesting mechanism using the proposed MMR mechanism can help to develop harvesting device to build up self-power energy source for highway transportation monitoring system.

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Executive Summary

The highway transportation plays a very significant role in the nationwide economy and society development, including in UTRC2 area. For the routine traffic management and future planning of the highway infrastructure and other transport systems associated with it, a reliable traffic monitoring system is highly needed along the highways. However, the cost-effective, convenient and reliable power supply needed for the traffic monitoring system is still a big challenge. The objective of this project is to develop a sustainable solution of on-site energy to the critical challenge and power demand for traffic monitoring systems, by harvesting the energy from the road using smart motion mechanism.

We proposed an innovative type of high energy density, compact energy harvester. This cuboid-shape energy harvester is designed to be installed under the road surface. When a car runs over the road surface, specifically above the top plate, the car's weight and running speed give impact-like input to the top-plate and this input power is used to rotate the main shaft of the harvester which is connected to the generator. As soon as the car's front wheel passes by the top plate, top plate will recover to initial position before the rare wheel arrives. To achieve this goal, one-way clutch was installed to joint between the top plate and main shaft, and a spring was installed under the joint part. In addition to decrease the time and cost of the installation construction, the harvester was designed in very compact size (6"×6"×15") and the specially designed detachable joint allows the power train part can be easily exposed by removing the top plate. The most significant advantage of the proposed design over traditional energy harvesters is our design will not slow down the speed of the traffic while it harvests energy from running vehicles.

Theoretical modeling, simulation, and experiment test of the proposed on-road energy harvester has been conducted. The simulation and experiment results verified the effectiveness of the proposed design. After the lab test we will install the on-road energy harvester prototype in Stony Brook University campus for in-field test.

1. INTRODUCTION

1.1 Background and Significance

For the problem of natural resources shortage, US Department of Energy said "energy crisis" is only a small example of what will happen to us in the future [1]. The speed of energy consumption has been faster than the speed of natural resources re-generation for many years. In this sense, numerous researchers are working on technologies for renewable energy harvesting, and exploring to increase the energy harvesting efficiency of the energy harvester system.

Almost all the people in the United States need to use highways very often, in the forms of riding cars, taking buses, etc. The power supply and associated maintenance are important issues for traffic monitoring and detection system, which is critical for transportation safety and mobility. The challenge is due to not only the fact that the transportation sector consumes almost one-third of the nation's energy (Bureau of Transportation Statistics, 2007 [2]), but also the fact that the transportation system covers such a large portion of the nation's surface area and providing traditional power supply (such as grid power) is extremely difficult, if not impossible, to certain areas such as remote areas [3].

Inductive loop detector, composing a big metallic loop buried under the pavement, is the most widely used technology today including in UTRC2 area because of its high accuracy. However, there is currently a significant gap national wide in providing energy supply to cover the entire monitoring and detection system. This particularly true for traffic sensing and detection purposes as existing traffic monitoring sensors and communication infrastructures rely heavily on grid power and/or batteries. In remote areas, grid power and communication lines are sometimes technically or economically impossible to access. Wireless sensors may provide a promising solution but still with significant challenge in battery energy supply. The SenSys vehicle detection sensors, for example, have been installed in some of the nation's freeways and arterials. Such devices are primarily powered by batteries. The battery life is claimed to be 2-10 years (repeaters and nodes), but needs to be verified in high-volume traffic and in extreme temperatures. The highway pavements are typically designed for 20 years cycle life, and some states like Minnesota have extended the pavement design life standard to 40-60 years. Replacing millions of batteries for tens of thousands of wireless sensors would be a huge logistic problem.

And the maintenance cost could be huge to replace batteries of sensor nodes embedded in the pavement. Another important concern is the environmental impact of disposing the used batteries.

For solving the power supply problems in traffic monitoring system, especially in remote regions, an innovative idea is proposed in this project, which is using a smart motion mechanism to convert the motions due to the passing vehicles on highways to electrical energy. It is a green regenerative energy harvesting system. On the other hand, due to the wide deployment of energy harvesters on the highway system, grid power is eliminated or is only deployed at limited places (like near major infrastructures for monitoring and communication purposes). As a result, the time and cost are significantly reduced for grid power installation and battery replacements within the highway system. The total energy consumption of the transportation system is also much reduced, which leads to a more sustainable transportation system.

1.2 Literature Review

As one of the most popular type of existing road energy harvesters, many researchers are working on piezoelectric material. Piezoelectric materials are widely using in energy harvesting area to generate energy to power low energy consuming equipment [4]. Piezoelectric generating units have advantage of compactness of design. However, the drawbacks of using piezoelectric material is the amount of harvesting energy is order of μW. As one of the most recent work, Rui Li et al. introduces piezoelectric vibrator can be mount on the road [5]. According to the result of the study, their single unit of energy harvester was able to generate 2.67mJ theoretically. Brandon Alexander Hall did investigation on piezoelectric film to check whether it can generate enough energy to translate signal through RF transmitter [6]. He used 52μm film of poly vinylidene fluoride, and his prototype could generate the energy with range of 400-800μJ when a car run over the film which was around 4-8 times of required power to transmit 4 packets of 12 bit of data with his transmitter. Haim Abramovich et al. published patent of energy harvesting unit for on-road and airport runway by using piezoelectric material [7]. His work produced as a product in energy harvesting company name of Innowattech. Innowatech claims that their onroad energy harvester unit can generate 200kw/h for 1km lane of road [8]. However it is hard to believe its validity because there isn't practical product which is been using.

The other type of popular road energy harvester is electromagnetic energy harvester. Electromagnetic energy harvester generate electricity by absorbing the external vibration into the moving part of the harvester. If the moving part is magnet, then fixed part of the harvester should be coil and vice versa. The benefits of using electromagnetic energy harvester is, the limitation of size of harvester is not crucial as much as piezoelectric energy harvester. Compared with piezoelectric energy harvesters which should ensure large contact area or large number of units to generate large amount of energy, electromagnetic harvester can make one unit powerful by using strong magnet and heavy weight of moving mass. When we consider the output power form one unit of harvester, an electromagnetic harvester's output can be much larger than a piezoelectric material energy harvester. Also electromagnetic harvester generate comparably high current output. On the contrary, most of the electromagnetic energy harvester has larger size than piezoelectric material harvester and generate comparably low voltage [9]. One of the most practical electromagnetic road energy harvester provider is Highway energy service LTD, in United Kingdom. The inventor of the harvester says the output power of a one unit of harvester is depends on the speed of the cars and period of running over cars, but generally able to generate 5 to 10kW of energy [10].

