# Optimizing Road Safety: Energy Harvesting Bumps and Intelligent LED Lighting for Low-Visibility Mountainous Roads

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In recent years, the safety of Lebanese roads has been a growing concern due to poor maintenance and insufficient lighting caused by the electricity shortage. According to the Lebanese Traffic Management Center (2024), 1299 accidents occurred during June 2024, taking the lives of 187 individuals. Consequently, accidents in Lebanon have become a major problem, mainly on mountainous roads, where drivers fail to react in time due to darkness impeding drivers' full control over the vehicle's speed (Jägerbrand & Sjöbergh, 2016).

Endeavors have been initiated to implement efficient energy harvesting mechanisms in order to reduce the number of accidents occurring on Lebanese roads. For instance, while solar panels paired with lithium batteries have been used to illuminate various roads in Lebanon during the night, these solutions have proven to be inefficient and cost-prohibitive, especially in the current economic crisis context.

Recently, focus has shifted to generating energy from the road itself, thereby reducing the costs associated with transporting electricity to streetlights. One approach involves piezoelectric structures, which produce electricity from the mechanical stress caused by vehicles on the asphalt (Wang et al., 2022). While these technologies have high implementation costs in Lebanon, this design could be scaled on available structures, such as bumps (Abi Esber, 2012).

This paper explores the implementation of an efficient lighting scheme based on harvested electricity via mechanical motion exerted by vehicles passing on an average mountainous road characterized by tight curvature and low visibility.

First, energy-harvesting bumps integrated on both ends of the road will be presented. Second, we will examine the storage and the respective wiring of these sources to storage elements. Finally, a suitable LED network equipped with sensors and logic circuits will be modelled to process road conditions and trigger a blinking behavior to signal danger.

# Resources

**Network and Lighting**
- Amber Street Light LEDs, Resistors, capacitors, inductors, copper wires.

**Mechanical Components**
- Pinion with a rack and flywheel, DC generator with a belt, rubber and steel.

**Storage and Control**
- Voltage controller BQ24650, Lithium-Ion batteries, and Schottky diodes.

**Electronic Devices**
- Operational Amplifiers UA741 (OpAmp), BJT and MOSFET transistors,

**Sensors Components**
- Light Dependent Resistor (LDR), Infrared (IR) LED and phototransistor.

**Logic Circuitry**
- OR Gates integrated chips LS7432, AND Gates integrated chips LS7408, LM555 timer.

**Software and Simulator**
- Circuit-diagram.org, Altera Quartus II.

# Procedure

## I. Energy Harvesting Bump Design

The energy harvesting mechanism is found by mechanical compression of the springs and rotational motion of the belt connected to the rack and the pinion. This rotational motion is responsible for energy generation through a DC generator.

### Bump Design

In the following design, rubber could be used for the outer shell, while the internal frame should be supported with steel to reinforce the bump from the vehicles' weight while passing.

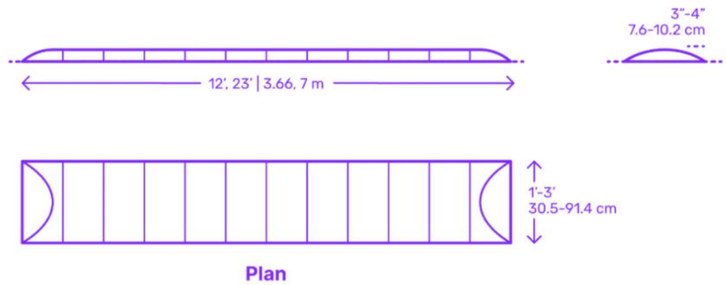


*Figure 1: Dimensions of the speed bump*

The bump will be around 7m in length with 3.5m for each direction, 30.5 to 91.4 cm in width and with a height of 7.6 to 10.2cm. This bump will have a moderate height, rather it has a flatter shape to help drivers avoid heavy crashes due to high speeds.

**Generating Electricity from Mechanical Motion**

After a car passes over the speed breaker, it exerts a downward force on the bump, compressing the springs underneath. This initial compression is the first step in the energy generation process. The compressed springs then push a toothed bar, known as a rack, downward. The rack is engaged with a pinion, a small gear that rotates as the rack moves. This interaction between the rack and pinion is crucial for converting the vertical motion of the bump into rotational motion.

