From Observation to Prototyping: A Hands-On Undergraduate Research and Design Experience

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Abstract– This paper details the problem solving process used in creating functionally sound prototype solutions aimed at working out a neglected safety complication that two-wheeled vehicles, particularly bicycles, experience: elevated road objects that cause the vehicle and rider to lose control and flip forward. The process focuses on utilizing resources available through Florida Atlantic University along with the integration of mentor-based learning to enable undergraduate-level students to approach and resolve challenging design problems The essential first step in the problem solving process is observing: in our case, seeing and feeling the impact that a bicycle and its rider experience. This knowledge allows the real problem to be defined: how can the effect of an impact between a forward moving bike and an elevated road obstacle be minimized. An example of an obstacle is a narrow, yet high, speed bump or a parking lot park stop. The fact is that this problem has not yet been addressed, and therefore no solution exists. This requires the process to differentiate from a typical design solving process. In this case, the team had to explore the problem and its conceptual, multi-faceted potential solution dimensions. These include exploring the effects of the road, the bike, and the rider, as well as the type of engineering to apply, i.e., mechanical, electrical, computer, into consideration (or combinations of the above) applying concepts from multiple engineering disciplines. These kinds of open ended problems challenge the student's mind more comprehensively than an average textbook problem. Thorough discussions and critical thinking characterize the next step of the process. This is followed by thinking divergently to generate possible solutions, experimenting, testing, and identifying pros and cons of the prototyped designs. Despite the apparent simplicity of a bicycle, it must obey particularly complex geometrical constraints and dynamic behaviour, which makes the problem solving process even more challenging for project members. While exploring the statics and dynamics of a bicycle, the real problem comes into focus and the problem can be more narrowly redefined by exploring the fact that the diameter of the front wheel is too small to handle the "bump." This realization encourages the creation of innovative ideas, motivates the use of different perspectives, and promotes outside-the-box thinking. Students who are engaged in this type of unique project have obtained hands-on technical, design and development experiences in addition to enhanced problem solving, effective communication, punctual time management skills, and practiced accepting constructive criticism. The solution being presented by our team, alongside the problem solving process, is an add-on mechanism attached to the front fork of a bicycle aiming at reducing the impact of an obstacle on a rider and prevents the vehicle from flipping forward. The idea is based on the fact that the geometry of wheels with larger diameters reduces the impactful effects of obstacles better than wheels with smaller diameters.

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I. INTRODUCTION

The bicycle is one of the simplest vehicles mankind has created and is a common mode of recreational transportation around the world today [1]. Its straight forward design and good durability led to its rise in popularity nearly two centuries ago. However, despite these advantages, controlling a bicycle and keeping it stable and safe is relatively complicated due to the governing mechanics and dynamics associated with its physical construction and usage. Apart from its physical operation, a bicycle also provides the rider little protection in the case of an accident. Simply losing control and falling over onto the ground is sufficient to cause discomfort and pain. The point being made here is a bicycle is inherently unstable and unsafe until riders become adapted to riding it.

Each year bicycle riders are killed or injured for various reasons. Data gathered by the National Highway and Traffic Association (NHTSA) shows that in 2012 alone, 726 individuals died and another 49,000 individuals were injured in bicycle-related incidents.

Year	Total Fatalities	Pedalcyclist Fatalities	Percent of Total Fatalities
2003	42,884	629	1.5%
2004	42,836	727	1.7%
2005	43,510	786	1.8%
2006	42,708	772	1.8%
2007	41,259	701	1.7%
2008	37,423	718	1.9%
2009	33,883	628	1.9%
2010	32,999	623	1.9%
2011	32,479	682	2.1%
2012	33,561	726	2.2%

Fig. 1 Pedal Cyclist Fatalities and Total Fatalities in Traffic Accidents 2003-2012 [2].

By observing Fig. 1 it is clear that the total number of traffic-related fatalities has decreased more than 20 percent over the past nine years. However, the number of bicycle fatalities has remained almost the same. This reflects on improvements that have been made in automotive safety, and perhaps drivers' awareness; however, this also shows the lack of progress in bicycle safety. There are many factors that need

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to be taken into account in analyzing accidents, including human, environmental, and structural.

In a typical scenario, a bicycle rider loses control and crashes when he/she hit an obstacle on the ground. This causes the front wheel to abruptly decelerate and lose traction, and jerk forward and/or sideways. This scenario normally ends with the rider lying on the ground.

II. Motivation and Goal

From a hands-on engineering perspective, the goal of this project is to create, design, and test functional prototypes. The prototypes, or mechanisms, must be able to withstand the typical impact forces and moments an object/obstacle exerts at the average bicycle speed. The prototypes must also be able to absorb the impact, enough to increase the riders comfort. Finally, the rider should not lose control of the bicycle due to the impact. From an academic perspective, the goal of this project is to provide students with a real-world learning experience and have them gain or improve upon skills not normally taught in a typical engineering classroom environment. These skills include:

1) Creativity: disregarding physical, political, and financial limitations to come up with as many different durable solutions that reduce impact and prevent flipping.

2) Innovation: thinking outside-the-box and coming up with a solution to justify the practicality of the idea.

3) Hands-on building skills: taking our thoughts and ideas, putting them down on paper, gathering/selecting materials, building, testing, and troubleshooting and correcting any flaws in assembling the final design.

Students also gain more experience in the following soft skills (already present in their engineering curriculum:

1) Communication: Conveying messages and ideas between mentor and student.

2) Time management: Students practice prioritizing tasks associated with the project and their coursework.

3) Problem-solving: Overcome obstacles in design and implementation of ideas.

4) Accepting constructive criticism: Being open to and learning from input received from others.

The technical motivation behind our efforts stem from the current state of the bicycle needing to remain equally simple to build and maintain, while at the same time become safer for the rider. Furthermore, the scope of this project is constrained to normal bicycle riding habits, which enables us to maintain focus on the most common usage scenario of a bicycle [3, 4]. No fancy tricks or off-road adventures here.

III. Design Process

The manner used to come up with our ideas is being called the *creativity and innovation process* which consists of six steps:

1) Observation: A look at the present: observing it in action; exploring what is currently being used.

2) Discussing and thinking critically: From what is observed determine the strengths and weaknesses of the existing design. What can be improved? What can change?

3) Redefinition and re-representation: Given the more broadly-understood real problem, we can now redefine and re-represent the problem, so it can be later solved in a broader sense.

4) Ideation: Thinking divergently to generate multiple alternatives; the most promising ideas continues to the next step.

5) Prototyping and Testing: Experimenting with materials to determine which is best suited for each idea, designing and building the prototype, and testing the prototype.

6) Evaluation: Through the observation and collection of data from testing, the design will be determined whether it is effective or not.

Step 6 will be done using the following criteria:

1) Identify potential problems: Determining possible faults or design flaws that could, for example, result in personal injury due to design failure.

2) Manufacturing complexity and cost effectiveness: Does the prototype make sense cost-wise and production-wise? Perhaps if a severe injury can be prevented it might be worth the cost.

3) Measured feedback: Making sure that the rider can maintain control and receive little discomfort from the impact.

In addition, several non-technical aspects are considered for our ideas:

1) Sustainability: If implemented, how long will the mechanism remain effective? What are the potential faults/weaknesses? What limits, such as speed and object material/size, would be reasonable to account for in the design?

2) Commercialization: Relative to a typical bicycle, how does it compare aesthetically? What would be the advantage of promoting the mechanism?

3) Legal: Are there any liability considerations that need to be taken into account?

4) Environmental: Are the materials recyclable? Do the materials break down and leave non-biodegradable impurities behind?

IV. Applying the Design Process

In the following subsections we walk the readers through our design process, allowing them to follow our thought process and understand the reasoning that went into each decision.

A. Observation

Our process had begun around our neighborhoods and on our University campus, where we observed bicycle riders losing control, or heard their recollection of their dramatic bicycle experiences, as they explained the source of the cuts and bruises on their legs and arms. Some riders lose control because it’s raining, i.e., due to wet ground. Others try to hop the curb at the edge of the road onto the sidewalk and come up short and flip forward. And some unfortunate fast riders are taken out by the impact they receive traversing a speed bump, sending them flying and in pain for weeks.

Most of us have experienced the lasting discomfort of a bicycle accident. Seeing how helpless we become as ragdolls flying off a bicycle, we set out to challenge ourselves and solve this pressing problem. Readers can further their knowledge on the dynamics of the bicycle by looking at *Appendix A*.

B. Discussing and thinking critically

After some open discussions we pinpointed more specific observations/sub-problems:

1) The material composition of the objects hit by the bike's front wheel were dense and stationary. Light objects that are easily moved or squeezed do not cause the flipping, unless being hit at high speed or become caught in the spokes.

2) Rounded and elongated objects like speed humps do not cause much of the effect, even at high speeds, but narrower and taller speed bumps do [5]. Square-like objects create an even higher chance of flipping.

3) The abrupt deceleration/jerk must be minimized to reduce the potential of flipping.

C. Redefinition and re-representation

Upon further discussion and some critical thinking, we made a decision to confine the solution to a mechanical add-on modification of the bike. We redefined the problem from a bicycle hitting an object causing a flip, to a geometrical problem; focusing on the ratio of object shape and size, bicycle tire size, and bicycle speed. Going one step further, the cause of the problem can be re-represented as a sudden vertical offset and sudden deceleration. Therefore, as speed increases, so does the force caused by the sudden deceleration, resulting in a higher chance of flipping.

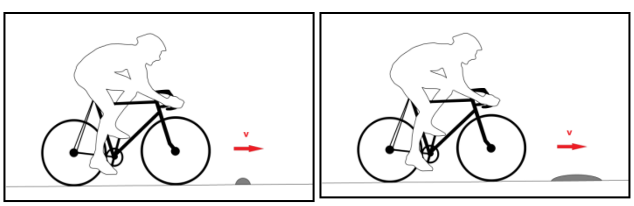

Fig. 2 Bicycles approaching sharp and rounded speed bumps of equal height.

Looking at Fig. 2 above, which of the two bumps would have a higher chance of causing a flip? The bump on the left is narrow, while the bump on the right is wide. Logically one can conclude the bump on the left has a higher chance of causing a flip since the ramp-up from the bottom to the top is steeper; therefore, increasing the deceleration.

A real-world example can be seen in Fig. 3 which shows a rider on a bicycle purposely riding into a curb in a parking lot. Frames 10 and 11 show the displacement generated by the rapid vertical offset created by the curb. Hitting the curb creates a large horizontal force, which causes the bike to abruptly decelerate; while at the same time causes the front wheel to accelerate upward. Imagine the amount of force at or above 10 mph. The bike is sure to halt in a very short distance, possibly leading to a flip.

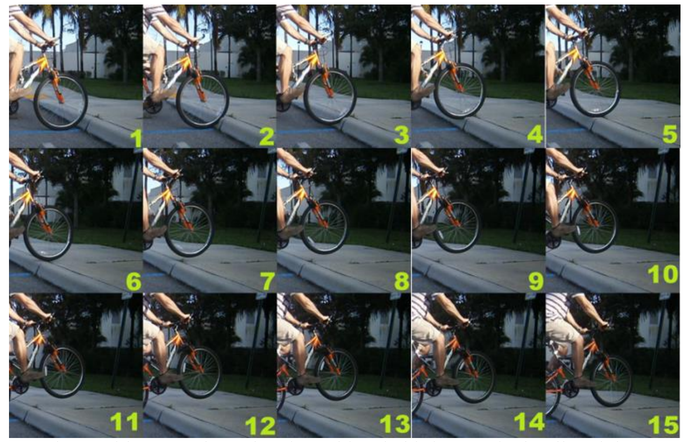

Fig. 3 Video snapshots showing a bicycle hitting a 5-inch tall curb in a parking lot below 5 mph.

D. Ideation

In solving this problem, we examined the current design of the modern bicycle, shown in Fig. 4 below.

Fig. 4 A typical bicycle produced in the 21st century.

Intuitively, to reduce the amount of impact, the wheels of the bicycle must have a larger diameter. Looking back several hundred years coincidentally shows us a potential answer to our problem, shown in Fig. 5.

The high-wheeler has such a large front wheel, that the majority of obstacles present on the roads today could be traversed with ease if such a wheel diameter could be effectively implemented into a modern bicycle design. This is where we had a "eureka!" moment and realized we could increase the front wheel's diameter… without actually increasing it using an add-on extension that increases the diameter for the task at hand, i.e., overcoming road bumps. Fig. 6 shows a general overview of the idea. The add-on meets the obstacle prior to the front wheel with a smaller impact angle which elevates the front wheel at a lesser acceleration; therefore, dampening the impact and increasing the stability of the bicycle. To learn more about bicycle stability, refer to *Appendix B*.

Fig. 5 A high-wheeler, otherwise known as Penny-Farthing, bicycle from the 19th century.

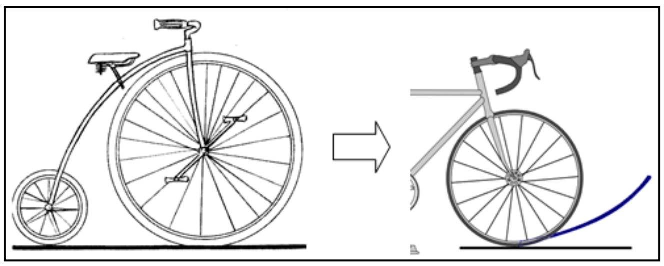

Fig. 6 An add-on mechanism to create a "local larger wheel"

E. Prototyping and Testing

i. First Design – BD1

From the beginning, we knew this project was very unique, in terms of our desire to improve bicycle safety. But, with no related literature we kept the construction as simple as possible to meet the basic criteria. The first design took on a triangular shape and utilized Teflon roller wheels to ease passing over an object. The design had the roller wheels unit that acts as an extension of the front wheel, mounted at a 20 degree angle with respect to the ground, allowing objects up to six inches to pass under it. This design was mounted to the front fork of the bicycle, minimizing the need for modifying/removing existing components. Fig. 7 shows the initial sketch and design of the prototype.

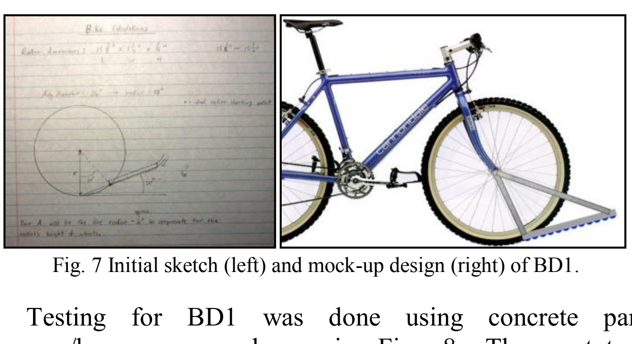

Fig. 7 Initial sketch (left) and mock-up design (right) of BD1.

Testing for BD1 was done using concrete park stoppers/bumpers, as shown in Fig. 8. The prototype performed as expected, coming into contact with the object before the front wheel and raising the front of the bicycle with a slightly reduced impact. However, the rider was unable to turn the front wheel more than a couple degrees without the prototype scraping and catching on the ground. BD1 was an insightful first step, and the collected information was used to design the next prototype, BD2.

Fig. 8 Final construction of BD1 (left) and testing (right).

ii. Second Design – BD2

The second prototype, shown in Fig. 9 and Fig. 10, was comprised of a triangular frame made of aluminum with a red eight inch diameter inflatable tire. In addition there are two more wheels. The bottom one is a four-inch diameter scooter wheel to fill the gap between the red wheel and the front wheel and is free to rotate. The top one is a wheel used to transfer the rotational motion from the front wheel of the bike to the red wheel. This added wheel enables the red wheel to rotate in the same direction and at the same linear speed as the front wheel of the bicycle. This enables the red wheel to rotate even prior to contact with road bumps/objects. This mechanism is presented to also reduce the impact felt by the rider.

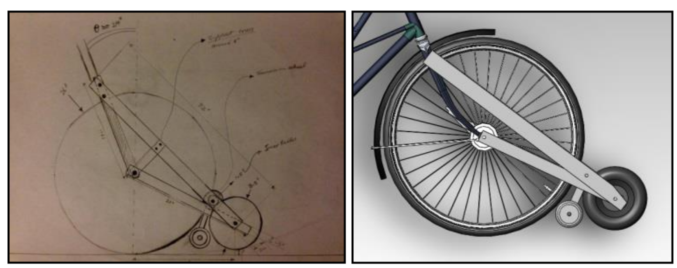

Fig. 9 Initial sketch (left) and mock-up design (right) of BD2.

Fig. 10 Final construction of BD2 outside (left) and indoors (right).

The design of BD2 was stronger than BD1 and more pragmatic engineering-wise. In testing BD2, the initial impact was reduced considerably due to the flexibility of the air-filled red wheel. Comparing the results of BD2 to BD1, a vast improvement was achieved. Also, an unexpected safety feature is provided by BD2 in which the red wheel prevents the bicycle from flipping forward during an intense stop using the front brake. However, the rotational motion of the red wheel did not help as much as expected. It created too much friction which disturbed the rider during a regular biking routine.

Looking at Fig. 11, it can be seen that the front wheel of the bike started to elevate well before it touched the curb. In Frame 4 there is a visible separation from the ground, which shows how much of the impact is absorbed by this design. To learn about bike shock absorbers, refer to *Appendix C*.

Fig. 11 Video snapshots showing BD2 hitting a 5-inch tall curb in a parking lot below 5 mph.

iii. Third Design – BD3

With the successes of BD2 and better understanding of its drawbacks we tried to improve upon the structure and flexibility of the design. The frame of BD3 was streamlined and constructed using two curved steel parallel pieces instead of the multiple used to create a triangular shape. The excessive potential friction was removed by individually mounting each wheel (similar to BD1) and using four rollerblade wheels. This change provides a desired impact-absorbing flexibility that improves upon BD2's performance. Fig. 12 shows the initial sketch and final design of the BD3 prototype.

As expected, BD3 showed better results in testing, as can be observed in Fig. 13. The lighter weight design and simpler construction gives the rider better maneuverability compared to BD1 and BD2 when confronting an obstacle. The frame raises the front wheel and dampens the impact through the flexible frame. However, the hard roller blade wheels and unique curved steel frame lacked the durability and became deformed during testing. Overall, BD3 was the best design we created, but it was evident that it must be further modified to improve durability.

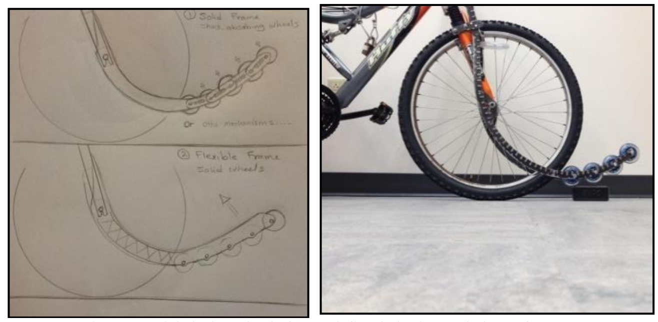

Fig. 12 Initial sketch (left) and final design (right) of BD3.

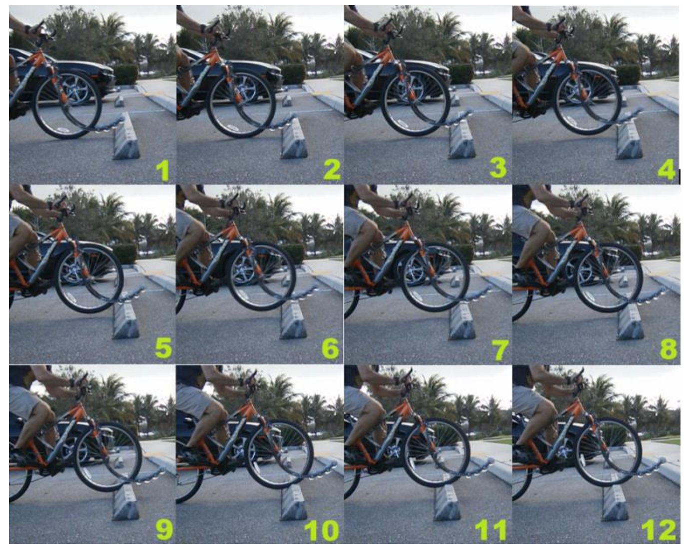

Fig. 13 Video snapshots showing BD3 hitting a park stop/bump in a parking lot below 5 mph.

F. Evaluation

At the time of writing this paper we are still in the prototyping and testing stage. Should one of the three prototypes move forward to evaluation, it would be BD3.

V. Conclusion

The most valuable part of the project, at least from an engineering education point of view, was that students experienced a comprehensive, hands-on, mentoring-led team-based approach to problem solving. This covered many areas from problem exploration, observation, ideation, design, testing and multiple level improvements.

Based on the advantages and disadvantages of the different designs, we plan on improving the designs to a point where add-ons to the bike will minimally affect the riding experience during regular operation. They will rather safeguard the rider and the bike from undesired and unexpected motions.

Since BD3 was the last and the most acceptable design of this project so far, the team is focused on developing this particular design by changing the frame material from commercial steel to stiffer composite materials. One suggestion is using carbon fiber or leaf springs in the structure of the frame, to potentially improve the flexibility and the durability. Moreover, using inflatable small wheels or softer rubber wheels instead of rollerblade wheels can reduce the initial impact to the frame and the rider even more.

Working on this project, and seeing what has been accomplished in a short amount of time has shed light on the fact that in many courses the design process, going from idea to prototype, is mostly left up to the student to decide which method is best. Yet, from our individual experience, the partially unguided nature of these courses tends to lead to disorganization and wasted time on trial and error methods of design. For this project we were guided and mentored using the *creativity and innovation process* outlined in this paper. We are taught to observe and interpret the things we take for granted around us and see them as a source of inspiration for improvement.

We have laid out a *creativity and innovation process* for any other interested parties to use. There is no single best way to come up with ideas, but we believe we are heading towards an excellent start that can be included or re-visited in some capstone design courses.

VI. Appendices

The following appendices include technical aspects of the operation and construction of a bicycle.

Appendix A: Bicycle Dynamics

As mentioned earlier, in spite of the apparent simple structure of the bicycle, it involves relatively complicated physics and dynamic behavior that allow the vehicle to be stable and ridable. Yet there are not many articles or studies that thoroughly explain the related dynamics equations. Most of the "rules" and concepts were found out by experience over time. These experiences led to some insights. For instance: changing the angle and position of the front wheel axis, leads to a different ground-touching point of the wheel, which can make the bike harder to ride and reduces the stability unexpectedly [6]. Fig. 14 helps understanding this rule.

The dynamics of a bicycle can be expressed as a complex relation between different effects such as the gyroscopic effect of the wheel, rider steering response, acting forces and moments. Some mathematicians such as S. Timoshenko and D. H. Young tried to explain the unique motion of the two wheel vehicle; however, their theories were not comprehensive enough to answer the questions and to be accepted by experienced cyclists.

Appendix B: Stability of a Bicycle

A research scientist, David E. H. Jones, has disproved some of the theories that were previously stated by mathematicians by conducting some experiments. His overall goal was to examine some of the accepted concepts about the stability of the bicycle. Part of his experiments included building some "un-ridable bicycles" that nullify the gyroscopic effect of the front wheel. For this reason he mounted a counter-rotating wheel on the front wheel axis to neutralize the gyroscopic effect, and displaced the front wheel axis by reversing the front fork, adding an interface [6]. Fig. 15 and Fig. 16 show David Jones' experiments.

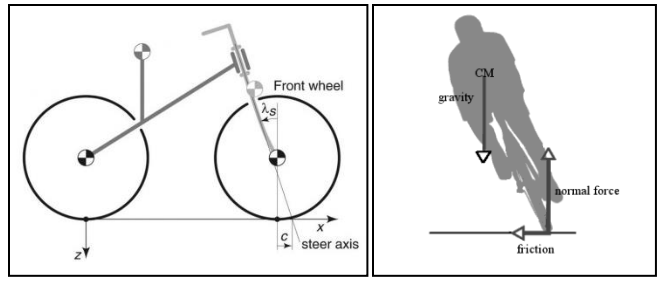

Fig. 14 Bicycle Front Wheel Geometry and Dynamics.

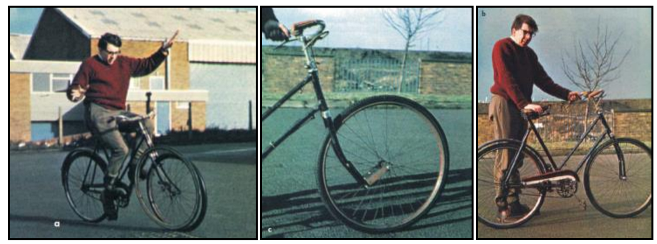

Fig. 15 David E. H. Jones Experiments 1970.

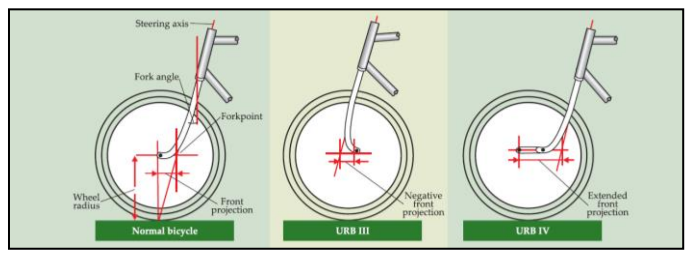

Fig. 16 Changing the Front Fork Geometry.

Based on these experiments Jones demonstrated that the gyroscopic effect of the front wheel does not play an important role in stability of the bicycle. He also concluded that giving a negative front projection does not make the bike unfit to ride; however, the extended front projection almost creates the "un-ridable" condition. Jones' experiments disproved some of the theories about stability and steering effects. Additionally, although he provided very useful information about the bicycle dynamics, he did not provide a theory about bicycles [6].

Appendix C: Shock-absorber Designs

Obviously shock absorbers, or suspension systems, provide a smoother ride for bicycle riders. The history of using shock absorbers in bicycles goes back to the 19th century. An example is shown in Fig. 17.

Shock absorbers are implemented in different sections of the bicycle, such as front or rear fork, saddle, or in the frame structure to provide a more comfortable ride. Since this paper discusses the stability of the bicycle on objects such as speed bumps, studying the effects of shock absorbers in terms of stability can be useful. The effect of shock absorbers on stability depends on many factors such as the level of damping or the movement level of the suspension under the load. In general, shock absorbers make the bicycle more stable. Fig. 18 shows some usual suspension systems.

Fig. 17 1885 Whippet safety bicycle.

Fig. 18 Various shock Absorbers.

One of the contemporary clever innovations is wheels with built-in shock absorbers or soft wheels which contain a suspension system inside the wheel. The idea was first coined by an Israeli company known as Softwheel [7]; the company claims that this idea can be applied to cars, trains, airplane landing systems, and any vehicle that has wheel. If the performance of this new system is indeed proved, the traditional suspension systems can be replaced by these new Mechanisms. Fig. 19 shows two types of wheels with built-in shock absorbers.

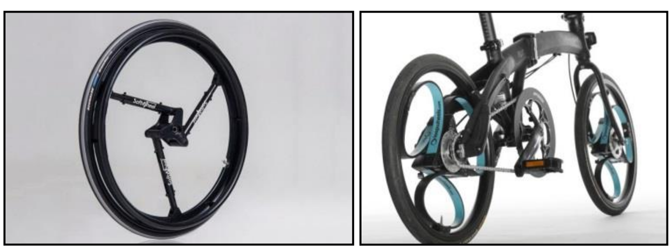

Fig. 19 Softwheel and Loopwhee [8].

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