Mechanical vibration and motion have gained a lot of attention due to reasonable energy density, embedability, and less dependence on weather conditions. We found several mechanical vibration energy harvester patents. Calvo [11] proposed a kind of highway power generator in 2004, as shown in Figure 1. When a car runs over the actuator buttons 3, input load is transmitted to the recoiling spring 30, which will hit the connection part 56 and it will rotate the main shaft 15 to drive generator. The disadvantage of the system is that due to so many components in the system, the structure is too complicated, which may increase the maintenance cost. Meanwhile, the complexity will result in low energy harvesting efficiency.

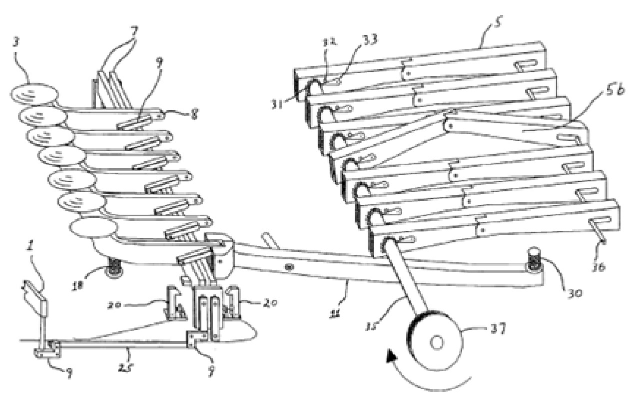


Figure 1. Highway electric power generator [11]

Another type of road energy harvester is shown in Figure 2. When a car runs over the bumps 12, the bumps are pushed down and this vertical motion rotates cranks 19, which will rotate the alternator 20 and generate electricity [12]. The disadvantage of the system is that it requires a lot of space underneath the road, and the design is not compact enough.

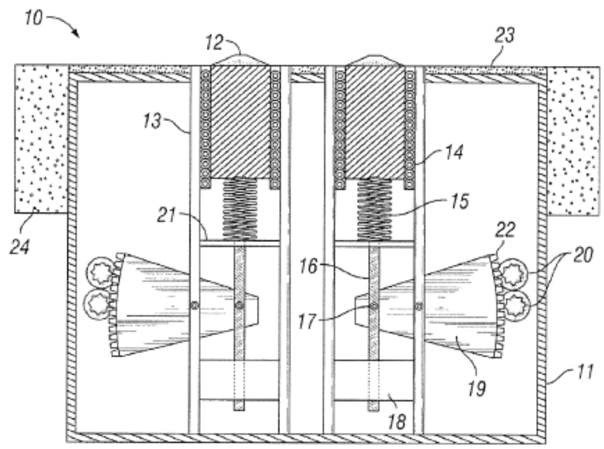


Figure 2. Roadway power generating system [12]

Martinez [13] proposed a "highway turbine" energy harvester, as shown in Figure 3. The system uses ratchet mechanism to rotate the big gear. The drawback of this design is the pedal part 39 on the road surface, which will slow down the traffic. According to the highway regulation of NYC they don't allow any extruded structure on the highway in safety purpose. The potential disaster is that when a vehicle changes lane but the drive didn't notice the pedal structure on the road, it will cause big accident or at least severe damage to the vehicle.

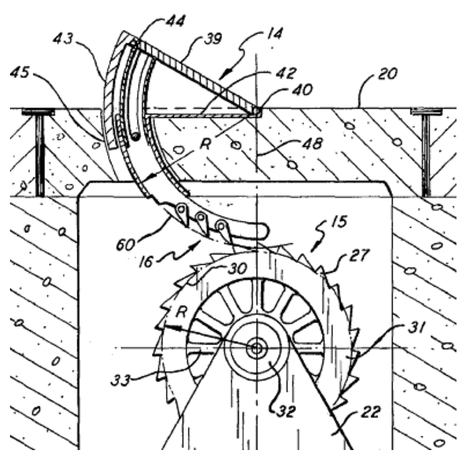


Figure 3. Highway turbine [13]

2. DESIGN and PROTOTYPE

2.1 Concept design

As shown in Figure 1, vehicle tires rollover a harvester installed under road ground, the weight of the car pushes the top plate of the harvester downward, which drives the electromagnetic generator to rotate and to product electrical energy. The concept design of the on-road energy harvester is demonstrated in Figure 2 (a). Designed parameter of the vertical stroke of the harvester and the width of the top plate in the vehicle lateral direction are determined according the average tire deformation between contact patch and the wheel hub, by which the tire deformation caused by the by the interaction with the top plate is in the same range as that when the tires roll over on ground. Thus, the response of vehicle passing through the harvester is similar to that rolling over on the ground, by which vehicle movement will be not influenced when passing through the harvester. Therefore, when tires pass through the harvester, the normal force reacting from the harvester to tires will not change much than that reacting force from the ground, and the vehicle need not to be slowed down.

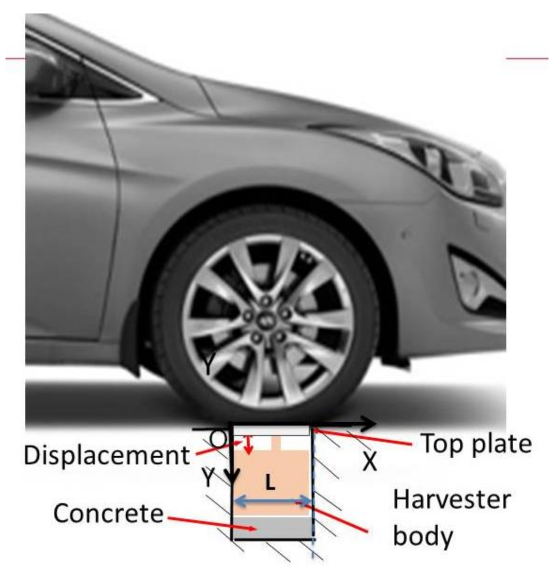
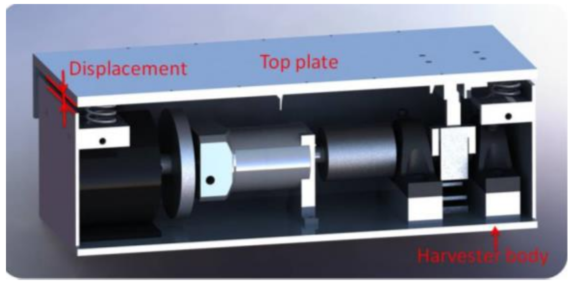
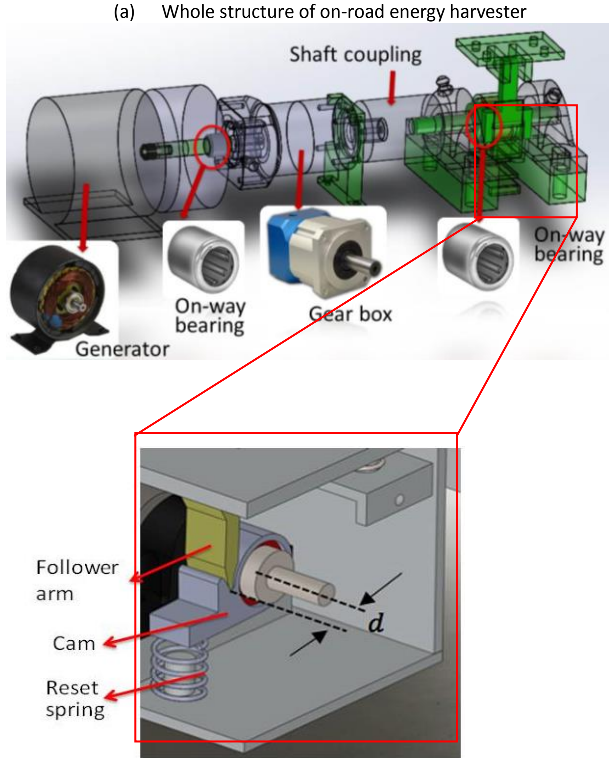


Fig. 1. The schematic of on-road energy harvester



(a) Whole structure of on-road energy harvester



(b) Kinetic energy conversion mechanism of mechanical motion rectifier

Fig. 2. Concept design of on-road energy harvester

In order to regenerative maximum energy, a high efficient energy conversion mechanism of mechanical motion rectifier (MMR) is designed as shown in Figure 2(b), which includes one shaft, one pair of arm-cam, two pair of one-way bearings, a gearbox, a generator and a flywheel. The one-way bearing embedded in the cam is similar to the one used in bicycle gears or engine starters to transmit motion in one direction. When the top plate moves downward, the one-way bearing is engaged, and the generator is driven to rotate and to produce electricity. When the top plate move upward under the rebound force from the supporting spring, the one-way bearing is disengaged from the generator shaft, and the generator can continuous to rotate under inertia moment to produce more electricity. Thus the generator can always rotate in one direction, which can achieve high energy transmission efficiency and lessen backlash to make the harvester to be more reliable.

This MMR design in engagement and disengagement in one-direction is actually a half-wave function of the MMR, which can transfer two direction vibrations into one direction as developed in our other energy harvesters the authors [12-16]. This half-wave form MMR mechanism can solve the fundamental problem in large-scale impulse vibration energy harvesting due to short-time shock from vehicle to the harvester to achieve high energy harvesting efficiency. The gearbox is used to increase the rotation speed of shaft to the generator and to increase the electrical transmission energy of the generator.

There is another one-way bearing embedded between the flywheel and the shaft. Once the flywheel spins at higher speed than the shaft, the one-way bearing disengage flywheel from the shaft, which can absorber the shock energy and protect the regenerator to be drastically driven by gearbox. Later on, the energy stored in flywheel can be released smoothly to the generator and improve the energy transmission efficiency and working reliability.

In order to regenerate more energy from the twice impulses movements of the harvester caused by the front and rear wheel tires without influence to the vehicle speed, a special flexible connection between the following arm and cam structure is designed, as shown in Figure 3 (b). The interaction between the arm and cam is in contact connection to avoid fixed connection in order to disengage the top plate from the generator shaft much easily without any screwing connection. Moreover, the disengagement of the one-way bearing in half-wave form MMR also enables the cam to be quickly disengaged with the following arm and to recover the top plate to its original position. Since the speed of vehicle need not to be slowed down and the wheelbase between the axles of front and rear is limit, the time duration between the front and rear tires passing through the harvester is very short. A kind of quick rebound mechanism of the top plate to its original position after the front tires run over the top plate and before the rear tires touch the harvester is designed by using a set of supporting springs and position limitations to the top plate. The set of reset springs can enable the top plate to reset its original positon in short time after vehicle tires pass through the harvester, and then the top plate of the harvester can be prepared for the next downward press to regenerate energy. The rebound time of the spring set recovering from the maximum pressed position after the front axle pushes down the springs is important to make the plate to its original position before the rear wheel axle contacts with it. If the top plate can be pushed down again in its maximum displacement by the rear wheel, the twice press shocks from both front and rear tires can regenerate electricity energy twice to increase the harvesting energy.

The design parameters of stiffness of supporting springs and the displacement of the top plate are important to meet the requirement of quick rebound, which need to be carefully considered according to the time between the two wheel axles passing through the harvests. The position limiters can constraint the movement of the top plate in a certain range and also help to secure its continuous working to produce more electricity when many vehicles pass by continuously. Furthermore, the shape design of the following arm is important to reduce the contact area for improvement of the energy conversion efficiency, lessen the recovering time and to increase the reliability of both arm and came. Since the large shock transferred from tires to arm-cam connection, the strength of the arm and the friction between the contact surfaces of arm and cam are critical to the reliability of the structure. Figure 3 demonstrates the optimized shape of the arm with sharp end instead of round end based on finite element analysis of the arm-cam interaction. This proposed flexible contact interaction can simplify the structural parts, improve the energy harvesting efficiency, reduce the cost for production and release the maintenance load without influence to vehicle traffic on road.

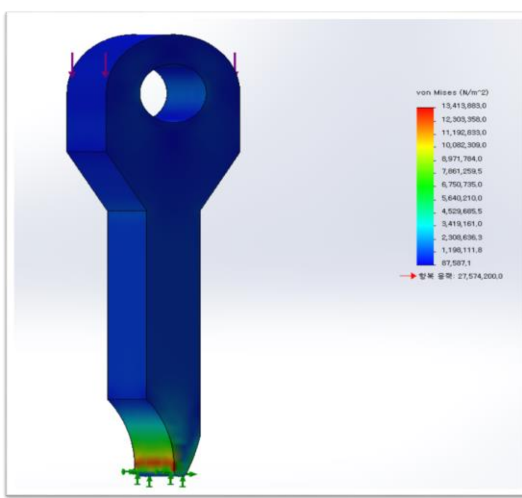


Fig. 3. Finite element analysis of following arm

2.2 Prototyping

The fabricated prototype is as illustrated in Figure 4. The size of the top plate is length of 0.406m and width of 0.152m, the displacement of the top plate is 5mm. The gear ratio is 1:9 and the regenerator is 3 phase with maximum output voltage of 24V and maximum output power of 100W.

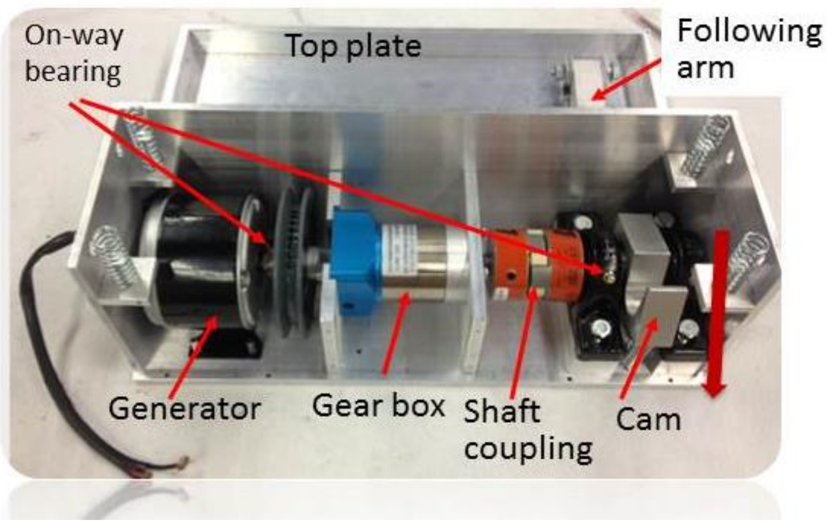


Fig. 4. Prototype of the on-road energy harvester

3. MODELING and SIMULATION

3.1 Modeling of the half-wave form MMR in harvester

The electromagnetic model of the generator is shown in Figure 5 (a), the electromotive voltage can be expressed as $V_g = K_g \cdot \dot{\theta}_g$ and induced electromagnetic torque is $T_g = K_t \cdot i_g$, here V_g, K_g and $\dot{\theta}_g$ are the electromotive voltage, counter electromotive voltage constant and rotational speed of the generator, K_t and K_g the torque constant and the external current. Then, we can get

$$T_g = K_t \cdot \frac{V_g}{R_i + R_0} = \frac{K_t K_g \dot{\theta}_g}{R_i + R_0} \tag{1}$$

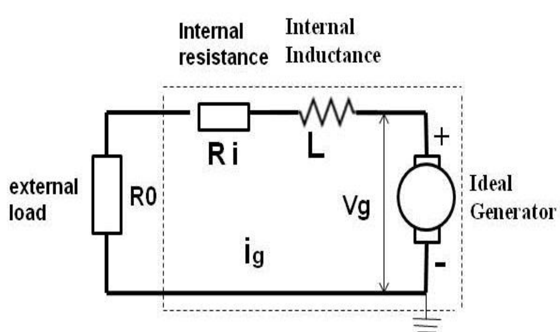
Torsional dynamic model of the harvester in Figure 2 (b) is built up according to the physical prototype in Figure 5, which includes three parts: (1) Assemble mass of following arm-cam; (2) Inertia of I_p the cam and the outer of one-way bearing; (3) shaft with generator, gearbox, shaft coupling, flywheel and the inner shaft of one-way bearing. Here the inertia of one way bearing is neglected. The torsional dynamic equations of the shaft can be indicated as:

$$T\ /r = F \tag{2}$$

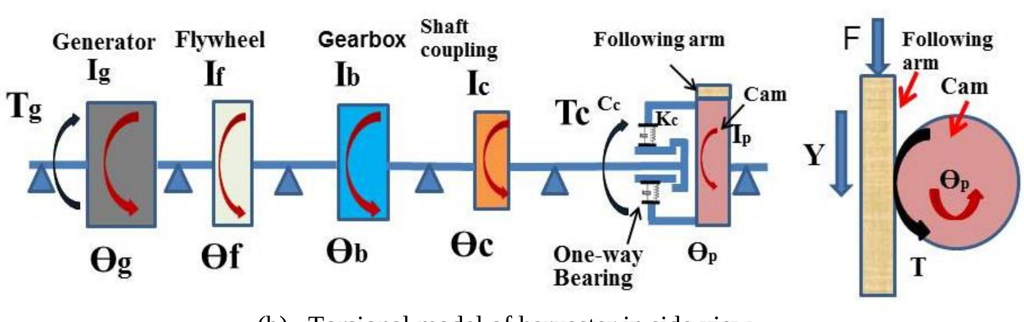
$$I_p \ddot{\theta}_p = T - T_c \tag{3}$$

$$(I_s + n_b{}^2 I_{g1})\ddot{\theta}_b = T_c - T_g \tag{4}$$

where T is the torque of the cam, F the force from arm, and r the radius of cam; I_p is the inertia of cam, I_s the sum of the inertia of coupling shaft and gearbox $I_s = I_c + I_b$, and $I_{g1} = I_g + I_f$ is the inertia sum of the generator and flywheel; y_3 is the vertical displacement of the following arm; $\ddot{\theta}_p$ and $\ddot{\theta}_b$ are the angular acceleration of cam and coupling shaft; the angular acceleration of generator $\ddot{\theta}_g = n_b \ddot{\theta}_b$, n_b is gearbox ratio; T_1, T_c and F are the torque loaded on cam, one-way bearing and the force loaded on the following arm. One-way bearing can be modeled as a discontinuous contact model with stiffness of K_c and damping of C_c. The torque on the one-way



(a) Electromagnetic model of generator



(b) Torsional model of harvester in side view

Fig. 5. Dynamics model of on-road energy harvester.

clutch can be expressed as

$$T_c = K_c(\theta_p - \theta_b) + C_c(\dot{\theta}_p - \dot{\theta}_b) \tag{5}$$

where θ_p and θ_b are the rotational angular of the cam and coupling shaft. Damping of one-way bearing is small and neglect, the torque equation can be expressed as

When one-way bearing is engaged,

$$T_c = K_c(\theta_p - \theta_b), \qquad (\dot{\theta}_p - \dot{\theta}_b) \geq 0 \tag{6}$$

The shafts of generator and cam rotate together driven by arm movement, the Equation (2-4) can combined into one equation as

$$(I_p + I_s + n_b^2 I_{g1})\ddot{\theta}_b = F \cdot r - T_g \tag{7}$$

Since $I_p + I_s$ is much smaller than $n_b^2 I_{g1}$ due to the amplification of gearbox ratio, $I_p + I_s$ is neglected. The Equation (7) can be simplified as

$$n_b^2 I_{g1} \cdot \ddot{\theta}_b = F \cdot r - T_g \tag{8}$$

When one-way bearing is disengaged:

$$T_c = 0, \qquad (\dot{\theta}_p - \dot{\theta}_b) < 0 \tag{9}$$

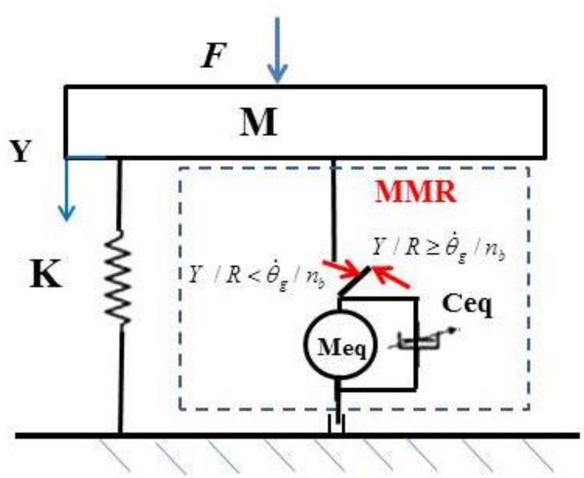


Fig. 6. Dynamics model of interaction of harvester with vehicle.

The cam shaft and generator shaft rotate separately. Their dynamic equations can be separately expressed as,

$$I_p \ddot{\theta}_p = F \cdot r \tag{10}$$

$$(I_s + n_b{}^2 I_{g1})\ddot{\theta}_b = -T_g \tag{11}$$

Equation (11) can be simplified by neglecting I_s

$$n_b{}^2 I_{g1} \cdot \ddot{\theta}_b = -T_g \tag{12}$$

3.2 Modeling of the interaction of harvester with vehicle excitation

The following arm and cam structure converts the translation movement of top plate driven by vehicle tires into the rotation of generator shaft. The interaction of the harvester with tire excitation can be modeled as single mass model, as shown in Figure 6, where M is the mass of the top plate, K the stiffness sum of the supporting springs, F the force that tires loaded on the top plate. The movement of top plate described in Y can be converted into the cam rotation of $\theta_p = Y / r$. Oppositely, the rotation of generator shaft of equation (8) can be expressed in the equivalent translation movement of following arm as followings,

$$\frac{n_b{}^2 I_{g1}}{r^2} \cdot \ddot{Y} + \frac{K_t K_g n^2{}_b}{(R_i + R_0) r^2} \dot{Y} = F \tag{13}$$

Here define the equivalent mass is $Meq = \frac{n_b{}^2 I_{g1}}{r^2}$ and the equivalent damping $Ceq = \frac{K_t K_g n^2{}_b}{(R_i + R_0) r^2}$.

The working process of the harvester when a vehicle passing through the harvester can be set up in three steps.

I. Tires starting to touch the top plate

The horizontal displacement x is $x = V \cdot t$ in the range of $0 \le x \le L$, where V is the vehicle speed, t the time that a vehicle passes through the plate. The force loaded by tires is $F = x \cdot W_1 / L$, assuming the load to the top plate is proportional to the area of the tire contact patch on the top plate. Here L is the width of top plate, W_1 the weight of one vehicle loaded on the top plate.

After the load pressed down the top plate drive the cam to rotate and MMR is engaged, the top plate and the MMR move together, the dynamics equation can be expressed as,

$$(M + M_{eq})\ddot{y} + Ky + C_{eq}\dot{y} = F \tag{14}$$

If the rotation speed of the input of gearbox is larger than cam speed, $(\dot{\theta}_p - \dot{\theta}_b) < 0$, the one-way bearing is disengaged and the top plate and MMR move independently . Their dynamic equations are separate as

Top plate: $$M\ddot{y} + Ky = F \tag{15}$$

Generator: $$n_b^{\ 2} I_{g1} \cdot \ddot{\theta}_b = -T_g \tag{16}$$

The interaction of the top plate and the MMR can be modelled as a switch as shown in Figure 6.

II. Tires starting to leave the top plate

The horizontal displacement x is in the range of $L \le x \le 2L$. The force loaded by tires is reducing proportionally at $F = (2L - x) \cdot W_1 / L$. Since the force on the top plate decreases, the interaction between top plate and MMR depends on the switch decided by relative rotation speed on the two sides of one-way clutch. If $(\dot{\theta}_p - \dot{\theta}_b) \ge 0$, the top plate and generator shaft work together as the Equation (14); if $(\dot{\theta}_p - \dot{\theta}_b) < 0$, the top plate and generator shaft moves separately as equation (15) and (16).

III. After tires running over the top plate

The top plate rebound to its original position before pressed under supporting force from springs. The rotation of generator disengages with the movement of top plate. The generator shaft rotates freely as Equation (16). The top plate also freely moves under spring force as

$$M\ddot{y} + Ky = 0 \tag{17}$$

3.3. Regenerative power

The output electrical power can be calculated by torque and angular speed of the generator by Equation (1) as,

$$P_{out} = \eta_b \cdot T_g \cdot \dot{\theta}_g = \eta_b \cdot K_g K_t \cdot \dot{\theta}_g^{\,2} /(R_i + R_0) \tag{18}$$

where $\dot{\theta}_g = n_b \dot{\theta}_b$ is the relationship of the generator rotation speed. η_b is the efficiency of gear box.

3.4 . Simulation results

Based on the modelling of the on-road harvester, the dynamics characteristics of the harvester are numerically analyzed when a vehicle passes through. The calculation is carried out by using Euler's method of differential ordinary equation using software of Matlab. The parameters of the harvester and vehicle are listed in Table 2. The simulation is carried out by assuming a vehicle passing the harvester at a constant speed and only vertical vibration is considered to be used to drive the movement of harvester top plate.

The displacement, velocity and loaded force of the top plate are predicted in Figure 7. The two impulses are excited by the front and rear wheel axles of the vehicle. Since the weight of the front axle is less than that of the rear wheel, the force of the first pulse is less than that of the second. The simulation results of output power in Figure 8 demonstrate that more power can be produced after the load on the top plate had been released. It approved the effectiveness of the

TABLE I. HARVESTER AND VEHICLE PARAMETERS

Symbol	Quantity	Parameter explanation
W_1	2670N	Front wheel axle mass
W_2	2670N	Rear wheel axle mass
L	0.152m	Width of the top plate
I_g	0.000075 Kg.m	Inertia of regenerator
K_g	0.0694v/(rad/sec)	counter electromotive voltage
K_t	0.0551 N.m/A	Torque constant
R_i	0.25ohm	Internal resistance
n_b	9:1	Gear ratio of gearbox
η_b	0.95	Efficiency of gear box

half-wave form MMR to improve the energy harvesting efficiency. Three design concepts with two kinds of motors with and without flywheel are compared. The design without flywheel can regenerate more power. The reason is that the excitation impulse produces the momentum of $F \cdot t$ to drive the movement of the plate and MMR by $(M + M_{eq})\nabla\dot{y} = F \cdot t$. The larger the inertia $M + M_{eq}$ is, the lower the velocity increase $\nabla\dot{y}$ is. According to Equation (18), the less energy will be regenerated. Therefore, to improve the output power, the flywheel is abandoned in order to reduce the inertia. Furthermore, the more lightweight generator with less inertia is adopted in the new design. The simulation result indicates that the output power is improved more than two times. The displacement of the top plate is limited as shown in Figure 7, which secures its quick rebound to its original position under the spring sets.

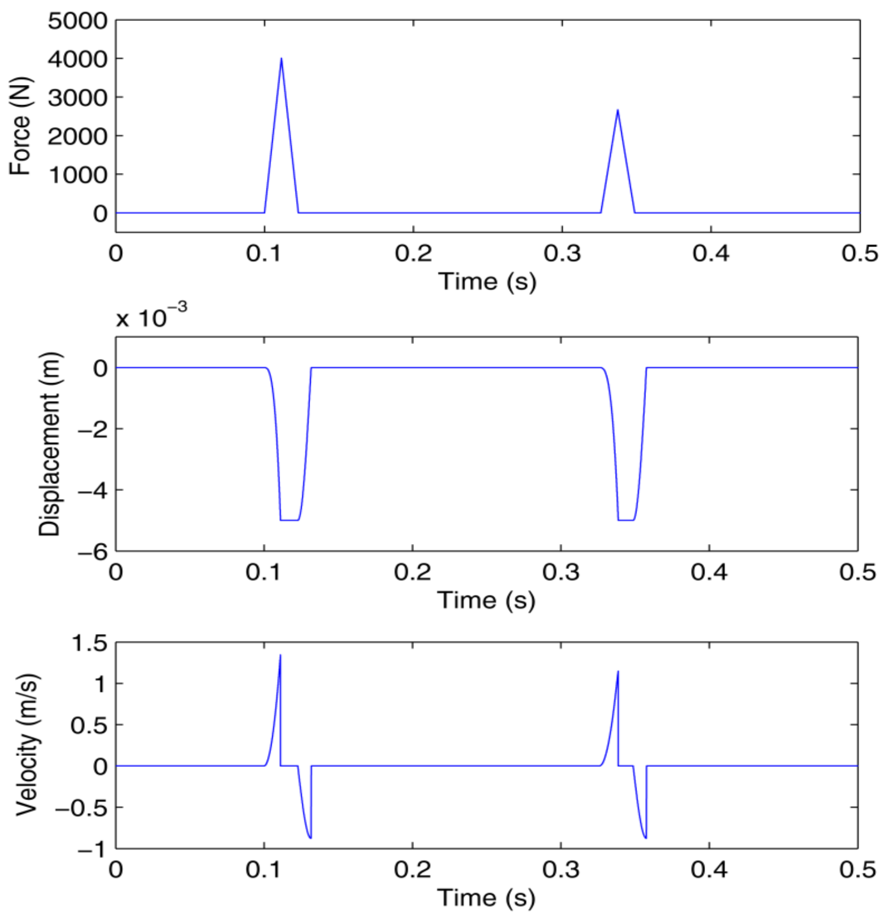


Fig. 7. Predicted dynamic characteristics of the top plate

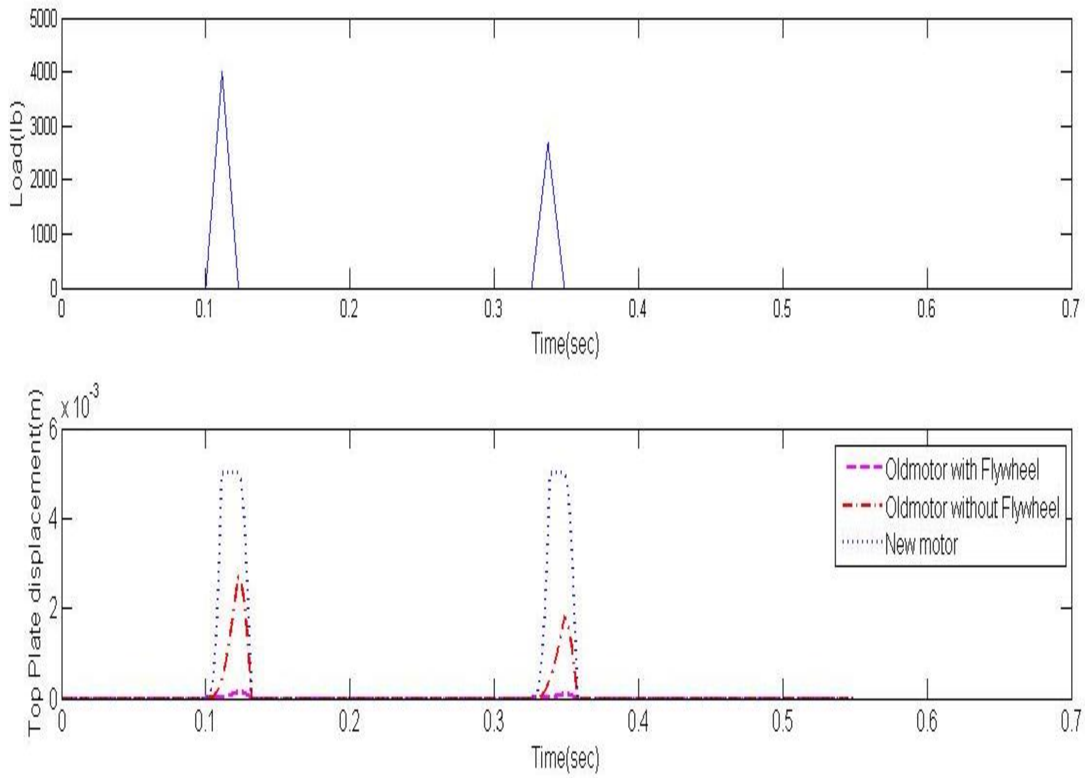


Fig. 8. Estimated regenerative power when a vehicle passing by

4. In-field test

In-field test is carried out by setup of wood stands platform for a sedan car to pass by. The regenerative electrical voltage and power under various vehicle speeds with the external resistance of 10 Ohm connecting with the regenerative are measured, as shown in Figure 9. The highest power of 24 watt with output voltage about 5V can be produced at the vehicle speed of 5Mph. The external resistance connecting with the regenerative has influence to the output power, as shown in Figure 10, the larger the resistance is, the more power can be produced.

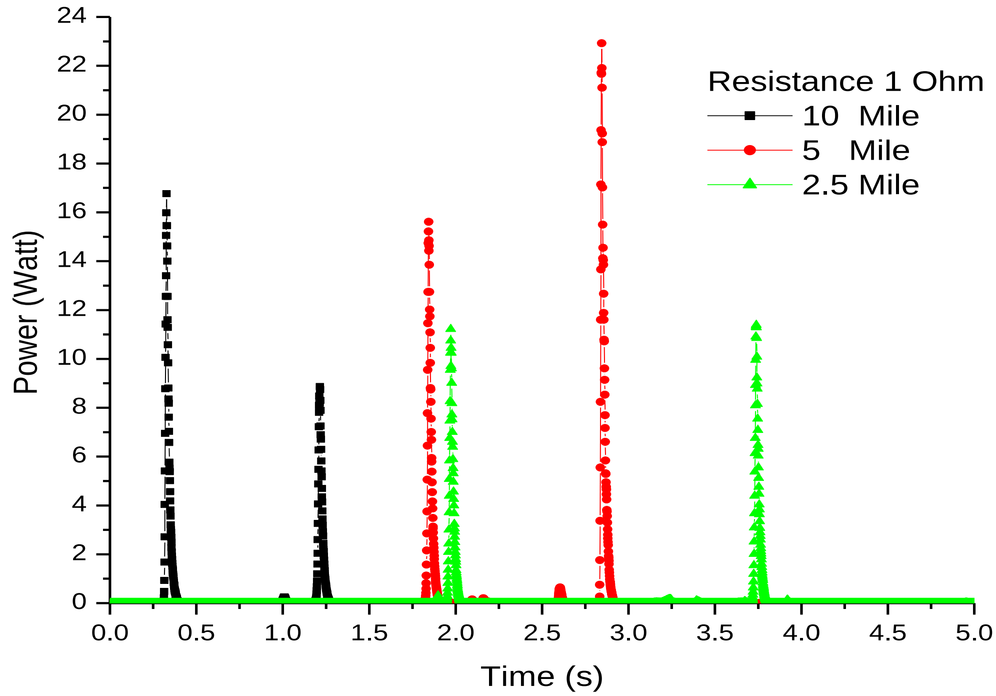


Fig. 9. Regenerative power of one phase in the regenerator under various vehicle speed with the external resistance with 10 Ohm.

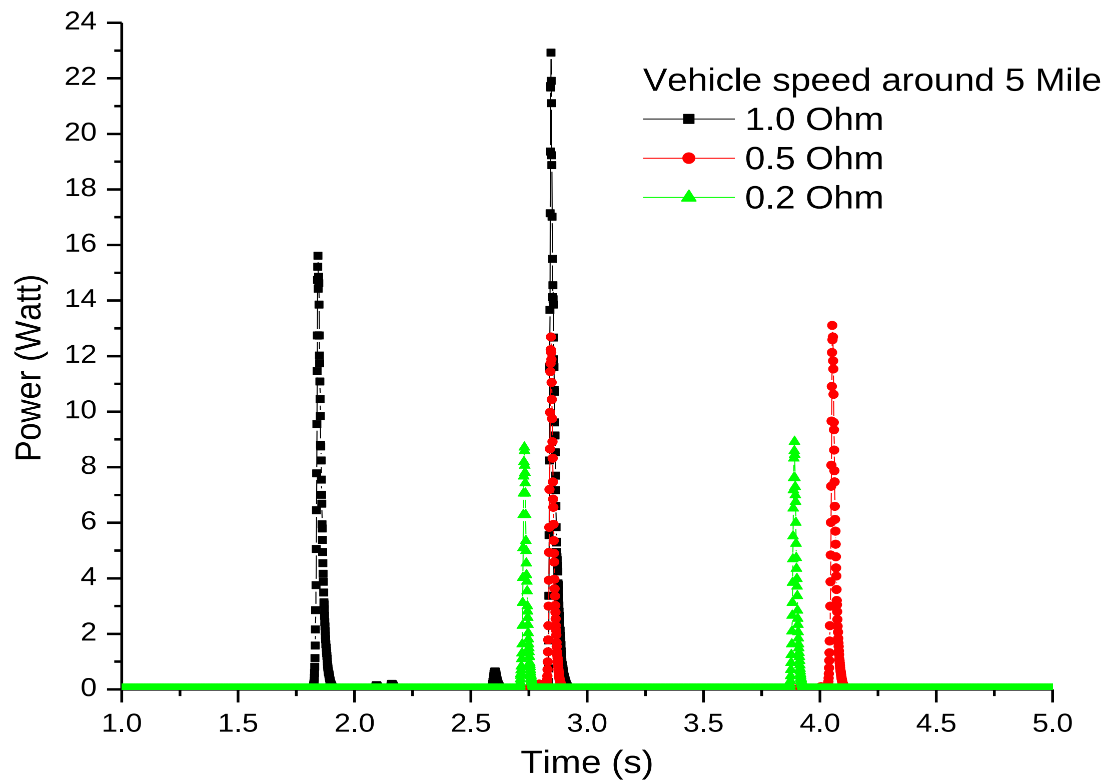


Fig. 10. Regenerative electricity power of one phase in the regenerator with various external resistance under vehicle speed around 5 Mph.

6. CONCLUSTIONS

As a conclusion, it turned out that this harvester can harvesting energy from the large-scale on-road vibration when a vehicle passes by. High energy conversion capability can be achieved by a special mechanical motion rectifier of MMR, which can keep continuous rotation after vehicle has rolled over the harvester. The dynamic model and simulation reveals the working mechanism of half-wave form MMR in the status of engagement and disengagement status. In-field test is carried out by using a sedan car passing by the fabricated prototype. The measured regenerative electrical powers about 24 watt can be harvested, which is much larger than the existing on-road harvester for highway transportation. The effectiveness of the proposed design approach and modeling method are verified by the test results. This large-scale impulse energy harvesting technology for highway has great potential to be applied in highway monitoring transportation system as a self-power energy source.

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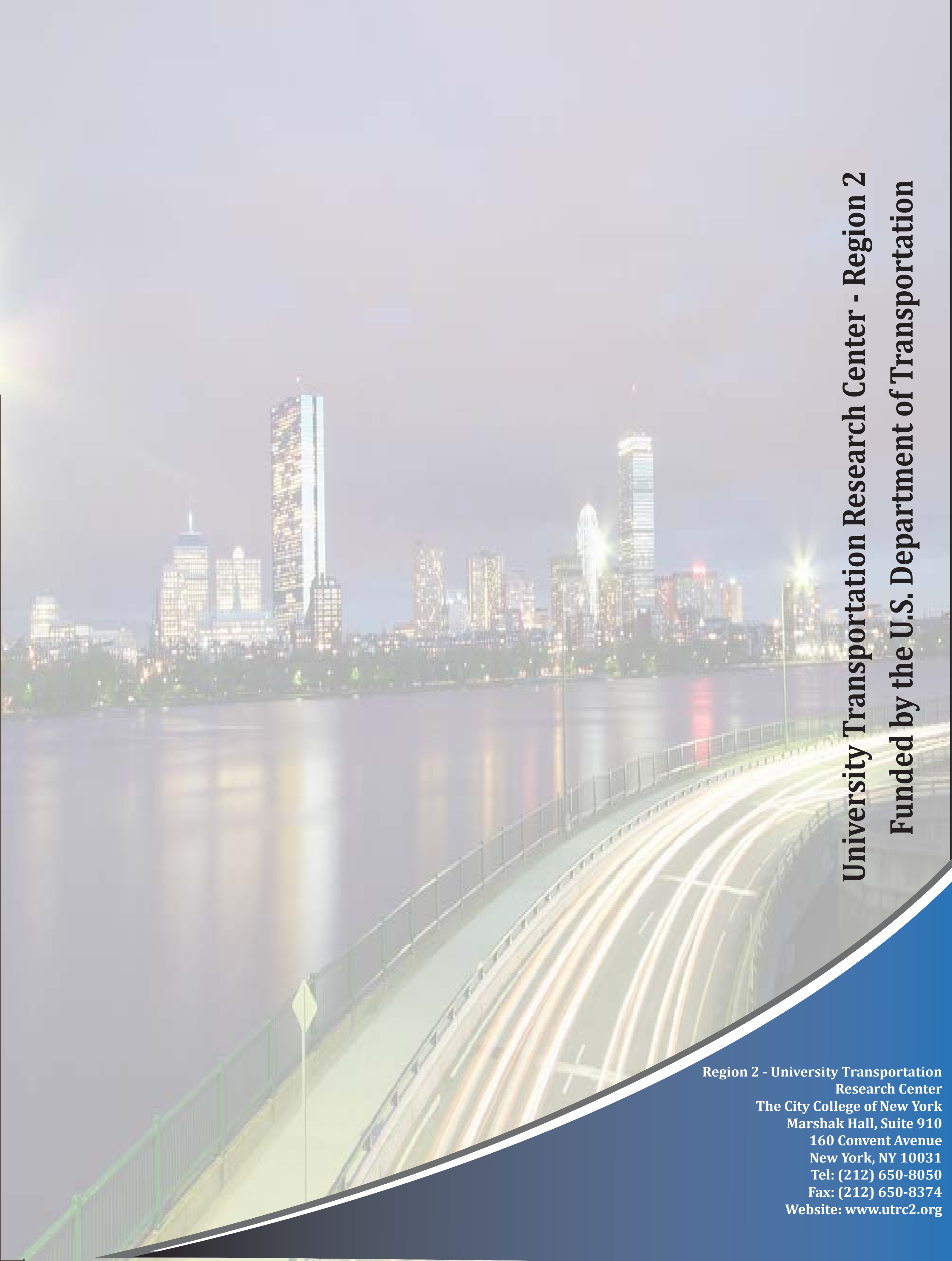

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