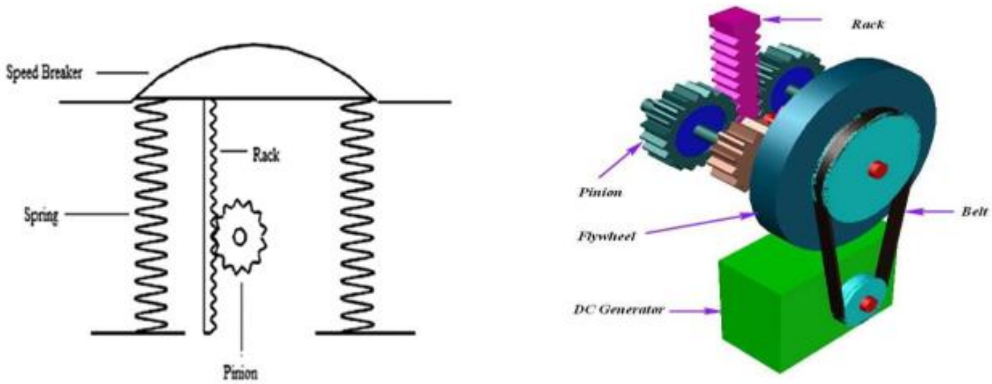


*Figure 2: Basic rack and pinion Mechanism (on the left) and mechanical transmission (on the right)*

The rotation of the pinion is transmitted to a flywheel via a belt mechanism. The flywheel is key in maintaining a consistent rotational motion, essential for stable electricity generation. Attached to the flywheel is a DC generator, which converts mechanical energy from the rotating components into electrical energy, specifically direct current (DC).

Each time a vehicle passes over the speed breaker, a burst of mechanical energy is generated and converted into electrical energy. By installing multiple such systems, significant amounts of energy can be harnessed from the movement of vehicles over these speed breakers. This not only contributes to energy efficiency but also promotes sustainability in urban environments. The system utilizes the common occurrence of vehicles passing over speed breakers to generate renewable energy, making it a practical and innovative solution for modern energy challenges.

As per our calculations, if a 1500 kg car passes over the bump, the speed breaker compression would be 5 cm, and using a mechanical efficiency of 70% and an electrical efficiency of the dc generator of 80%, it produces a voltage 82.24 V; which is enough to light up thirteen streetlight LEDs of 30W each.

## II. Energy Storage

In this section, the units involved in storing the energy harvested from the bumps are tackled; namely a voltage controller and lithium-ion batteries.

**Voltage Controlling Unit**

For this setting, we will use a stand-alone synchronous buck battery charge controller integrated into a BQ24650 chip. It implements a Maximum Power Point Tacking algorithm (MPPT), a technique used to maximize power output by dynamically adjusting the energy load to optimize transfer efficiency between the energy harvesting devices and the storage unit. This specific voltage adjustor was chosen due to its compatibility with lithium-ion batteries and its capability of adapting its voltage and current output to meet the battery's requirements, ensuring an increase in the battery's lifespan. It embeds an automatic sleep mode feature for power savings during idle periods, which helps protect the batteries from electrical leakage and unnecessary power use. Other features include high accuracy in voltage and current regulation, overvoltage protection, battery sensor detection ensuring proper battery connection, and a temperature sensor that prevents power delivery in case of battery overheating.

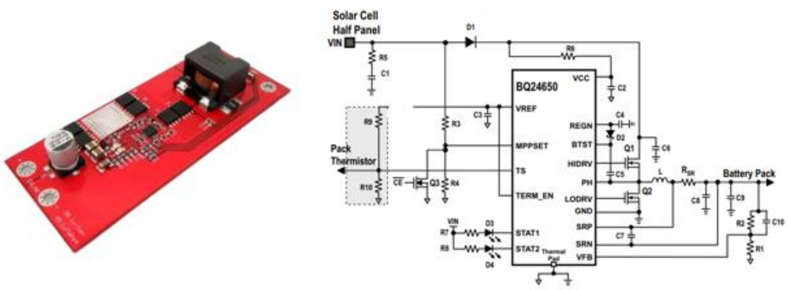


*Figure 3: Voltage controller and adjustor circuit using the BQ24650 chip*

**Lithium-Ion Batteries**

The aforementioned chip outputs the harvested energy from the mechanism into Lithium-ion batteries connected in parallel. A parallel connection is essential to ensure that our system will remain operational regardless of any malfunction that might occur in any of the batteries. A Lithium-ion battery operates by moving positively charged lithium ions from the anode (negative terminal) to the cathode (positive terminal) through an electrolyte, generating electrons and converting stored chemical energy into electrical current.

The separator within the battery ensures that the battery acts like a rechargeable power source. The usage of Schottky Diodes, semiconductor components that prevent the current from flowing in the opposite direction, makes up for the absence of such feature in the BQ24650, thus offering protection for the batteries with a negligible voltage drop in comparison with normal diodes.

**Estimation of Energy Needs**

Linked to these batteries are the streetlamps, operational amplifiers, the infrared transmitter, motion, and nighttime sensors, the clock generator and the counters for timing, the logic gate ICs and the BQ24650 chip.

All electric components apart from the LEDs require a voltage of 5V and a current of 0.15A to operate efficiently. Taking the LEDs into account, a total current of 36.9A and a minimum voltage of 20V are required from the circuit.

In a parallel connection, the voltage remains consistent across all batteries, with each battery outputting 21.6V. Given that current in parallel connections is additive, and with a requirement of 36.9A while each battery provides 1.5A, approximately 25 lithium-ion batteries are needed to meet the current demand.

## III. Motion Sensored LED Network

In the following design, optimization of energy usage is imperative since energy harvesting depends on the frequency in which cars travel on a given road. Such a network needs to be lit up only when needed, thus it needs to collect enough data to detect whether it is night.

### Illumination Distribution on Roads

To design a reliable lighting network, a representative Lebanese road with an extreme curvature of 0.1 $m^{-1}$ will be considered on which our system will be implemented on with the aim of fully lighting it up. To do so, we must calculate how many LEDs need to be installed before and after the curve for the driver to react in time and slow down for the curve.

On mountainous roads, drivers will be driving at approximately 40–50 km/h; hence, lighting up the road 40–50 meters before and after the curve would be most suitable. As for the curve, in the case of a turn with a curvature radius of 10 meters, the radius produces an arc length of 31 meters, with the arc being the curve length of the road. Adding up the measurements, we will end up with a road of 111–131 meters to light up with LEDs, with one side of the road being curvier.

Now for the light itself, considering an average case where each LED used consumes 30W to light up 4000 lx (1 lx = 1 lumen per square meter). Based on a study by Lam (2022), light emitted from an LED of this caliber can expand up to 10–15 meters in width while maintaining its luminous intensity, with the source being 4–6 meters high from the ground.

An extra feature of the design is that it includes five extra blinking LEDs signaling the arrival of another vehicle from the other side of the road, as well as two LEDs placed at the curviest part of the road that are lit up all the time. Due to that, the driver will be able to react in time and safely avoid any possible accident.

With the length of the road mentioned earlier, on average, the road requires around 10–12 LEDs on each side for efficient lighting, so around 22 in total and five working with half power consumption for the blinking effect. Finalizing our calculations, our batteries must serve a total approximation of 1335W of power, inclusive of all LEDs lit up on the road.

### Nighttime Sensor

A basic light sensor using a Light Dependent Resistor (LDR) can be efficiently implemented by taking advantage of daylight, which significantly reduces the LDR's resistance. Upon receiving sunlight, the resistance of the LDR would dramatically decrease, thus causing an abrupt drop in voltage across it. This voltage is constantly compared to a threshold of 1V using an Operational Amplifier in an open-loop configuration named comparator. Its output is high if the voltage does not drop below the threshold: when no sunlight is detected. A diode is used to digitalize the output (a digital signal that goes high and low instead of analog), by letting positive output pass through it and by transforming negative output into zero voltage by impeding its passage.

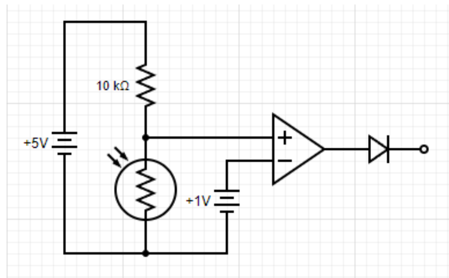


*Figure 4: Nighttime sensor design using light dependent resistor*

**Motion Sensor**

To further save energy, a motion sensor is designed to detect cars on the lane and activate the LED network for two and a half minutes. Motion-sensored lighting extends the lifetime of LEDs, providing efficient lighting with less power, maintenance, and light pollution (Lam, 2022). The design uses an infrared (IR) transmitter-receiver system that detects motion when the signal between them is interrupted by a vehicle. A phototransistor receiver is used due to its reliability in varying ambient light conditions and converts this IR radiation into an electric current.

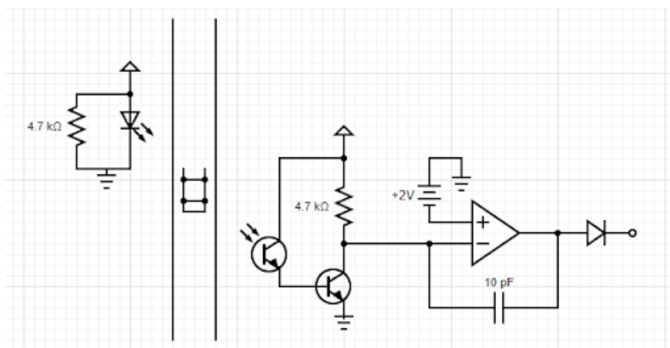


*Figure 5: Motion sensor design using infrared transmitter and receiver*

The current is amplified, passed through a resistor across which its voltage is compared to a threshold of 2V. When this voltage is below this threshold, indicating motion detection, the comparator outputs +5V. This voltage activates an LED. If enough signal is received, the comparator's negative output is blocked by a diode, indicating no obstruction by a passing car.

**Logic Circuit**

In this design, both motion sensors are connected to an OR Gate, which outputs a signal if at least one input is active. This output is then connected to an AND Gate along with the nighttime sensor, meaning both the nighttime sensor and at least one motion sensor must be active for the LEDs to turn on.

For the second part, all sensors are connected to an AND Gate resulting in the activation of blinking LEDs only when it is night and both motion sensors are triggered, warning drivers that another vehicle is approaching from the opposite direction. The simulation confirms the correct timing for activating both regular LEDs and the blinking LEDs with negligible delay.

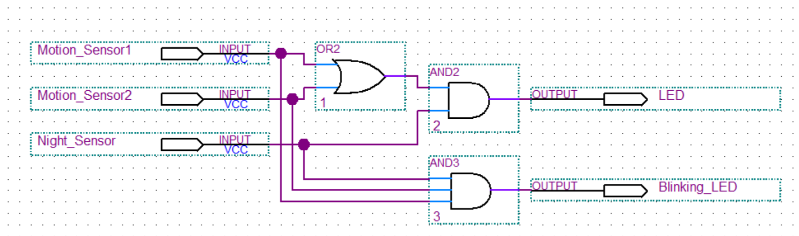


*Figure 6: Logic unit to activate different LEDs*

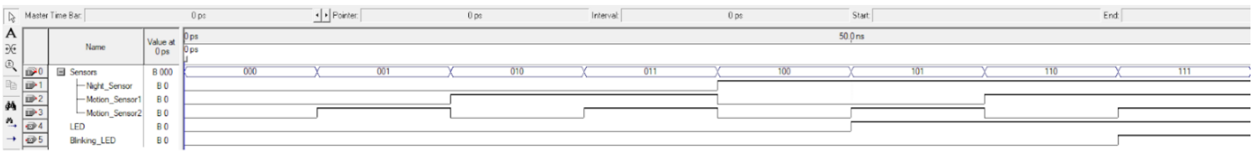


*Figure 7: Simulation of the logic unit on Altera Quartus II*

## Full Network Schematic

Assembling all the units together yields the following complete network. At first, when the lane is empty, the sensor transmitter sends an infrared signal to the sensor receiver that produces an output equivalent to "nothing detected". Once a car passes, the signal is blocked for an instant, during which this motion signaling unit would signal a high output corresponding to "motion detected". Then, this data is processed in the logic unit which also receives data from the nighttime sensor, indicating a current flow during nighttime. In that case, the timer circuit is activated and keeps the regular LEDs on for 150 seconds to ensure safety for drivers. On the other side, the output of another motion sensor on the other direction of the road is processed in the flickering unit that would turn on blinking LEDs if both sensors are simultaneously triggered. The second motion sensor was omitted for simplicity since its structure is the same as the first sensor. As for the LEDs, they are merely activated by the combination of the nighttime sensor and the motion sensors. Parameters of the counter and clock configurations are mentioned below.

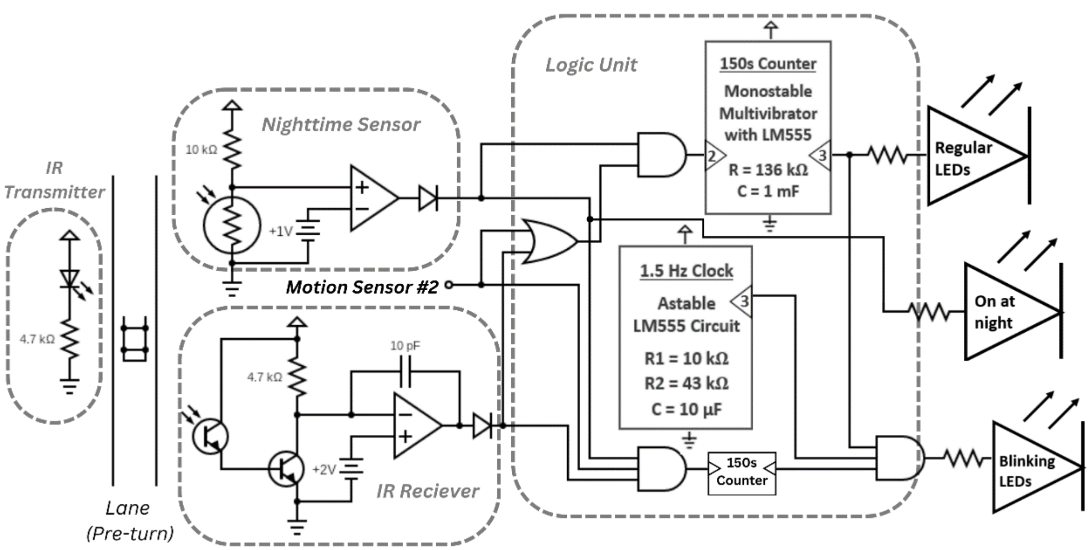


*Figure 8: Final LED network combining sensors and logic circuits*

## Conclusion

In conclusion, the mountainous road lighting insufficiency was tackled by harvesting energy on the road itself via bumps that convert the mechanical energy performed on it to a rotational motion inducing a direct current. The latter is regulated using a voltage adjustor via the BQ24650 chip before being stored in lithium batteries protected by Schottky diodes. Finally, an intelligent motion-sensored LED network constantly collects data from the nighttime sensor and two IR motion sensors. This information is processed by logic circuits to activate regular LEDs and blinking behaviors only when deemed necessary.

Nevertheless, the generalizability of this design is subject to a physical limitation, especially if the roadside is too narrow to accommodate enough space for the needed amount of lithium batteries, consequently limiting the storage capacity of the system. An additional uncontrolled factor is that of random fluctuations in the signals processed by the sensors, originating from external and environmental factors such as temperature, natural interferences, and proximity to other systems. Such may result in false positive sensor output if their impact was significant enough, thus increasing the chance of sensor inaccuracy in some extreme cases.

Future studies may consider the practicality of implementing this network in a hybrid combination of distinct energy harvesting techniques according to some specific characteristics of roads. For instance, the feasibility of complementing the designed network with wind turbines on windy roads could be researched. Another place for improvement might be to equip extremely vulnerable roads with advanced alarm systems to signal the occurrence of serious problems requiring maintenance, such as soil degradation, road fissures, erosions, or rockslides.

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