DESIGN OF A STEERING MECHANISM FOR A PERSONAL TRANSPORTER

by

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Dissertation submitted in partial fulfillment of
the requirements for the Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

DESIGN OF A STEERING MECHANISM FOR A PERSONAL TRANSPORTER

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8104

A project dissertation submitted to the
Mechanical Engineering Programme
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

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JUNE 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(YEW KWANG LIANG)

ABSTRACT

Personal transporter, particularly Segway is gaining its popularity in the western countries in the recent years as it helps to ease congestion and pollution problems in cities. However, this is not the case in developing countries like Malaysia, Vietnam, Myanmar and Sudan as there are not many people who can afford to buy it due to its exorbitant price. As part of the effort to come out with a low cost of a personal transporter affordable by citizens in developing countries, the author is working on designing an effective, highly maintainable and simple steering mechanism. This project is carried out for 2 semesters, where in FYP 1, the main focus was on literature review and journal readings to get as much information as possible in order to design an effective steering mechanism. While in FYP 2, the main focus is on designing the steering mechanism as well as to analyze its stability. As readers go though this report, he or she will get to see on how the objectives of this project is achieved as well as the final results of this project.

ACKNOWLEDGEMENTS

Thank you…

To my immediate supervisor, Mr. Azman Bin Zainuddin who has always been there to support and guide me whenever I need him throughout the two semesters. As a lecture in the Mechanical Engineering department, he has always been busy with loads of work and meetings. Yet, he never fails to lend a helping hand whenever I need it. I will never forget all the lessons that he had taught me and I will always bear his teachings in mind for my future use.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDY

Congestion and pollution problems are getting very serious in cities nowadays due to high population and high number of vehicles in cities. The two problems mentioned above are severely affecting urban peoples' well-being. Among the prominent efforts taken to solve the problems are invention of hybrid cars, stricter standards for vehicle emissions, improvement of public transportations and invention of personal transporters which have very good potential to solve both the problems mentioned above.

Since personal transporters have very good potential to solve congestion and pollution problems, the remaining part of this report will focus mainly on personal transporter. The most famous and commercially available personal transporter that we can see on market nowadays is the Segway personal transporter. With features such as battery powered, two-wheels based vehicle, self-balancing and zero-turning radius; it becomes immediately apparent that Segway provides an excellent solution to congestion and pollution problems in cities if it used as a main way of transportation in cities.

In developed countries such as in America, Japan and Singapore; the challenge of making commercially available personal transporter like Segway a prime mean of transportation in cities is less as the citizens in these countries are generally rich enough to afford Segway personal transporters. However, this is not the case in developing countries like Malaysia, Vietnam and China. Where the citizens in these countries earn less on average and personal transporter like Segway is considered luxurious way of transportation for them which ultimately led to the prevalence of congestion and pollution problems in cities. **Figure 1** in the next page shows a *Segway*[1] personal transporter.

Figure 1: Segway Personal Transporter

A Segway personal transporter costs approximately $5350 - $7200 (RM18000 – RM24000) each depending on model - Please refer to the article on *How much does a Segway personal transporter cost* [2] for more details on the cost of a Segway personal transporter. The cause of the exorbitant price lies mainly in the sophisticated technologies that are being integrated into Segway – drive by wire, self-balancing and high efficiency battery powered motors. Not to mention maintenance fees, the selling price alone is good enough to turn down buyers from developing countries.

There are no specific standard for a personal transporter. There have been a few different designs being designed by inventors around the world. Most designs available nowadays are of four wheels basis, except for a design which was unveiled in the year 2001 by Segway, which consist of only two wheels. Other similarities among all the personal transporters that are available nowadays are that they are all powered by rechargeable battery and they can only carry one or the most two people at a time.

Since we are focusing on solving congestion and pollution problems in cities, our focus will be on designing personal transporter which is powered by rechargeable battery or non polluting fuel, small in size, low cost and highly maintainable. To contribute to the design of personal transporter with the characteristics mentioned, the author will be designing a steering mechanism that is simple and highly maintainable to ensure that the overall cost of the newly designed personal transporter is as low as possible so that citizens in developing countries could afford it which will ultimately helps to solve the congestion and pollution problems in cities in developing countries when the number of users in big enough.

1.2 PROBLEM STATEMENT

Congestion and pollution problems are getting very serious in cities around the world. Personal transporters provide the best solution to both of the problems. Yet, highly priced commercially available personal transporter like Segway due to the high technologies embedded in it have placed a limit on the extent to which the problems could be ease particularly in developing countries. A new design of personal transporter which is simple and low in cost has to be developed in order to make personal transporter affordable to citizens in developing countries. **Figure 2** below and **Figure 3** in the next page show fish bone diagrams which illustrate the factors that contributed to the congestion and pollution problems in cities and factors that contributed to the exorbitant price of a Segway personal transporter respectively.

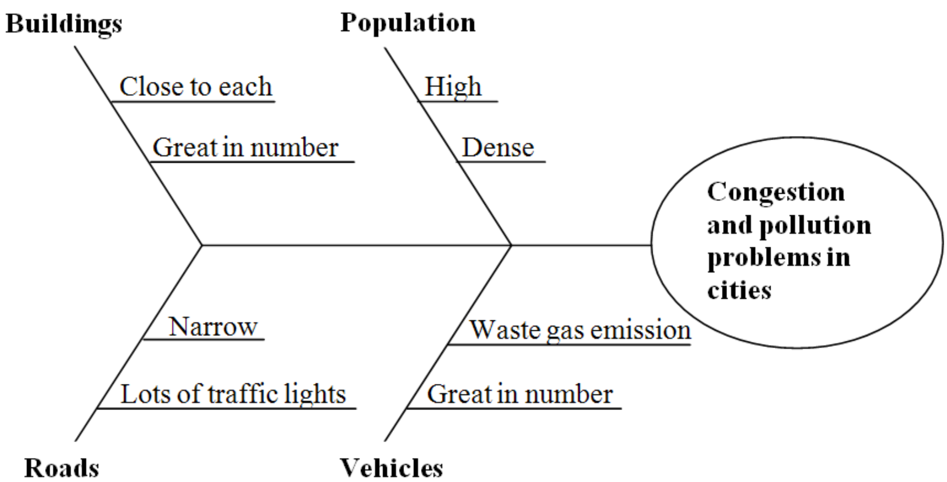


Figure 2: Fish Bone Diagram – Factors Contributed to the Congestion and Pollution Problems in Cities

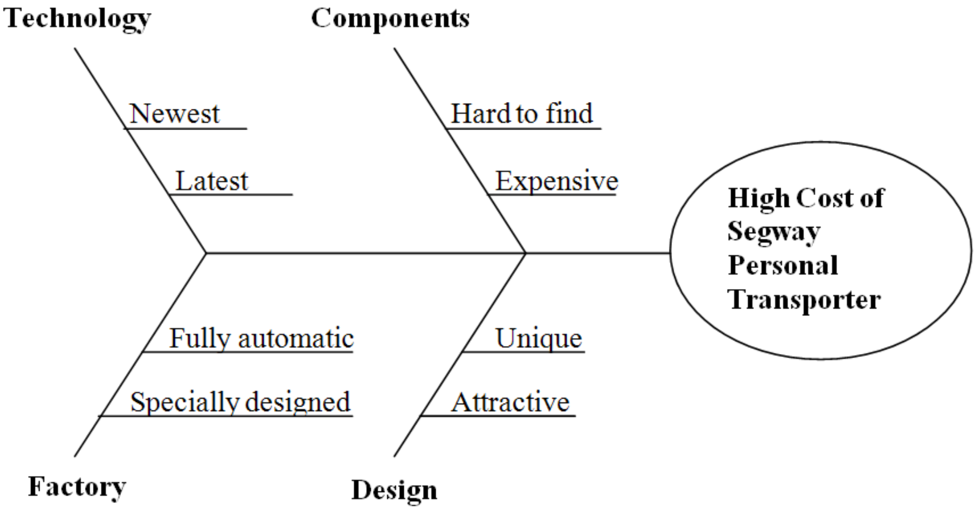


Figure 3: Fish Bone Diagram – Factors Contributed to the High Cost of Segway Personal Transporter

1.3 OBJECTIVE AND SCOPE OF STUDY

1.3.1 Objective

The objective of this project is to design an effective, simple and easy-to-maintain steering mechanism for personal transporter as part of the effort to come out with a new design of personal transporter which is affordable to people of developing countries.

1.3.2 Scope

This project focuses on the design of a steering mechanism for a personal transporter. In the process of designing the steering mechanism, assumptions will be made on some other components of a personal transporter which might influence the design of the steering mechanism. Among the components are:

- Size of the personal transporter platform.
- Dimensions of the wheels employed.
- The wheelbase.
- Height and distance of the steering handle bar.

No prototype will be produced at the end of this project.

1.3.3 Significance of project

The main significant of this project is that the output of this project – design of a steering mechanism for a personal transporter, will benefit the designer and the manufacturer of personal transporters by means of providing them with a low cost, reliable and effective steering mechanism. The success of this project will also provides city citizens of developing countries with affordable personal transporters which will ultimately helps to ease the congestion and pollution problems in cities which are caused by the heavy usage of fuel powered vehicles.

Besides, the success of this project will also help to cut down the maintenance cost of personal transporters' users in developing countries. At the moment, the only commercially available personal transporter in the market is the Segway personal transporter which is embedded with high-technology components that leads to the high maintenance cost due to the unavailability of expertise and technology in developing countries. Thus, coming out with a design of simple personal transporter with easily available components and technologies will definitely solve the current high maintenance cost problem of Segway personal transporters in developing countries.

Last but not least, the success of this project will help to improve the popularity of personal transporter in developing countries. The demand of the commercially available personal transporter - Segway is not high at the moment due to its exorbitant price. Thus, by designing a simple personal transporter which is low in price and maintenance cost will increase the popularity of personal transporter in developing countries.

CHAPTER 2
LITERATURE REVIEW

2.1 STEERING MECHANISM

As mentioned in the previous sections, there have been a few different models of personal transporter out there with different drive mechanisms, features, designs, and most importantly, different steering mechanisms. Up to this point, only one model, namely, Segway and *Yikebike* [3] personal transporters have been made commercialized. While the rest are inventions which either failed to grab the attention of any big companies to invest upon them or still in prototype stage. In the following sections, the author shall present the various steering mechanisms that he will take into considerations for his design.

2.1.1 Personal Transporters Steering Mechanism

Segway & Segway with skiing steering mechanism (Drive by wire)

Segway's balance-control system works in tandem with a pair of electric motors, one powering each wheel to balance the Segway so that it will always stays in upright position. The turning principle is simple, where turning is achieved by the pair of electric motors rotating at different speeds as the rider leans in the desired direction. In short, there are no mechanical gears involved in the steering mechanism of Segway personal transporter, turning is achieved by means of electronics components which control the rotation speeds of the wheels on Segway - Please refer to the article *The Technology Behind The Segway* [4] for more information on the steering mechanism of Segway personal transporter. Please refer to **Figure 1** in **section 1.1** for a figure of Segway personal transporter.

Having most of the components in a normal Segway personal transporter with the exception of the balance-control system, Segway with skiing steering mechanism is different slightly from its predecessor by having a skiing like steering mechanism.

Where to turn, rather than leaning body to the side, skiing like steering mechanism requires the rider to turn like how people do during skiing. