UNIVERSITY OF SOUTHERN CALIFORNIA
DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING

AME-410: ENGINEERING DESIGN THEORY AND METHODOLOGY
FALL 2013

<Regenerative Speed Reducer>

(Group 9)

FINAL PROJECT REPORT

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GRADE SHEET FOR FINAL REPORT

Category	Grade (max)
Final Presentation	___________**(5)**
Clarity of concepts	
Organization of contents	
Presentation style and effectiveness	
Overall Write-up	___________**(5)**
Comprehensiveness of report	
Development of theme	
Effectiveness of message	
Executive Summary	___________**(5)**
Conciseness	
Clarity	
Effectiveness	
Product Planning	___________**(10)**
Company description	
Market and situation analysis	
Product definition	
Product Specification	___________**(10)**
Requirement analysis	
Requirement list	
QFD house of quality	
Developing Functional Structure	___________**(15)**
Abstraction for essence of the problem	
Overall function definition (black box)	
Function structure	
Clarity of flows of energy, material, information	
Completeness of the functional structure	

Developing Design Concept __________**(15)**

Generating solution principles for major functions
Morphology chart
Variants generation and discussion
Feasibility judgment, technology assessment, go/no-go screening
Evaluation of variants and design concept selection
(Based on advanced decision matrix)

Product Design __________**(15)**

Preparation for product design
  Embodiment determining requirements
  Constraint assessment
Function carriers identification and parameter design
Layout drawing of the product
Use of principles (design reflection):
  Force transmission, Division of tasks, Self-help
Use of methods (design reflection):
  Constraints, configuration, connections, components material, production
Bill of Materials

Product Evaluation __________**(10)**

Performance evaluation
  P-Diagram and behavior modeling
  Sensitivity analysis
Cost evaluation and pricing

Conclusions __________**(10)**

Summary comments
2-5 conclusions
2-5 Recommendations
Future work (what are still left to be done to complete the design)

Total __________**(100)**

General Comments:

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EXECUTIVE SUMMARY

Energy shortage and pollution are urgent problems that our world faces in daily modern life. Vehicle, which is one of the greatest inventions of the industrial civilization, is a big contributor of this. According to the data, about 30% of the air pollution and more than 30% of the oil consumption is caused by the vehicles. In order to rebalance our transportation system in a much “smarter way”, intelligent transportation system has been research in many places. How to make the traffic system more efficient? How to make the vehicles less energy consuming? These kinds of questions have been brought to table. Base on the idea of solving these problems, we propose a design that not only slows down the vehicle without using the brake, but also transforms the kinetic energy to electricity as the car passes the system as a portion of our future traffic system.

Our Regenerative Speed Reducer (RSR) can be widely used specially by the government. RSR can be set on the streets for speed reduction. Also, government can use RSR in temporary situation, such as police check points, traffic control, and so on. The regenerated energy is stored in RSR’s battery and is then used to supply power for street lamps or warning signs or even traffic lights. Our new product will definitely have a huge impact on the existing bump market and may in the future take lead in this field. Based on our design we have come up with a spring damping system with linear turbulent generator, which we will discuss about it step by step.

INTRODUCTION

In this report, tools and methods will be used based on the order of designing process. Firstly, situation and market analysis will be done base on the existing problem and technology in order to do figure out the product definition. Secondly, based on the requirement from the customer the requirement list will be put out and properly weighted. Those requirements and weights as well as the info of the competitors will be put in to a big house of quality (QFD). And all the information will be show and compared in order to get the advantage and disadvantage of our competitors and ourselves. It will help us to define our problem and prospective design better. Thirdly, we will develop the function structure, which include all main and sub functions of our design, and also the EMS flow chart, which categorize the functions as the three main input and output of the system: Material, Energy & Signal. Fourthly, we will generate the concept from the Morphology Chart, which is a potential solution chart for each of the functions. We will select the final variants base on the decision matrix. Fifthly, the process will come to the product design, in which the carrier of the functions in our system will be determined. This part will also including the 3D AutoCAD draft of our design. Those layout drawing will be the basis of our future prototype. In the product design section, the principles and methods of our sub-systems will be introduced to you to have a detail understand of each part of our system. And then, the design evaluation will be focusing on the physical model analysis, because to verify our design we need to comparing our theoretical results to the experimental results we will have from our prototype. Despite the basic model of the main part of our system, the possible noise will also be considered as a basic assumption of our design. The comparison of the final results including the model theoretical results as well as the noise and the experiment results will be a great response to our design process. In the design evaluation, cost evaluation is another important aspect. This will testify the future business and industrial possibilities of our design. As a business design proposal, cost is always an important factor in the whole design procedure. After going through the whole process, we will be able to come to conclusion based on the results we have.

1 PRODUCT PLANNING

The goal of project planning is to formalize the process so that a product is developed in a timely and cost-effective manner. Planning is the process used to develop a scheme for scheduling and committing the resources of time, money, and people. Planning generates a procedure for developing needed information and distributing it to the correct people at the correct time. Important information includes product requirements, concept sketches, system functional diagrams, solid models, drawings, material selections, and any other representation of decisions made during the development of the product.
In the following chapter the RSR's product planning is explained and briefly covered initial parameters.

1.1 Our Company

JASMA

JASMA is a Mechanical Engineering Company which works in Mechanical Design domain. Product design is one of the contexts that this company focuses on. Members of this company are all mechanical engineers and have several project experiences in designing products and related areas.
JASMA's members are interested in concentrating on energy issues and optimizing harmony of urban areas. Therefore they are trying to increase the coordination of urban parts in order to recycle the energy which is wasted every day by them. RSR is their first designed product in their focused property.

Motivation

A speed bump, speed hump or ramp is a traffic calming feature of road design used to slow traffic, or reduce through traffic, via vertical deflection.
The use of speed bumps is widespread around the world, and they are most commonly found where vehicle speeds are statutorily mandated to be low, usually 40 km/h (25 mph), or 8 to 16 km/h (5 to 10 mph) in car parks. Although speed bumps are very effective in keeping vehicle speed down, their use is sometimes controversial as they can cause noise and possibly vehicle damage if taken at too great a speed. Poorly designed speed bumps often found in private car parks (too tall, too sharp an angle for the expected speed) can be hard to negotiate in vehicles with low ground clearance, such as sports cars, even at very slow speeds.
Speed bumps are used to decrease the speed of vehicles and it means there is some energy which waste every day. We can design a new kind of bump which could regenerate the kinetic energy of cars and also be useful for every kind of car.

Target

Our target for solving above mentioned problem, and our product is a system, which can provide two main functions.

- Reduce car speed: To satisfy traffic and safety issues
- Collect energy: To satisfy energy concerns

According to these two main functions we can figure out our situation in Market and Products.

1.2 Analysis of the situation

Reduce car speed

Right now systems that help the traffic fellow in order to reduce cars speed exist. The market includes all the companies, organizations and individuals who want to reduce speed of cars that pass specific points. (For example, in parking entrances or in crowded urban streets or in highways exits.) So our market already exists.
However, products which are used to satisfy the market needs, are all just tell drivers that they have to stop or reduce their car speed (existing products include bumps or all of other kinds of traffic signs.) There is no similar product which could directly reduce cars speed and because of that we think our situation is in the existing market and new product.

Collect energy

For collecting the wasted energy of cars during braking, the market includes all the companies, organizations or individuals that want to regenerate this amount of energy and make profit of it, and this market just exists for cars owners or drivers right now. (Regenerative brakes in Hybrid and Pure electrical cars)
So our market is a new market in this domain, and again our product is a new product.
Based on these considerations our overall situation is shown as Figure 1.1.

Figure 1.1 Market analysis

1.3 Product definition

The problem is showing a pool of opportunities that includes big amount of energy that cars waste every day. Also this system would be a pioneer to help drivers prevent from accidents that are caused by driver's mistake.

Each car wastes -55000 J in each normal braking before a speed-bump in average. If getting Efficiency about 70% and the price of Electricity in California, 19.3 cents per kWh in August 2013, we can collect 0.19 cent per car! In average urban areas in order of traffic, the profit is as high as $273 per month per bump!
On the other hand, each car wastes -108000 J in each normal braking in Highways Exits in average, so we can collect 0.379 cent per car. That is $6,500-11,000 per month per exit!

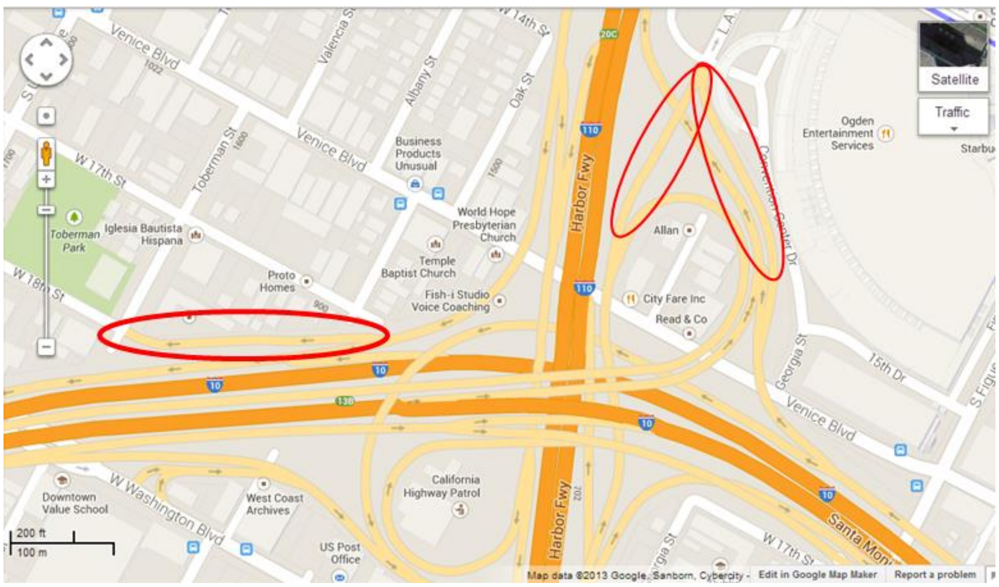


Figure 1.2 The target places of our product

Our Product is a novel product in an existing/new market. We find out that there are positions that is possible to design a system which could be placed there and reduce cars speed by converting car's kinetic energy to some other storable state of energy. For instance, in urban areas when cars have to brake for exiting highways, there is a potential to implement this system without disturbing drivers' maneuverability.
We chose our product's main function based on what lacks in Traffic controlling systems and considering majority of non-EV and not hybrid cars.

2 PRODUCT SPECIFICATION

The Regenerative Speed Reducer (RSR) is a wide use product, and our main customer is government. Government can set RSR on the streets for reducing speed as a normal speed bump. Also, government needs RSR in urgent situation; such as temporary police checkpoint, temporary traffic control, and so on. The regenerative energy will be stored in the battery of RSR and then further be used to supply power for street lamps or warning signs or even traffic lights. Therefore, the end-user of RSR is every driver, and the citizens are our undirected users who take and enjoy the benefits of RSR. The other group of our customer is parking owner. Not only RSR can use at the entrance and exit of parking lots and structures for slowing vehicle's speed down, but also the regenerative energy can be applied to space counter, ticket machine, lever machine, and so on. Besides, we can directly sell our product to government and parking owners, and also we can authorize a manufacture to produce and sell this product. Thus, the manufacture will be one of our customers. Rather than fixing on one customer to cater for specific condition, we set the RSR to be an innovative product to match and satisfy above customers' needs.

2.1 Requirement analysis and Requirement list

Based on the view above, we analyze the requirements of all the customers by different types of customer requirements (Table 2.1) and the weights of different customers' requirement (Table 2.2).

Table 2.1 Types of customer requirements

Functional performance	**Life-cycle concerns**
High energy transformation High energy storage Much speed reduction	Ease of energy reuse Good maintainability (long life time) High stability of energy source Environment protection
Human factors	
Comfort Good appearance	
Physical requirements	**Resource concerns**
Small underground placement Good damage prevention Absorbing impact	Less manufacture cost Much funding or many sponsors
Reliability	**Manufacturing requirements**
Good robustness High safety	Easy manufacturing Low equipment cost High quality

For functional performance, we concern the major functions of our product, and then high-energy transformation, high-energy storage, and much speed reduction are listed, as our customer needs. And for the human factors, drivers need comfort most, and citizens need good appearance most. For the physical requirements and reliability, the safety issue is the most important concerns, so we listed good damage prevention, absorbing impact, good robustness, and high safety in the requirement list. Besides, the customers may also need underground space for another use, so small underground placement is listed. The life cycle and resource concerns are ease of energy reuse, good maintainability, high stability of energy source, environment protection, less manufacture cost, and much funding or many sponsors. Most of them are mainly focused on the issues of cost, maintenance, and environment. Unsurprisingly, the manufactures care manufacturing requirements most, and other customers also hope good quality of this product.

Table 2.2 Weights of customer requirements

	Original importance (1~10) / Adjusted weight (sum of 100)									
Customers	Drivers (end-user)		Government		Parking Owners		Citizens		Manufacturer	
Requirements	Ori.	Adj.	Ori.	Adj.	Ori.	Adj.	Ori.	Adj.	Ori.	Adj.
High energy transformation	4.0	3.3	9.0	5.5	9.0	5.7	9.0	6.0	5.0	4.0
High energy storage	4.0	3.3	10.0	6.1	10.0	6.3	8.0	5.3	5.0	4.0
Much speed reduction	10.0	8.2	8.0	4.9	8.0	5.1	6.0	4.0	5.0	4.0
Comfort	10.0	8.2	6.0	3.7	6.0	3.8	3.0	2.0	5.0	4.0
Good appearance	8.0	6.6	7.0	4.3	7.0	4.4	10.0	6.6	7.0	5.6
Small underground placement	5.0	4.1	9.0	5.5	9.0	5.7	10.0	6.6	8.0	6.3
Good damage prevention	9.0	7.4	7.0	4.3	7.0	4.4	8.0	5.3	5.0	4.0
Absorbing impact	10.0	8.2	7.0	4.3	7.0	4.4	7.0	4.6	5.0	4.0
Good robustness	5.0	4.1	10.0	6.1	10.0	6.3	8.0	5.3	9.0	7.1
High safety	10.0	8.2	10.0	6.1	10.0	6.3	10.0	6.6	6.0	4.8
Ease of energy reuse	5.0	4.1	10.0	6.1	10.0	6.3	10.0	6.6	5.0	4.0
Good maintainability (long life time)	7.0	5.7	10.0	6.1	10.0	6.3	8.0	5.3	7.0	5.6
High stability of energy source	7.0	5.7	8.0	4.9	8.0	5.1	9.0	6.0	5.0	4.0
Environment protection	7.0	5.7	9.0	5.5	9.0	5.7	10.0	6.6	2.0	1.6
Less manufacture cost	5.0	4.1	8.0	4.9	8.0	5.1	9.0	6.0	10.0	7.9
Much funding or many sponsors	3.0	2.5	10.0	6.1	5.0	3.2	9.0	6.0	7.0	5.6
Easy manufacturing	1.0	0.8	6.0	3.7	5.0	3.2	3.0	2.0	10.0	7.9
Low equipment cost	3.0	2.5	10.0	6.1	10.0	6.3	7.0	4.6	10.0	7.9
High quality	9.0	7.4	9.0	5.5	10.0	6.3	7.0	4.6	10.0	7.9

(The marks with different colors are the more important requirements of each customer.)

2.2 QFD house of quality

The QFD house of quality (HoQ) is a method to process from voice of customer to product design. It has eight parts as the Fig. 2.1 shows.

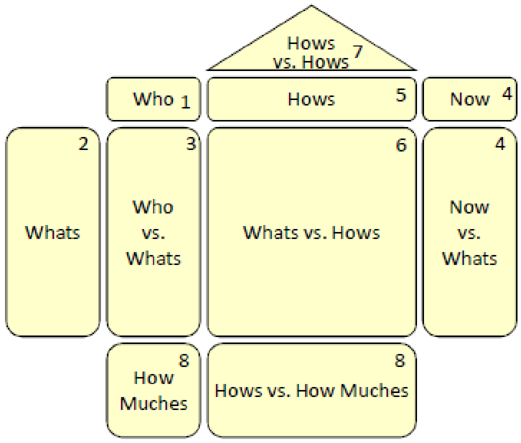


Figure 2.1 The skeleton of House of Quality

(1) Identify Customers

The first step is to identify customers. According section 2.1, we identified our customers are drivers, government, parking owners, citizens, and manufacturer. And the end-user is driver, so we put the driver to the HoQ as a representative.

(2) Determine Customer Requirements

According to section 2.1, we have already determined our customer requirements. There are 19 main customers' requirements shown in Fig. 2.2.

(3) Determine Relative Importance of the Requirements

The third step is to determine relative importance of the requirements. But here, we only put the relation of the importance and requirements of our end-user, driver, in the house of quality. Other customers' related weights could be looked up in the Table 2.2.

1	9	3.3	4.0	High Energy Transformation
2	9	3.3	4.0	High Energy Storage
3	9	8.2	10.0	Much Speed Reduction
4	9	8.2	10.0	Comfort
5	9	6.6	8.0	Good Appearance
6	9	4.1	5.0	Small Underground Placement
7	9	7.4	9.0	Good Damage Prevention
8	9	8.2	10.0	Absorbing Impact
9	9	4.1	5.0	Good robustness
10	9	8.2	10.0	High Safety
11	9	4.1	5.0	Ease of Energy Reuse
12	9	5.7	7.0	Good Maintainability (long life time)
13	9	5.7	7.0	High Stability of Energy source
14	9	5.7	7.0	Enviornment Protection
15	9	4.1	5.0	Less Manufacture Cost
16	9	2.5	3.0	Much Funding or Many Sponsors
17	9	0.8	1.0	Easy Manufacturing
18	9	2.5	3.0	Low Equipment Cost
19	9	7.4	9.0	High Quality

Figure 2.2 Who vs. Whats

(4) Identify and evaluate competition

This is a novel view of the bump on the road, so in fact, the original competitor is only the speed bump company, such as SA Speed bumps. However, we still can find some competitors based on the two major functions of our regenerative speed bump, which are speed-reducing and the energy saving. The fig. 2.3 shows our competitors, and they are hybrid car company, stinger spike system, Adaptive cruise control system (ACC), speed-bump company, and traffic control signs. According to the competitors' performance in each requirement, we evaluate them by scoring with the range of 0-5. The 0 is the worst, and the 5 is the best. In this competitor analysis part, our product seems in a good situation because others scores are vary hugely in contrast with ours.

Competitive Analysis
(0=Worst, 5=Best)

Our Company	Competitor 1: Hybrid Car Company	Competitor 2: Stinger Spike System	Competitor 3: Adaptive Cruise Control System	Competitor 4: Speed-Bump Company	Competitor 5: Traffic Control Signs
3	3	0	0	0	0
3	3	0	0	0	0
4	1	4	3	3	3
4	5	1	5	0	3
3	4	1	0	1	1
3	5	5	5	5	5
3	4	0	5	2	5
4	0	0	0	3	0
4	4	1	4	4	5
4	5	0	5	3	3
5	4	0	0	0	0
4	4	1	5	4	5
3	5	0	0	0	0
5	5	3	4	3	4
3	1	4	2	4	5
5	4	1	3	1	3
3	1	3	2	5	5
4	0	4	1	5	5
4	4	4	4	4	5

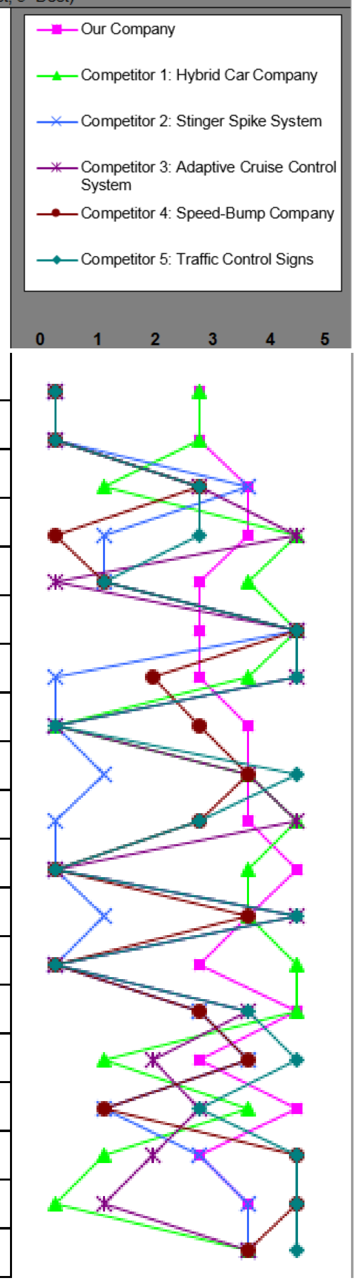


Figure 2.3 Now vs. Whats

(5) Generate Engineering Specifications

For the engineering specification part, which is also called the functional requirements or hows, there are high energy conversion rate, batteries with high capacity, conspicuous color, high quality buffer (cushion), simple mechanism, heat emission, shape, vehicle moving direction, component size, toughness, stable car flux, cost per regenerative speed bump, electricity generation, air pollution index, and ultimate passing speed. (see Fig. 2.4)

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	x	▲	x	▼	x	x	▼	▲	x	▼	▲	▼	▲
Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	High Energy Conversion Rate	Batteries with High Capacity	Conspicuous Colour	High Quality Buffer (cushion)	Simple Mechanism	Heat Emission	shape	Vehicle Moving Direction	Component Size	Toughness	Stable Car Flux	Cost per Regenerative Speed Bump	Electricity Generation	Air Pollution Index	Ultimate Passing Speed

Figure 2.4 Hows

Basically, they come from the "whats" part, and we generated these "hows" by asking the questions: how to achieve those customer requirements? We also defined the direction of improvement of each "hows" with the symbols: "▼" means the smaller is the better, "▲" means the larger is the better, and "X" means it is a target.

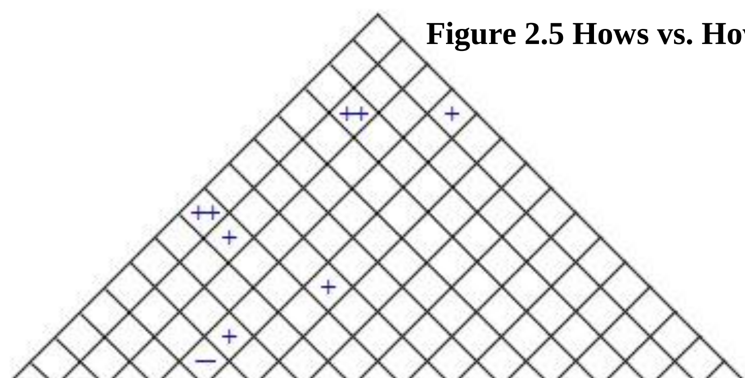
(6) Relate Customers' Requirements to Engineering Specifications

In this sixth part, we put the relation between customers' requirements to engineering specifications. Basically, each customer's requirement has at least one engineering specification to achieve with strong relationship. We use ⊙, ◯, and ▲ to represent strong, moderate, and weak relationships respectively. (Fig. 2.6)

(7) Identify Relationships between Engineering Requirements

After came out these engineering specifications, we identified the relationships between them. As you can see in Fig. 2.5, we use "++" representing "strong positive correlation", "+" representing "positive correlation", "-" representing "negative correlation", and "▼" representing "strong negative correlation". Most of them in our project are positive correlation, and only the relationship between "high quality buffer" and the "simple mechanisms" is negative. It's good for us to have the most positive correlation relationships, but we still need to find the balance between the complexity of mechanisms and the quality of buffer.

Figure 2.5 Hows vs. Hows



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	x	▲	x	▼	x	x	▼	▲	x	▼	▲	▼	▲
Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	High Energy Conversion Rate	Batteries with High Capacity	Conspicuous Colour	High Quality Buffer (cushion)	Simple Mechanism	Heat Emission	shape	Vehicle Moving Direction	Component Size	Toughness	Stable Car Flux	Cost per Regenerative Speed Bump	Electricity Generation	Air Pollution Index	Ultimate Passing Speed

(8) Set Engineering Targets

The last step, we set our target / limit value for each functional requirements, and they seems not too hard to reach (Fig. 2.7). The high quality buffer and the high toughness both are two of the most important functional requirements in this form.

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	x	▲	x	▼	x	x	▼	▲	x	▼	▲	▼	▲
Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	High Energy Conversion Rate	Batteries with High Capacity	Conspicuous Colour	High Quality Buffer (cushion)	Simple Mechanism	Heat Emission	shape	Vehicle Moving Direction	Component Size	Toughness	Stable Car Flux	Cost per Regenerative Speed Bump	Electricity Generation	Air Pollution Index	Ultimate Passing Speed
High Energy Transformation	⊙	⊙				⊙									
High Energy Storage	○	⊙				▲									
Much Speed Reduction	○			○				⊙							
Comfort				⊙			○								⊙
Good Appearance			⊙				⊙		▲						
Small Underground Placement					○		▲		⊙						
Good Damage Prevention				○						⊙					○
Absorbing Impact	▲			⊙						⊙					
Good robustness										⊙					
High Safety			⊙							○					▲
Ease of Energy Reuse	▲	⊙									○		⊙		
Good Maintainability (long life time)					⊙					⊙		⊙			
High Stability of Energy source	▲	▲									⊙				
Enviornment Protection				▲						▲				⊙	
Less Manufacture Cost	▲	▲		▲	⊙					▲		⊙			
Much Funding or Many Sponsors	▲			○						▲	▲		⊙	▲	
Easy Manufacturing					⊙		○								
Low Equipment Cost	▲	▲		▲	⊙							⊙			
High Quality	⊙	⊙		⊙		▲			○	⊙	▲		⊙	○	⊙

Fig. 2.6 Whats vs. Hows

Target or Limit Value	25%	50Ah/unit	Yellow & Black Mosaic	Reduce Speed of 15%	Pistons & Plates Construction	0	round edge	go up and down	1cm2	50 Mpa.m^(1/2)	at the exit of highway	$1,000	370000 J	∞	50mph
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	0	0	8	8	9	0	3	3	5	4	8	8	1	8
Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance	157.4	174.6	132.8	280.3	130.3	40.2	90.2	73.8	65.6	332.0	73.8	110.7	125.4	76.2	170.5
Relative Weight	7.7	8.6	6.5	13.8	6.4	2.0	4.4	3.6	3.2	16.3	3.6	5.4	6.2	3.7	8.4

Fig. 2.7 Hows vs. How Muches

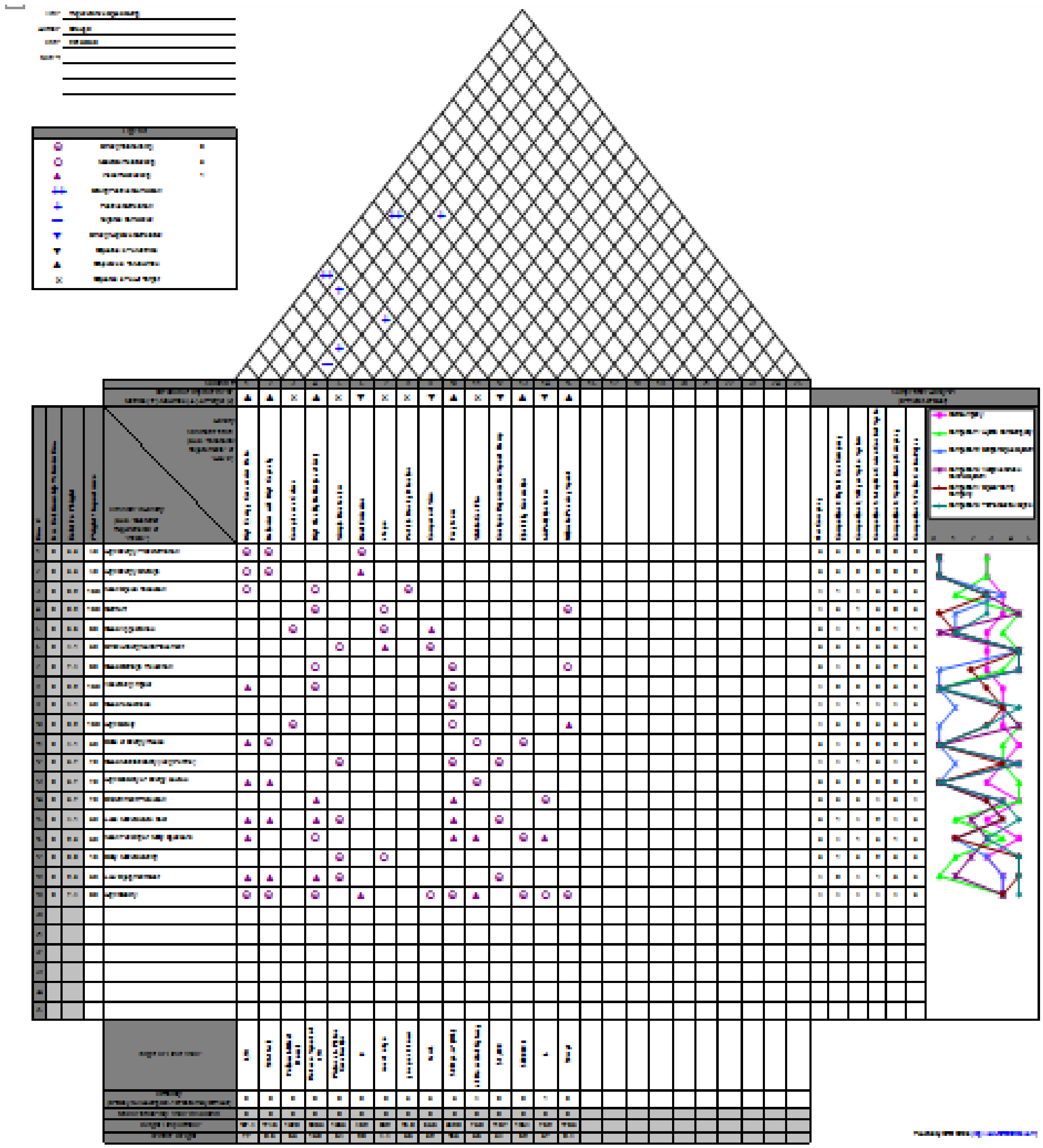


Figure 2.8 House of Quality

3 DEVELOPING FUNCTIONAL STRUCTURE

Developing functional structure is a step-by-step process starting from massy list of requirements and further finding out cruxes the product must has. It enables designers to think broadly, to see the big picture of product in the beginning and then converges designers' thought in the end. It makes it possible for designers to think in proper sequence. Following sections show how we catch the crucial points for our product.

3.1 Abstraction for essence of the problem

S1, S2:

Energy conversion rate: 20%~40%
Battery capacity: 30Ah/unit~70Ah/unit
Yellow & black mosaic
Working cycle: 15,000,000~25,000,000 times
Energy waste saving: 30%~40%
Speed reducing: 15%~25%
Loading weight: 45~60 Mpa.m^(1/2)
Electricity generation: 370,000J~400,000 J
Material/Texture: Plastic and steel
Air pollution index: 8
Noise: 50~60dB
Passing speed: 50~55mph

We eliminated some requirements of personal preference from the massy requirements list in S1, since personal prejudices usually oblique, not considering whole aspects. Moreover, we also deleted those not relevant with the functions/ constrains of product, like yellow and black mosaic and material/texture, in S2.

S3:

High-energy conversion rate
High battery capacity
Long duration
Low energy waste
Various speed reducing
Various loading weight
High speed passing

In S3, we transformed quantitative data in qualitative and omitted those no essential, such as air pollution index and noise index.

S4:

Recycle energy in high-energy conversion rate
High battery capacity
Long duration
Various vehicles passing with high speed

We generalized some remaining requirements into a phrase, and refined the list once more.

S5:

Recycle energy by various high-speed vehicles in long duration speed bump with high-energy conversion rate and store in high capacity battery.

Finally, combined all S4 phrases in one for problem formulation.

3.2 Overall function definition

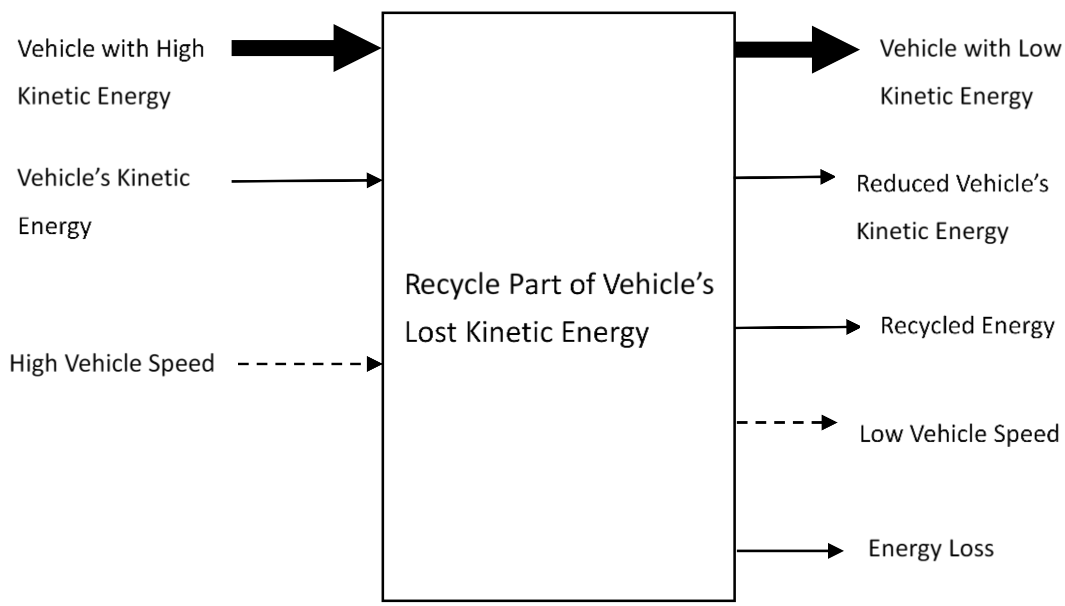


Figure 3.1 Overall functions

As Figure 3.1 shown above, the main function of this design is to recycle the lost energy coming from vehicles going over bumps as much as possible. We would like to convert and collect part of the vehicle's kinetic energy (Ek), so we have vehicles with high Ek become vehicles with low Ek, have vehicle's kinetic energy become reduced vehicle's Ek, have high vehicle speed become low vehicle speed, and energy loss of course.

3.3 Develop function structure

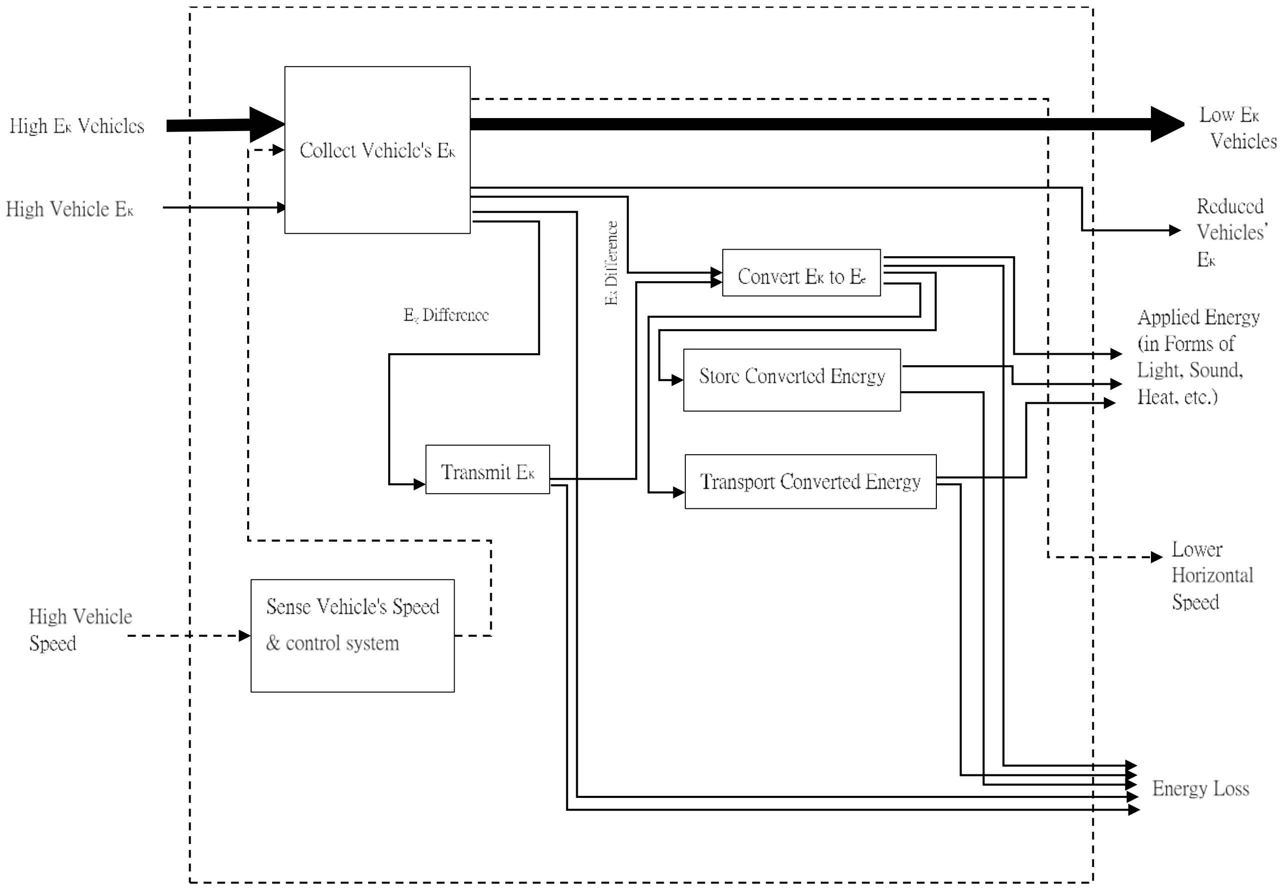


Figure 3.2 Functions structure

For energy part, we would like to have high Ek coming to the system, collect some of it, and convert it. So we would have reduced Ek, which is from vehicle's aspect, coming out from the system, and have collected Ek going into convert Ek to Ee function to get the energy in forms we need or to get it stored. We also have transmit Ek function to transmit the collected energy from the vehicle end to the mechanism end, and finally, energy loss coming out from the system. For material part, we simply have vehicles with high Ek to be collected energy from coming into the system and then vehicles with low Ek coming out of the system. For signal part, we would like to have a function to deal with the status of vehicles and of the speed reducer. We have all vehicle's speed information coming into our system and then determine which way is best to deal with the vehicle's info at the moment. For example, in Figure 3.2 we have lowered horizontal speed coming out as a signal since at the step of collect vehicle's Ek, we have sense vehicle's speed & control system function to calculate and determine which way to realize the vehicle speed reduction and the energy collection.

3.4 Develop activity EMS flow

Stage / Flow	Preparation	Use/Application	Conclusion
Material related		Collect vehicle's E_K	
Energy related		Transmit E_K Convert E_K to E_E	Store converted energy Transport converted energy
Signal related	Sense vehicle's speed & control system		

Table 3.1 Activity EMS flow

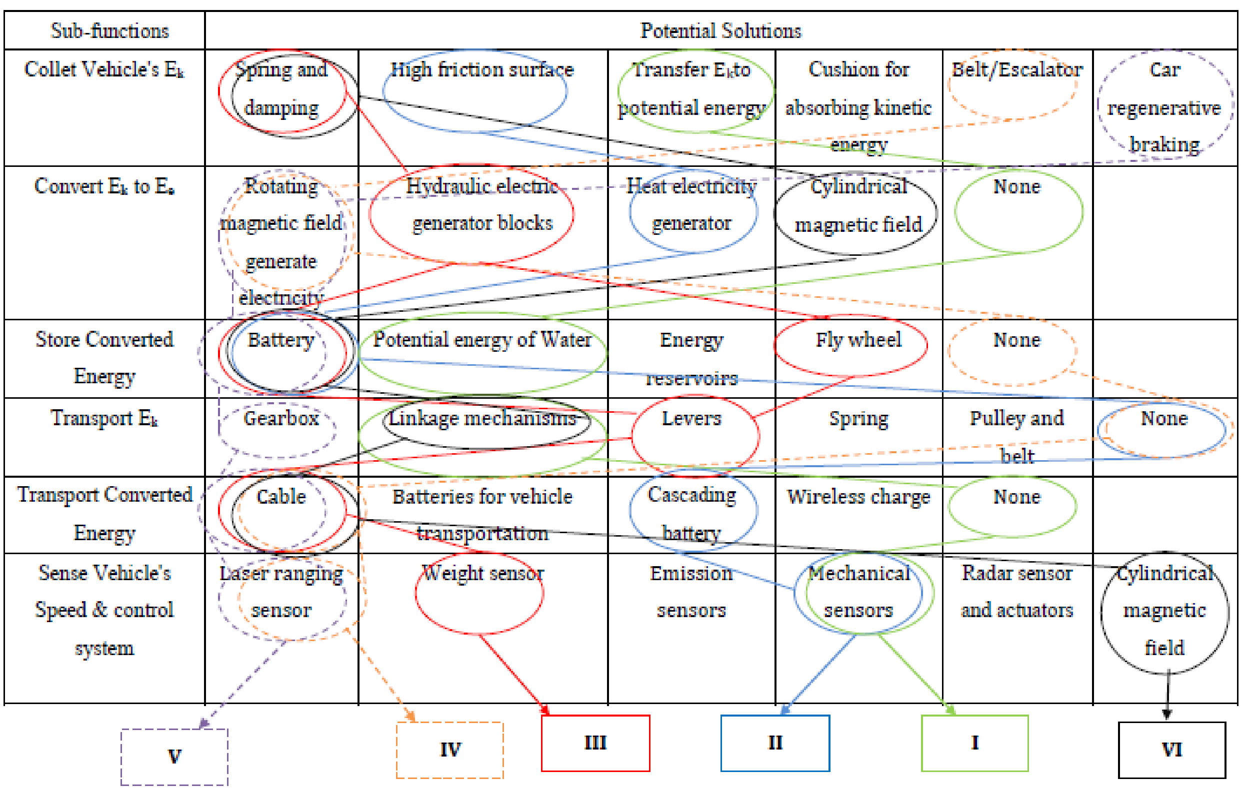
In the preparation stage, the sensor detects how fast and what type of vehicle that is going to pass through the bumper. By the data the sensor get, RSR adjusts the stiffness of bumper to insure effectiveness for reducing vehicle speed. Once the vehicle contacts with bumper, RSR starts to collect its kinetic energy and transmit them for electrical converting in use/application stage. In the end, electricity can be stored or transported by RSR in conclusion stage. Sport/transport converted energy are crossover functions between stage of use/application and of conclusion. The activity flow of RSR is shown as Table 3.1 above.

4 DESIGN CONCEPT DEVELOPNENT

In this part of report, the conceptual design is generated based on the technique which uses the functions identified to foster ideas. This technique is often called the “morphological method”. There are three steps to this technique. The first step is to list the decomposed functions that must be accomplished. The second step is to find as many concepts as possible that can provide each function identified in the decomposition. The third is to combine these individual concepts into overall concepts that meet all the functional requirements. The design engineer’s knowledge and creativity are crucial here, as the ideas generated are the basis for the remainder of the design evolution. This is highly modified from the morphology done at Irwin to protect their intellectual property.

4.1 Morphology chart and Variants selection

Based on last report of JASMA Company, RSR’s main function could be decomposed in 6 major functions which are: Reduce vehicle’s kinetic energy, Transport kinetic energy, Convert kinetic energy to storable energy, Transport converted energy, Store converted energy, and Sense vehicle’s speed and controlling system.
Accordingly, after we generate a list of concepts for each of the functions, we combine the individual concepts into six complete conceptual designs (Variants).



Sub-functions	Potential Solutions					
Collet Vehicle's E_k	Spring and damping	High friction surface	Transfer E_k to potential energy	Cushion for absorbing kinetic energy	Belt/Escalator	Car regenerative braking
Convert E_k to E_e	Rotating magnetic field generate electricity	Hydraulic electric generator blocks	Heat electricity generator	Cylindrical magnetic field	None	
Store Converted Energy	Battery	Potential energy of Water	Energy reservoirs	Fly wheel	None	
Transport E_k	Gearbox	Linkage mechanisms	Levers	Spring	Pulley and belt	None
Transport Converted Energy	Cable	Batteries for vehicle transportation	Cascading battery	Wireless charge	None	
Sense Vehicle's Speed & control system	Laser ranging sensor	Weight sensor	Emission sensors	Mechanical sensors	Radar sensor and actuators	Cylindrical magnetic field

Figure 4.1 Morphology Chart

Variants description:

I. Reduce vehicle's kinetic energy by transfer it to potential energy of some liquid like water and then use this kind of energy. This system uses mechanical sensors.

II. Reduce vehicle's kinetic energy by High friction surface then convert the heat to electricity and then store it in a series of cascading batteries. This system uses mechanical sensors.

III. Reduce vehicle's kinetic energy by a kind of spring-damper system then it uses hydraulic electrical generator blocks to convert the energy to electrical energy, and then store the electrical energy in battery. In this system small part of kinetic energy of vehicles is stored in flywheel which would be used by hydraulic electrical generator blocks. This system uses weight sensor.

IV. Reduce vehicle's kinetic energy by a kind of flat escalator then uses normal generator to convert the energy to electrical energy. This system uses laser ranging sensor.

V. Reduce vehicle's kinetic energy by regenerative braking system in cars and store the energy in a battery in cars. This system uses laser ranging sensor.

VI. Reduce vehicle's kinetic energy by a kind of spring-damper system, and then convert it to electrical energy by linear electrical generator blocks. Then store this energy in battery. System does not use any extra sensor and just get the information by linear electrical generators.

4.2 Evaluation of variants

In order to evaluate variants, we use the decision-matrix method, or Pugh's method, which has proven effective for comparing alternative concepts. The method provides a means of scoring each alternative concept relative to the others in its ability to meet the criteria. Comparison of the scores in this manner gives insight to the best alternatives and useful information for making decisions.
Table below shows RSR's decision matrix. We consider seven criteria for our decision process, which "Energy conversion efficiency" is the most important and "Appearance" is the less important one based on their weights. The score or total values produced in the Decision Matrix are measures of satisfaction, where *satisfaction* = *belief that an alternative meets the criteria*. Thus, the decision-maker's satisfaction with a variant is a representation of the belief in how well the variant meets the criteria being used to measure it.

Table 4.1 Advanced Decision Matrix

SRS	Concept		Alternatives					
Criteria	Weight	Baseline	I	II	III	IV	V	**VI**
Speed reduction (> 10mph)	20	0.5	0.9	1	1	0.5	0.74	**1**
Energy conversion efficiency (>10%)	22	0.5	0.7	0.42	0.9	0.9	0.9	**0.9**
Life time (>2 years)	9	0.5	0.7	0.62	0.66	0.8	0.8	**0.74**
Capacity of energy storage (>100Ah)	13	0.5	0.9	0.9	0.9	0.5	0.9	**0.82**
Appearance (conspicuous)	5	0.5	0.9	1	1	1	1	**1**
Cost/bump (<$8000)	18	0.5	0.66	0.82	0.82	0.82	0.82	**0.82**
Energy generation (>175J)	13	0.5	0.82	0.5	0.8	1	0.9	**0.9**
	Satisfaction		78.44	72.78	87.60	76.26	84.96	**88.58**

Based on the decision matrix variant VI is the JASMA's selection, meanwhile figure 4.2 is the belief map of the variant VI.

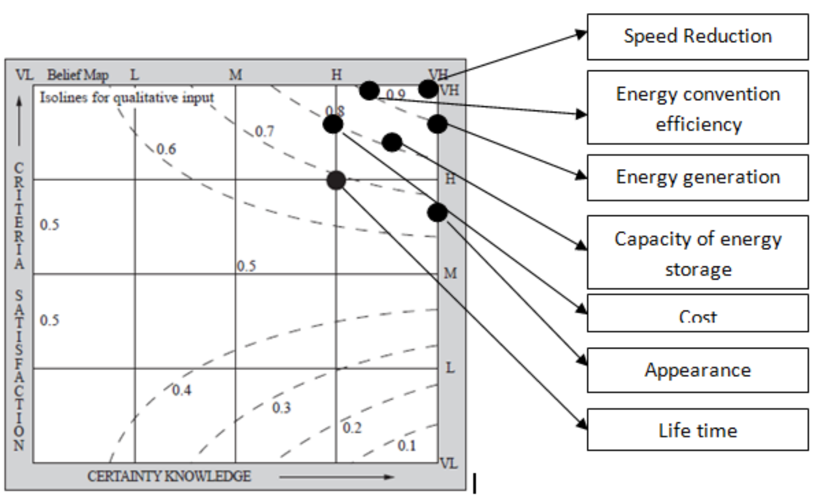


Figure 4.2 Belief Map

4.3 Selected design concept

Our selected variant for Regenerative Speed Reducer (RSR) is using the following function carriers: MCK (spring-damping) system, tubular generator, linkage mechanism, cable, and battery. The design product collects the kinetic energy from cars by pressing down a plate in the linkage mechanism system, which transports the kinetic energy to MCK system. And MCK system collects the kinetic energy so that the tubular generator can convert the kinetic energy into electrical energy. We use cables to transport the electrical energy to battery, and then the battery stores the electrical energy for further use. Because of the kinetic energy reduction, the car will reduce its speed when leaving our product system (Fig. 4.3). Both the linkage mechanism and cable are simple, and the tubular generator is efficient and safe with no mechanical energy loss. Also, it is easy to put a battery into the system, and the datasheets of all the carriers are easily looked up. Therefore, with these function carriers, it is easy to achieve both our purposes: reducing vehicle's speed and regenerating vehicle's kinetic energy.

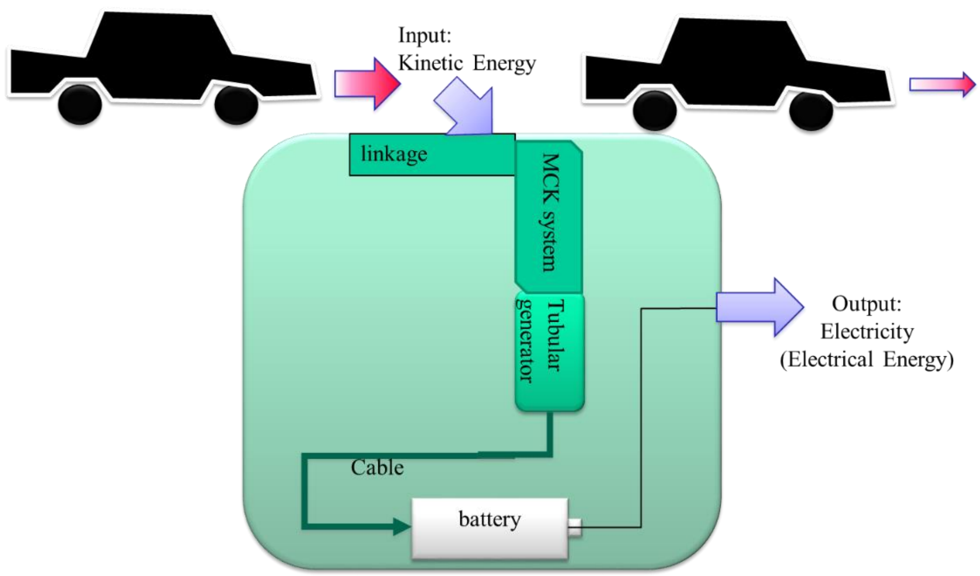


Figure 4.3 Selected design concept

By combining these carriers, we would like to make it like a block which can put on the road as speed bump does (Fig. 4.4). It can be spread as a 6x9 matrix on the road or spread under a plate with the form as a normal speed bump (Fig. 4.5). We will describe the different types of the product with same function carriers in detail in section 5.4.

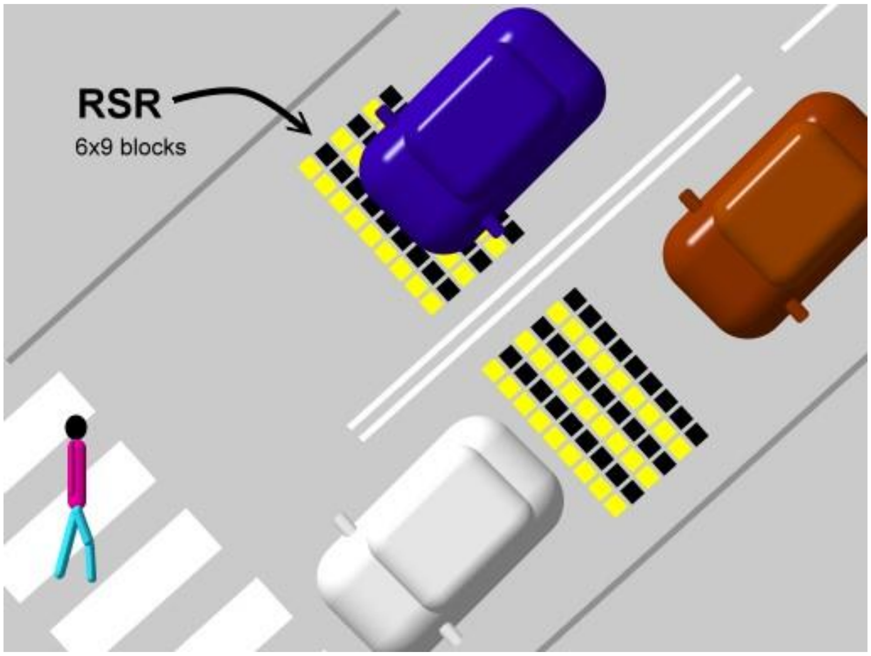


Figure 4.4 the scenario of RSR

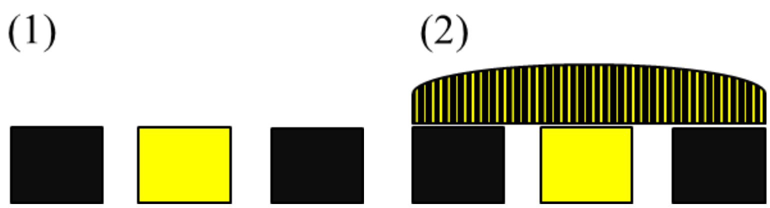


Figure 4.5 the different forms of RSR

5 PRODUCT DESIGN

After deciding the basic function carriers and have basic concept of our design product, we will do the product design in detail. Here, we first prepare for product design, and then identify the parameters of each function carrier. Then, we use Solidworks to do the CAD drawing for more detail design, and also describe the different types of our design. In the final part of this section, we describe the use of principles and methods in our design.

5.1 Preparation for product design

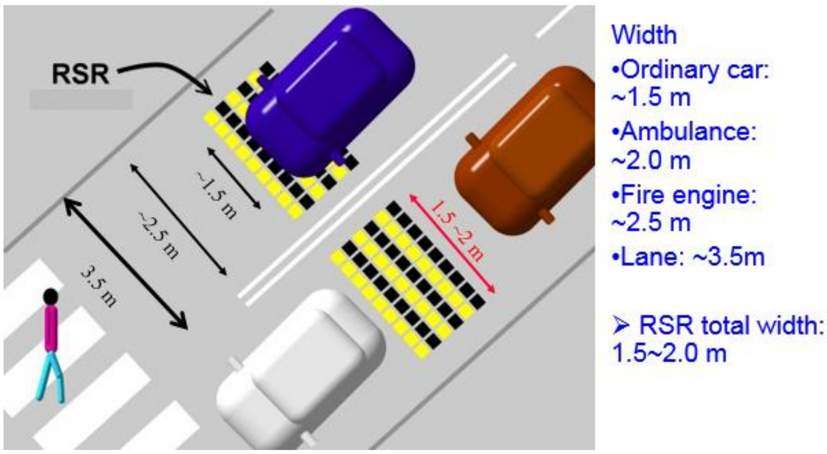


Figure 5.1 Spatial Constraints

Before doing detailed design, we first consider the scale of our product with spatial constraints (Fig. 5.1). Because the lane width in America is about 3.5 meters, the ordinary vehicle width is around 1.5 meters, and the width of emergency vehicles such as ambulances and fire engines are larger than 2.0 meters, we decide to make the total width of our product is between 1.5 and 2.0 meters. With this constrain, we can ensure our RSR won't lower the emergency vehicles' speed but reduce the ordinary vehicles' speed and collect their kinetic energy. The longer of the product spread, the more the speed of vehicle reduced, so the total length of our product put on the road is determined by how much the speed requires to be reduced. The normal speed bump reduces about 10 mph of a car with the speed range 45~65 mph, so we set our speed reduction is around 20% (relatively more stable than speed bump) with the vehicles under 65 mph. Besides, vehicles in general are less than 30 tons, so the maximum loading weight is set to be 30 tons. In addition, passing 10,000 times the 1km long spread hydraulic generator blocks can generate 1200kWh electricity; in other words, one hydraulic generator block can generate 2×10^{-6} kWh electricity. Thus, we decide to generate more electricity than the hydraulic generator block. We also consider the battery capacity (> 0.2 kWh/unit) and the material we would like to use (Plastic, Copper, Rubber, and Steel), and further consider the working cycle to be more than 5 years. Therefore, we identify the embodiment determining requirements as following.

The embodiment determining requirements
Total width put on road: 1.5~2.0 m
Ek→Ee Energy conversion rate: >30%
Battery capacity: > 0.2 kWh/unit
Material/Texture: Plastic, Brass, and Steel
Working cycle: > 5years
Speed reducing: ~ 20%
Passing speed range: < 65mph
Electricity generation: > $2x10^{-6}$ kWh/unit
Loading weight: < 30 tons

5.2 Function carrier identification and parameterization

To do the detailed design, we need to know how these function carriers work and their parameters. As we know, the MCK system consists of spring and damping, and the linkage mechanisms are some mechanical linkages such as plates and rods. The tubular generator is a permanent magnet passing through a lot of coils back and forth. The battery and cable are the common ones.

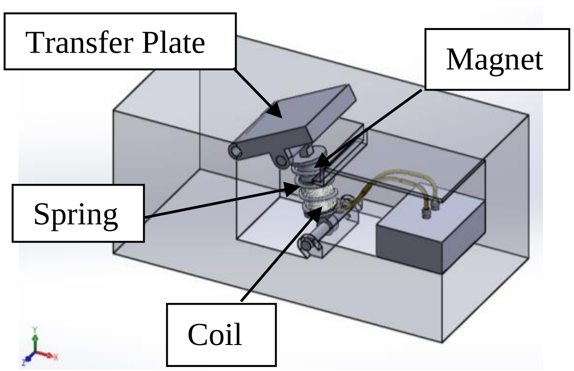
Table 5.1

Functions	Function Carriers	Characteristics
1. Collect Vehicle's Kinetic Energy (Ek)	MCK (mass, spring, damping) system	Mass m Spring coefficient k Damping coefficient c
2. Transport Ek	Linkage mechanism	Height h Angle θ Width w Radius r Thickness t
3. Convert Ek to Electrical Energy (Ee)	Linear tubular generator	Magnet speed v Electrical energy Ee Coil turns N Tube length L
4. Transport Ee	Cable	Length l Section area A Conductivity σ
5. Store Ee	Battery	Capacity Q Voltage V Current i
6. Adjust Vehicle's speed and control system	Linear tubular generator (we use one with these two functions, convert energy and adjust speed)	Magnet speed v Electrical energy Ee Coil turns N Tube length L

Based on their components and working ways, we determine the parameters of each function carriers (Table 5.1). For the MCK system, they are just m, c, and k (mass, spring coefficient, and damping coefficient). For the linkage mechanism, they are height, width, angle, radius, and thickness, which are the fundamental parameters of shape determination. And for the tubular generator, they are magnet speed, coil turns, tube length, and electrical energy, because it uses the change of magnetic flux to generate electricity. The parameters of a cable are just length, section area, and conductivity, which may affect the performance of the energy transport. And the parameters of battery are capacity, voltage, and current.

5.3 Layout drawing (Constrains, Configuration, Connection) of the product

To convert kinetic energy to electrical energy, electromagnetic induction is applied. The basic idea here is to make magnets move through coils. Once the magnetic flux through coils changes, electrical current is induced. Here are three prototypes.



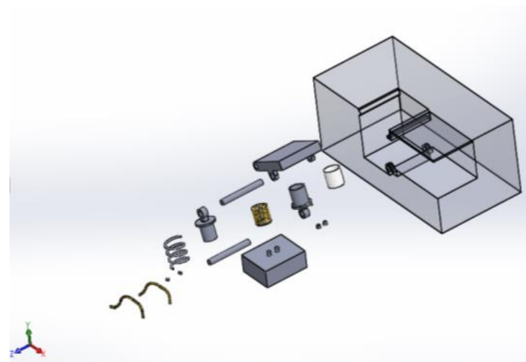
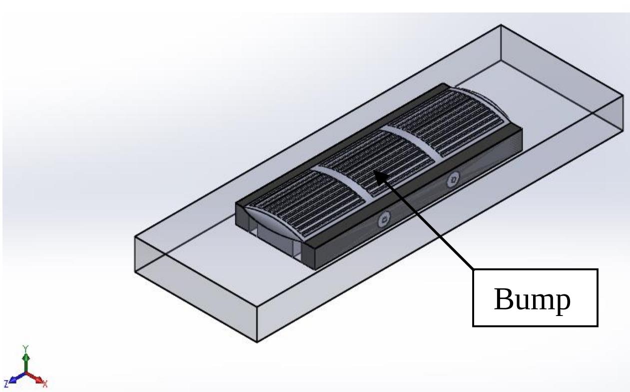


Figure 5.2: Prototype 1_Configuration (Left) & Exploded View (Right)

The configuration of the first prototype (Figure 5.2) basically comprises a skew plate, a spring, and a magnet-coil set. When vehicles go over and press the skew plate, the magnet is forced to move through the coil, and this movement can result in electricity production. Then, the spring rebounds the plate back to its original position. The advantage of this configuration is to ensure the pressure goes axially along the axis of the magnet-coil set so that only normal stress (no bending stress) will occur in the set and needs to be concerned. On the other hand, the abrasion to the contact face between the magnet and the cylinder can also be greatly lowered.



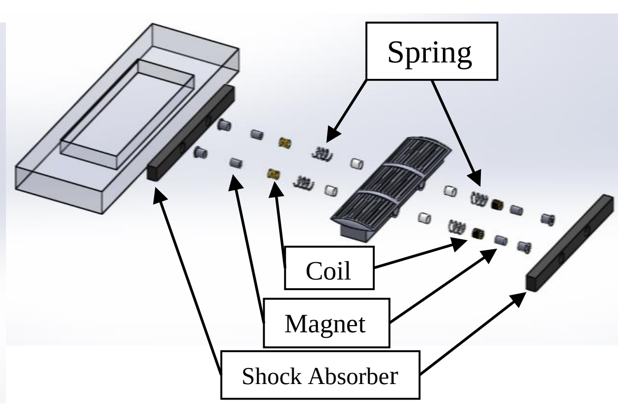


Figure 5.3: Prototype 2_Configuration (Left) & Exploded View (Right)

The big difference between prototype 1 and 2 is that prototype 2 has magnet-coil sets working on both of the opposite directions. When vehicles push the bump, the bump can move from side to side to produce electricity. This makes better generating efficiency since the magnet-coil sets on both sides can generate electricity at the same time, and the stress concerns can still fall within acceptable range.

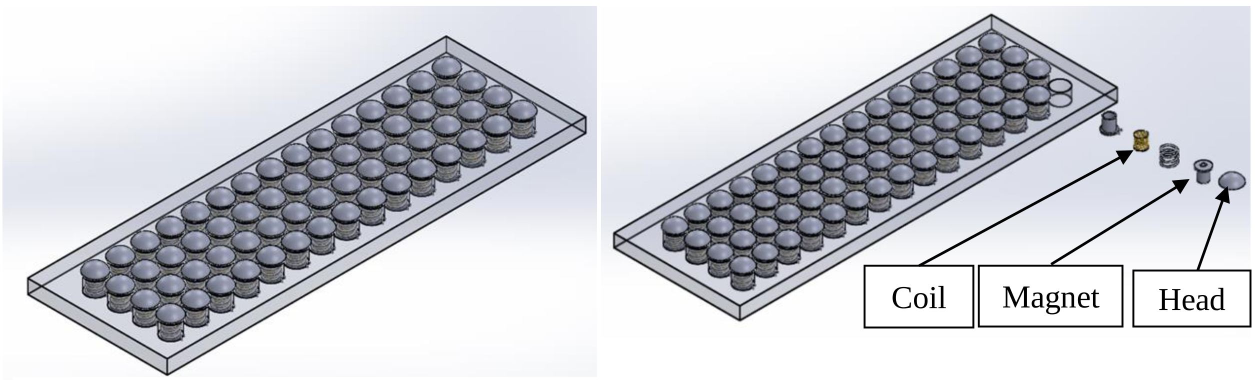


Figure 5.4: Prototype 3_Configuration (Left) & Exploded View (Right)

Prototype 3 is a matrix of magnet-coil sets, each of which can move vertically to generate electricity (Fig. 5.4). This configuration can be very easy to install and be easy to repair. However, the thing to be concerned about is that the bending to the whole cylinder can cause higher stress concentration at the rim between the hole and ground surface.

5.4 Final decision of the product

To make the device reliable and durable, analysis must be taken into account. In this section, we are going to trade off the pros and cons, and go through finite element analysis (FEA) to determine which prototype could be the proper finial design.

Trade-offs

Since security is of the top priority, prototype 1 can not be a nice configuration; it's mono-directional, which can cause vehicle's chassis being crashed when the vehicles are backing up. Furthermore, the additional advantage of RSR against ordinary bumps is power generation so that one of our goal is to maximize the power generated by the linear tubular generator (LTG) equipped on RSR; thus, the vertical displacement of prototype 3's LTG is limited by the maximum height of the LTG's top over ground surface, which is limited by the height of chassis from the ground surface. Prototype 2 acts horizontally; it will not get any trouble mentioned above, and for us, designers with these advantages at hand, we can maximize the power generation by adjusting the spring stiffness k to make the magnets going through the coils as deeply as possible. Hence, we choose prototype 2 to be the final configuration and add ribs on the bump top surface to increase friction, which can make the bump cooperate with the tires much better. In the following section, we are going to do FEA through the components to make sure no one would be crashed by vehicle's weight.

Dimension of the Final Design

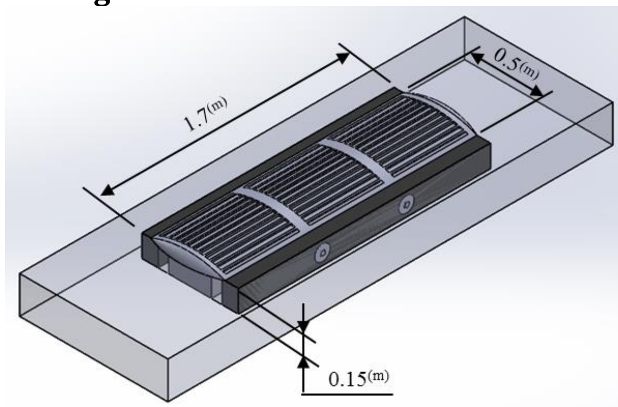


Figure 5.5 Dimension of the Final Design

For emergency and speed control concern, we don't want to slow down emergency vehicle's speed in the meantime when we try to get down the speed of general vehicles, so the width is determined to be 1.7(m), which is larger than the width of general vehicles but smaller than those of emergency vehicles. As to the length and the height, we refer to the dimensions of existing bumps since we don't have serious concern about them and scale them to be 0.5(m) and 0.15(m).

Finite Element Analysis (FEA) over the Bump

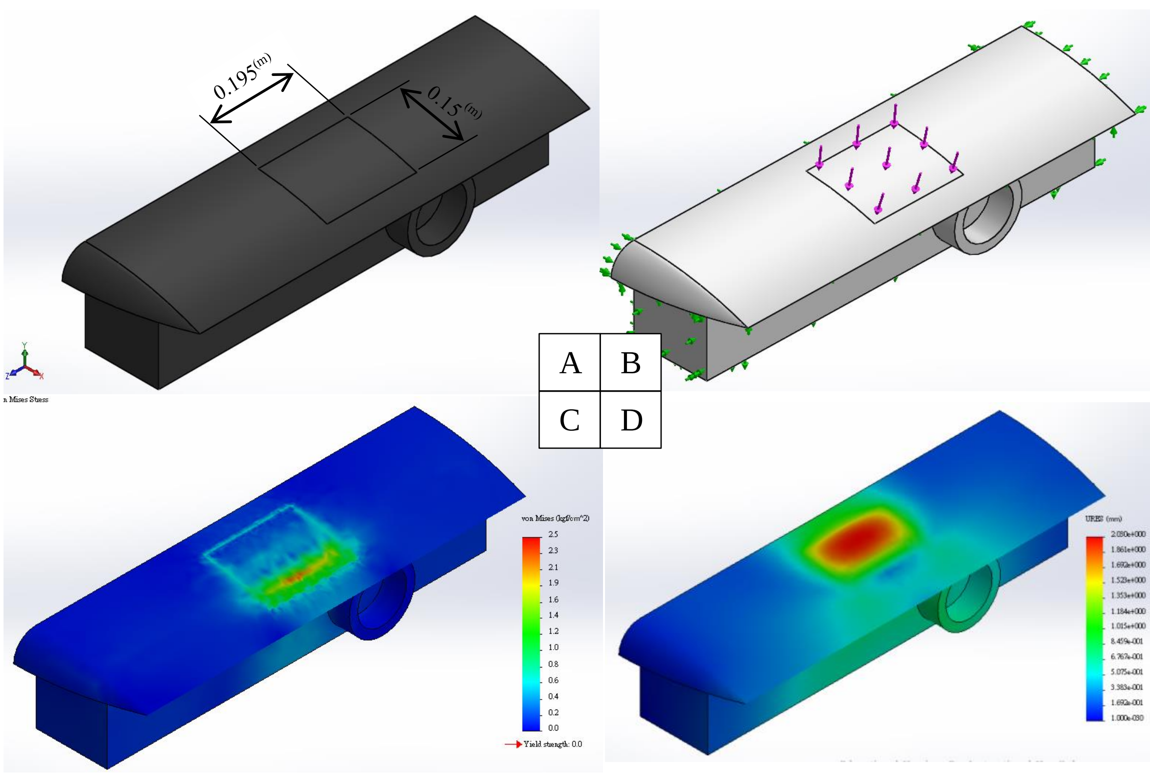


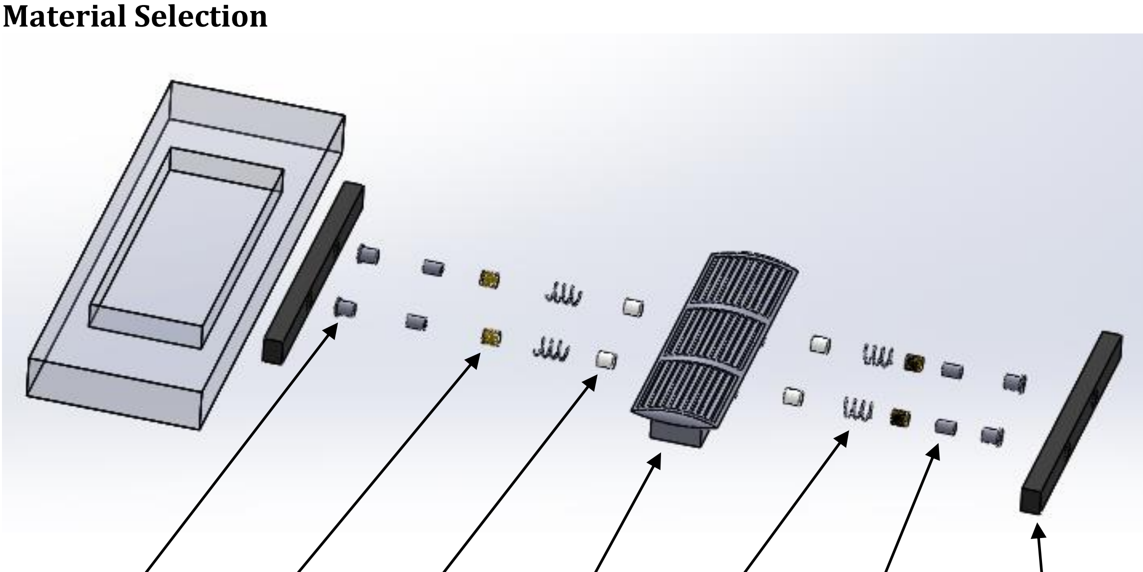
Figure 5.6: (A) Segment to Be Analyzed; (B) Loads & Constraints; (C) Stress Plot; (D) Displacement Plot

Table 5.2 FEA results through five different materials

Materials	Al 1060 Alloy	Alloy Steel	Gray Cast Iron	Ductile Iron	EPDM
von Mises Stress (kgf/cm^2)	1.9	1.9	1.9	1.9	1.9
Displacement (mm)	2.56×10^{-4}	8.76×10^{-5}	2.80×10^{-4}	1.50×10^{-4}	2.04
Yield Strength (kgf/cm^2)	281.18	6326.51	8433	5623.55	223.32
Mass (kg)	283.79	809.33	756.78	746.27	133.16

Since the bump is the key component, which bears most the loading and the impact from vehicles, we apply a load of $500^{(kg)}$ over a $0.195^{(m)}$ x $0.15^{(m)}$ area (in this analysis, symmetry is applied so that each tire gives a quarter of one vehicle's weight of $2^{(ton)}$) and do FEA to see the behavior of the bump. Figure 5.5 shows the von Mises stress and displacement distribution occurring throughout the bump, and the results over five different materials are attached in Appendix.

Material Selection



Cylinder	Coil	Wrap	Bump	Spring	Magnet	Shock Absorber
PVC	Litz Wire (Copper)	Plastic	EPDM (Rubber)	Steel	NIB (Neodymium Magnet)	Rubber

Figure 5.7 Components & Materials

To make RSR work properly and optimize the power generation, bump mass is a big issue. Based on the premise that the bump will not be crashed by the vehicle's weight, the lighter the bump mass is, the smaller the inertia it can have; by greatly decreasing the bump mass, the bump can co-work even better with the vehicles passing with high speed. Under the boundary conditions, the stresses falls within the yield strengths of the chosen materials, and the displacements are acceptable (Table 5.2 & Appendix). EPDM can be the best one since it gets the lightest mass and thus the smallest inertia. For the coil, we choose Litz wire, which is made of copper and tangled thin wires. Litz wire can effectively inhibit the alternative resistance by balancing the induced electromotive force (EMF) generated between tangled thin wires and can greatly lower down the cost comparatively to using high purity copper material and large caliber wires. We also install shock absorbers to prevent the bump from directly hitting the cylinder and magnets; for absorbers, we simply pick general rubbers. As to other components, they are typically out of crash concern, so we can simply apply general materials for them—for the cylinder tube, which is used as the support for the coil, PVC is applied; for the wrap, which is to protect the coil from rubbing the spring surrounding it, plastic is applied; for the spring and the magnet, the spring used for suspension systems and the Neodynium magnet (NIB) is applied.

5.5 Use of components principles and methods

A good designer must makes his/her toolbox diverse. The more tool/knowledge we have, the more ways we can get up to the goal. Following tables show the principle and method, we pick out from our toolbox that can fulfill function and make behavior operational. Besides, they also express the current forms applied in real life.

Force transmission

1. Collect kinetic energy

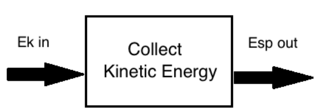
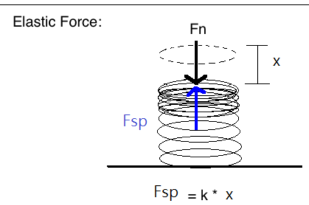
Function	Behavior/Physical Effect	Form
		

Table 5.2 Collect vehicle's kinetic energy (Ek)

In order to achieve RSR's main function, Collect Vehicles' Kinetic Energy, coil spring is such a good stuff to get up to this object. As Table 5.2 shown, once vehicles run over the spring, its' kinetic energy is converted to potential energy stored in spring. Spring's potential energy formula is shown below.

$$Esp = \frac{1}{2} * k * x^2$$

Where

$\boldsymbol{k}$ is the coefficient of spring (measured in Newton/meter, N/m),

$\boldsymbol{x}$ is the length of spring's compression (measured in meter, m).

We hope drivers won't feel uncomfortable while passing it, so the $\boldsymbol{k}$ of RSR must not greater than the $\boldsymbol{k}$ of cars' suspension spring, whose value is between 420,000 and 460,000. As the spatial constrain of the design, we only allow ***x=5cm*** so that prototype 2 is able to move 10 cm horizontally on the ground. According to the consequence of calculation, we find out the $\boldsymbol{k}$'s value should be around 16,000N/m used in RSR.

2. Transport Ek

There're three leakage mechanisms that are able to fulfill "Transport Ek" as Table 5.3 shown above. Each of them uses adjustable connection through hinge or compression springs, which are explained in prior part, transporting vehicles' Ek to spring and storing as potential energy.

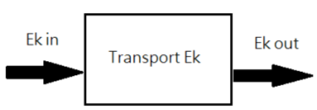
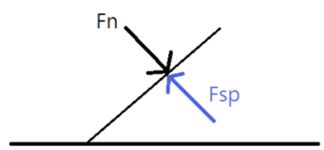
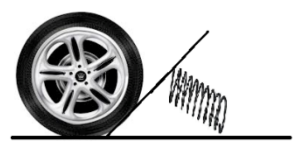
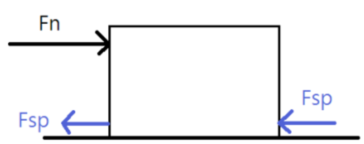
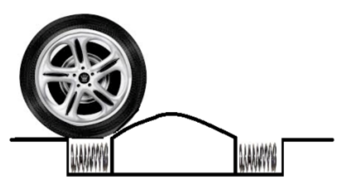
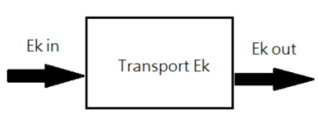
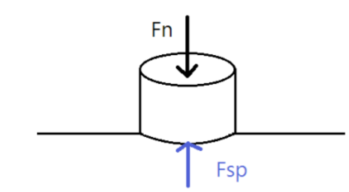
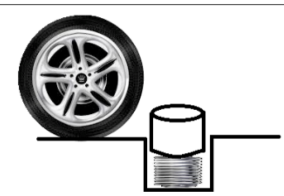
Function	Behavior/Physical Effect	Form
		
		
		

Table 5.3 Transport Ek

For prototype 1, a hinge connects board edge with ground. A compression spring holds the board, maintaining 30 degree between board and ground in unstressed condition. Once vehicle pass by RSR, the board rotates around the hinge axis, keeping compressing spring for storing energy until the angle is zero degree to the ground.

For prototype 2, the bumper is allowed to slide on the ground, so it can be seen there're rollers between itself and ground. Compression springs are put both front and rear of bumper, so that RSR can oscillate horizontally, compressing spring on both side while vehicle pass.

For prototype 3, the movement of cylinders is also slide, but rollers are seen surrounding cylinder. Spring is put under cylinder but above ground. Once vehicle pass, RSR oscillate vertically, making spring compressed to store energy from vehicle.

Division of tasks

1. Convert Ek to Ee; Adjust vehicle's speed and control system

The tool RSR use to convert energy is "Linear Tubular Generator" that uses induction of Faraday's law to generate electricity. There is a magnet fixed (non-adjustable connection) on leakage mechanism, and a tubular coil is placed inside compression spring. Once the magnet on leakage mechanism starts to oscillate, the changing magnetic field produces electricity in coil.

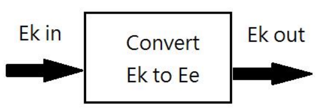
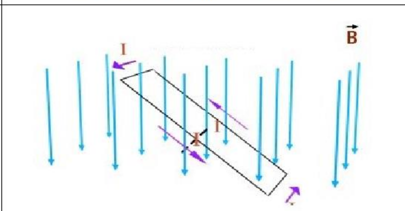
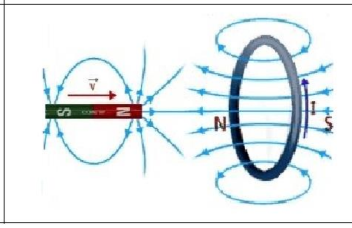
Function	Behavior/Physical Effect	Form
		

Table 5.4 Convert Ek to electrical energy (Ee); Adjust vehicle's speed and control system

Besides, "Linear Tubular Generator" can also slow vehicles' speed down by a resistant force of changed magnetic field and by spring. Every vehicle obtains different speed adjustment because of different magnetic field change.

2. Transport Ee

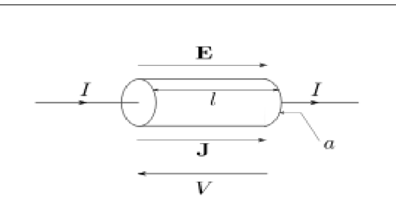
Function	Behavior/Physical Effect	Form
		

Table 5.5 Transport Ee

Electricity can be easily transported by copper cable as shown above, since copper has great electrical conductivity σ , which can be express by following formula.

$$\boldsymbol{J} = \boldsymbol{\sigma} * \boldsymbol{E} \qquad \text{or} \qquad \boldsymbol{\sigma} = \frac{\mathbf{1}}{\boldsymbol{\rho}}$$

Where

$\boldsymbol{\rho}$ is the resistivity of the conductor material (measured in ohm·metres, Ω·m),

$\boldsymbol{E}$ is the magnitude of the electric field (in volts per metre, V·m−1),

$\boldsymbol{J}$ is the magnitude of the current density (in amperes per square metre, A·m−2),

in which E and J are inside the conductor.

Besides, the conductivity $\boldsymbol{\sigma}$ is the inverse of the resistivity $\boldsymbol{\rho}$.

3. Store Ee

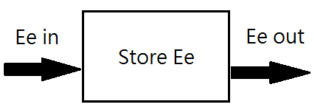
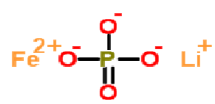
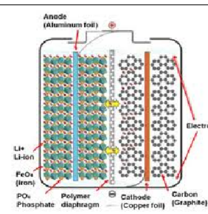
Function	Behavior/Physical Effect	Form
		

Table 5.6 Store Ee

Electricity can be easily stored LiFePO4 battery as Table 5.6 shows. Lithium iron phosphate (LiFePO4), also known as LFP, is targeted for use in power tools and electric vehicles. The insertion and extraction reaction of the lithium ions is shown below.

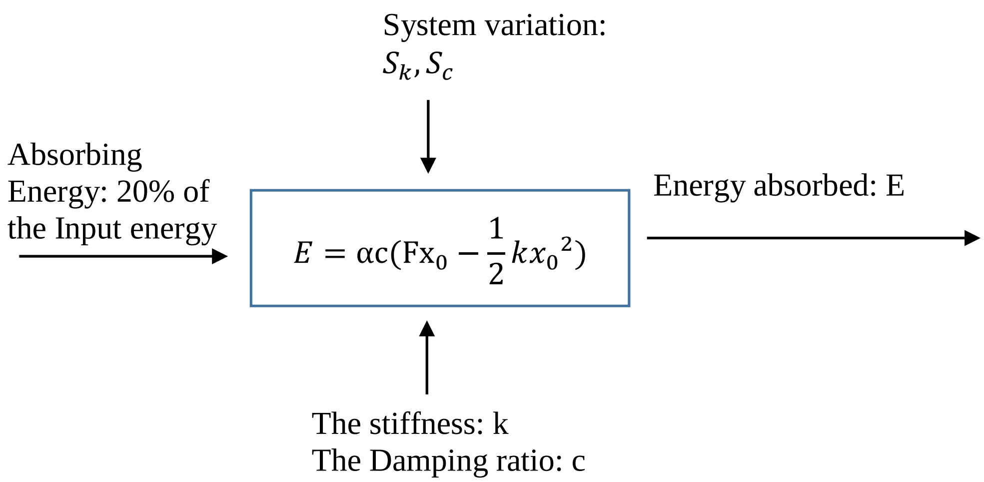
LiFePO4 <-> FePO4 + Li + e-

6 DESIGN EVALUATION

Our design evaluation will consist of two main parts, namely performance evaluation and the Cost evaluation. In the performance evaluation, P-Diagram will be introduced to represent the mathematical model of the main sub-system of our design. And for the future experiment the performance evaluation can be the reference data. While on the other hand, cost evaluation will determine the design is affordable for mass production in the future. The cost evaluation will not only include the material cost, but also the labor cost.

6.1 Performance Evaluation

P-Diagram



F is bouncing force act on the damper, α is the experiment parameter, x_0 is the force acting distance

This model has three inputs. The target is the 20% absorbing energy from the bouncing. The controlling parameter of this system is the stiffness ‘k’ and the damping ratio ‘c’, while the system variation is variation on stiffness and the variation on damping ratio. For the mathematical model of the absorbing energy is the energy input of the system subtract the energy will be stored in the springs then multiply with damping ratio and the experiment parameter. The experiment parameter is proportional to magnetic flux. And the output can be testified in the future experiment.

Error Propagation

Base on the equation:

The error cause by the variation of the stiffness and damping ratio will cause noise of our final system performance results. So we take variation of the k and c as the inevitable error of the system input.

$$S_E = [\left(\frac{\partial E}{\partial k}\right)^2 S_k{}^2 + \left(\frac{\partial E}{\partial c}\right)^2 S_c{}^2]^{\frac{1}{2}}$$

$$S_E = [\left(\frac{\alpha c x_0{}^2}{2}\right)^2 S_k{}^2 + \left(\alpha(\mathrm{Fx}_0 - \frac{1}{2}k x_0{}^2)\right)^2 S_c{}^2]^{\frac{1}{2}}$$

Optimization Problem
Base on the equation:

$$\mathrm{C} = [\left(\frac{\alpha c x_0{}^2}{2}\right)^2 S_k{}^2 + \left(\alpha(\mathrm{Fx}_0 - \frac{1}{2}k x_0{}^2)\right)^2 S_c{}^2]^{\frac{1}{2}} + \lambda(\mathrm{E} - T)$$

$$\begin{cases} \dfrac{\partial C}{\partial k} = \left[\left(\dfrac{\alpha c x_0{}^2}{2}\right)^2 S_k{}^2 + \left(\alpha \mathrm{Fx}_0 - \dfrac{1}{2}\alpha k x_0{}^2\right)^2 S_c{}^2\right]^{-\frac{1}{2}} \left[-S_c{}^2\alpha^2 x_0{}^2(2\mathrm{Fx}_0 - k x_0{}^2)\right] - 2\lambda\alpha c x_0{}^2 = 0 \\ \dfrac{\partial C}{\partial c} = \left[\left(\dfrac{\alpha c x_0{}^2}{2}\right)^2 S_k{}^2 + \left(\alpha \mathrm{Fx}_0 - \dfrac{1}{2}\alpha k x_0{}^2\right)^2 S_c{}^2\right]^{-\frac{1}{2}} 2c\left(\dfrac{\alpha x_0{}^2}{2}\right)^2 S_k{}^2 + \lambda\alpha(2\mathrm{Fx}_0 - k x_0{}^2) = 0 \end{cases}$$

$$\Rightarrow \begin{cases} c = S_c\sqrt{\dfrac{S_c{}^2}{4\lambda} - \dfrac{1}{4x_0{}^2 S_k{}^2}} = S_c\sqrt{\dfrac{S_c{}^2}{4\lambda} - \dfrac{25}{S_k{}^2}} \\ k = \dfrac{8\lambda F + \lambda - S_c{}^2 x_0{}^2 S_k{}^2}{4\lambda x_0} = \dfrac{128000\lambda - 0.01 S_c{}^2 S_k{}^2}{0.4\lambda} = 320000 - \dfrac{0.01 S_c{}^2 S_k{}^2}{0.4\lambda} \end{cases}$$

By taking the derivatives of the optimization equation we will be able to minimize the error in our design and will be very helpful to our control system designing process. The optimization equation is the sum of the error variation and bias. Then we take the example input as: Input force is the mass 1600kg multiply with the 10 m/s2 , xo= 0.1m. Then we can have 320000 N/m as the stiffness, which is less than 420000 N/m as the suspension system of the vehicle.

6.2 Cost Evaluation

The total cost of a product to the customer and its constituent parts are shown in figure 6.1. All costs can be lumped into two broad categories, direct costs and indirect costs. *Direct costs* are those that can be traced directly to a specific component, assembly, or product. All other costs are called *indirect costs.*

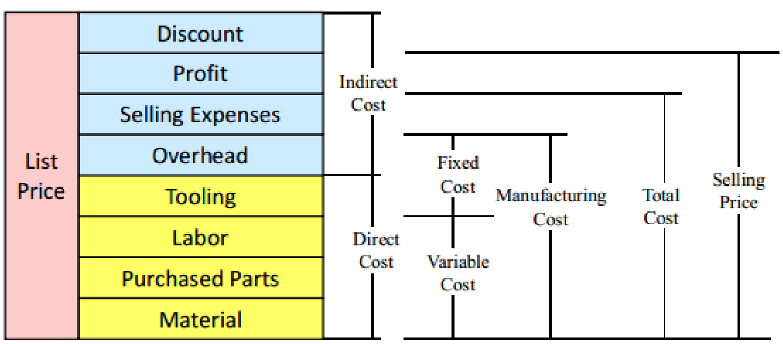


Figure 6.1 Cost types

Below table shows direct costs of each RSR's cell. In this table purchased parts prices are based on manufacturer's websites and we assumed that each cell has its own battery system with capacity of 0.25 KWh. in addition tubular linear generator is selected from *Oswald Company* and the purchasing price is an average one for four generator. (each RSR's cell has four generator and will be used for one lane)

Table 6.1 Direct Cost

	MSD system (steel, rubber)	Tubular linear generator (NIB, Litz Wire)	Battery (Li battery)	Linkage mechanism (PVC, EPDM)	Cable (copper)	Sum
Tooling	$20	$0	$5	$30	$0	$55
Labor	$15	$10	$10	$5	$5	$45
Purchased parts	$20	$500	$50	$0	$10	$580
Material	$0	$0	$0	$20	$0	$20
Sum	$55	$510	$65	$55	$15	$700

Overhead cost in this product includes transportation and installing. We estimate it around $45 for each RSR's cell, based on transportation issues and installation cost of existing bumps. Beside that we consider selling expenses about $10, since we have unique customers.

As explained before, Regenerative Speed Reducer is a product which makes energy and accordingly money after purchasing, so we need to consider it before determining the profit. However if we assume that our company would not benefit after selling the system, our profit could be determined about $135 for each cell which is 15% of whole price.

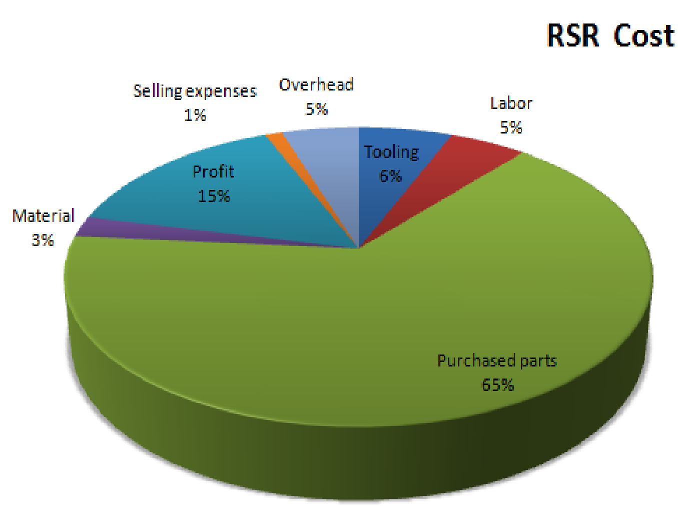


Figure 6.2 Product cost chart

According to the cost estimation each cell price is going to be $890.

6.3 Pros and Cons

After evaluation, we assess the pros and cons of our product, Regenerative Speed Reducer (RSR). Table 6.2 is the comparison between our product and our competitors, which mentioned in HoQ in section 2.2. We ignored the Stop Sign as one of our competitors here because, in fact, it has none of the two major functional requirements, to reduce speed directly and to generate power.

Table 6.2 Comparison of RSR, Hybrid Car, Speed Bump, and Stinger Spiker

	RSR	HYBRID CAR	SPEED BUMP	STINGER SPIKER
Speed Reduction	Automatically Adjust (~20%)	N/A	~10 Mph	Stop
Power Generation	Less Control Loss	More Control Loss	N/A	N/A
Energy Applied Targets	Wide Application	Only For Car Itself	N/A	N/A
Cost	$890	> $20,000	~$30	~$10
Car Damage	Very Slight Wear	No	A Little Bit	All Tires
Lifetime	~10 Years (Battery: ~5 years)	~10 Years (Battery: ~5 years)	~10 Years	Replace Spikes Every Time

Speed reduction

For the speed reduction, hybrid car can't really reduce the speed itself; it requires driver to press the brake. Although speed bump and stinger spiker can reduce vehicles' speed, both of them cannot adjust the reduce quantity based on the speed of the vehicle passing through. RSR can adjust the speed reduction automatically with its magnet. According to Lenz's Law, an induced electromotive force always gives rise to a current whose magnetic field opposes the original change in magnetic flux; that is the higher the speed of the vehicle the larger the resistance force provided by magnetic field.

Power generation and Energy applied targets

Speed bump and stinger spiker do nothing for generating energy, but both RSR and hybrid car collect the kinetic energy from vehicle and convert to electricity. Hybrid car regenerates the power from braking, so it wastes more power than RSR when controlling the system. Besides, the regenerative braking system of a hybrid car is installed on car, so it can only supply the regenerative power to the car itself. However, the power generated by RSR can be applied widely, such as road lamps, traffic lights, and speed meters.

Cost

The cost of a hybrid car is really high (the highest of the four), so the RSR is superior to the hybrid car with the cost issue. Although the cost of RSR is much higher than the speed bump and stinger spiker, customers can get the benefits from the power generation. If calculating the generated power with the price of electricity, the cost can be balanced in only 3 months. So, after 3 month, RSR is a benefit-generator, not a cost-producer. This way, RSR is still the most excellent of the four in cost assessment.

Car damage

Since RSR has damping system to buffer the impact and the friction from passing vehicles, the wearing of RSR is lighter than that of speed bump for each use. However, RSR is not the best one within the four; the hybrid car doesn't damage the car tires or other outer parts because it is installed inside. Stinger spiker breaks all the vehicle's tires every use, so it is the worst for reducing vehicle's speed by placing on the cross sections or exits of highways.

Lifetime

The lifetime of RSR is similar to hybrid car and speed bump, but RSR requires the owner to replace its battery around 5 years, which is the same as the hybrid car's battery. Since the spikes will prick into the passing tires, the stinger spiker should be replaced its spikes every use.

According to the comparison above, our product, RSR, is the best of the four overall.

CONCLUSIONS

As we can see, after the regular procedure of doing the product planning, product specification, function structure and concept generate, according to the current advanced matrix, our concept with the highest satisfaction has been selected as the first option. Then the Auto The main structure of our system has been confirmed as well as we brainstormed some good solution of our technical problems. By using pugh's method, we were able to compare the pro and cons of each alternative concept. And we also were able to use the decision matrix to make our last choice of our concept. After finish the AutoCAD as well as the FEA simulation the detail design has been finally confirmed. At this very stage, we accomplish all parts of idea design and virtual model design, more details has been determined. Basically, according to the decision matrix, we select our final concept, which is Reduce vehicle's kinetic energy by a kind of spring-damper system, and then convert it to electrical energy by linear electrical generator blocks. Then store this energy in battery. System does not use any extra sensor and just get the information by linear electrical generators. This design is mainly focusing on the situation that suitable for most of the off ramps on the highway. Our RSR system is designed with 5 years life cycle and 30 tons load-bearing the system can be continuously functional for a relatively long time. The energy saving, which is regarded as the core feature of our system, is well embodied in our design with 30% energy transfer efficient and 20% speed reduction. Next step was to evaluate our design in two aspects: performance and cost. By doing the mathematical calculation the relationship between the system variation and the controllable parameters has been confirmed.

1. By doing some case study the model was prove to be acceptable in theory, but we still need to do the experiment in the future to verified the idea.
2. For our cost evaluation the price which is $500, even it is way higher than the ordinary damper, given the energy it will save and accident it can reduce the price is acceptable. For each damper we normally can balance the revenue and cost in less than a year, which can made a huge profit in the future.

During the process of our project, our team understands more and more of our product's customer requirements and how important they are. But still there's many improvements can be put into this design.

1. Self-adaptive control system should be added to the system in order to overcome the complicated traffic system.
2. With so many energy saved as electricity, connecting the system to the national electricity network can also be another trend in the future.
3. New shape of damper can be design in order to improve the energy absorption efficiency

Since our detail design has been finalized In order to saving the design cost as well as have a full preparation before the full prototype testing, the computer testing will be as close to the real situation as possible. And after finish the prototype, more tests will be taken. Those testing compared to our system model can a great feedback to our design finalization.

APPENDIX
(Finite Element Analysis Data)

Table 1

EPDM Rubber (Ethylene Propylene Diene Monomer)		Mass=133.16 (kg)			
Point #	Mesh Size	Stress (kgf/cm^2)	Convergence	Displacement (mm)	Convergence
1	0.03	1.8397	N/A	2.0411	N/A
2	0.015	1.739	-5.47%	2.0258	-0.75%
3	0.0075	2.1023	20.89%	2.0399	0.70%
4	0.00375	2.2109	5.17%	2.0301	-0.48%
5	0.00187	1.8905	-14.49%	2.0547	1.21%
6	0.00093	2.2939	21.34%	2.0418	-0.63%
7	0.00046	1.8523	-19.25%	2.0462	0.22%
8	0.00023	2.1966	18.59%	2.0305	-0.77%

Table 2

Aluminum 1060 Alloy		Mass=283.79 (kg)			
Point #	Mesh Size	Stress (kgf/cm^2)	Convergence	Displacement (mm)	Convergence
1	0.03	1.856	N/A	2.56E-04	N/A
2	0.015	1.8563	0.02%	2.55E-04	-0.25%
3	0.0075	1.7878	-3.69%	2.57E-04	0.59%
4	0.00375	1.8581	3.93%	2.57E-04	-0.07%
5	0.00187	1.7729	-4.59%	2.57E-04	0.00%

Table 3

Alloy Steel		Mass=809.33 (kg)			
Point #	Mesh Size	Stress (kgf/cm^2)	Convergence	Displacement (mm)	Convergence
1	0.03	1.8701	N/A	8.76E-05	N/A
2	0.015	1.8753	0.28%	8.74E-05	-0.28%
3	0.0075	1.7935	-4.36%	8.79E-05	0.58%
4	0.00375	1.8397	2.58%	8.79E-05	-0.05%
5	0.00187	1.7755	-3.49%	8.79E-05	0.05%

Table 4

Gray Cast Iron		Mass=756.78 (kg)			
Point #	Mesh Size	Stress (kgf/cm^2)	Convergence	Displacement (mm)	Convergence
1	0.03	1.8732	N/A	2.80E-04	N/A
2	0.015	1.8809	0.41%	2.79E-04	-0.29%
3	0.0075	1.7935	-4.65%	2.81E-04	0.59%
4	0.00375	1.8367	2.41%	2.81E-04	-0.04%
5	0.00187	1.7761	-3.30%	2.81E-04	0.06%

Table 5

Ductile Iron		Mass=746.27 (kg)			
Point #	Mesh Size	Stress (kgf/cm^2)	Convergence	Displacement (mm)	Convergence
1	0.03	1.8618	N/A	1.50E-04	N/A
2	0.015	1.8641	0.12%	1.49E-04	-0.25%
3	0.0075	1.7893	-4.01%	1.50E-04	0.58%
4	0.00375	1.8501	3.40%	1.50E-04	-0.07%
5	0.00187	1.7738	-4.12%	1.50E-04	0.03%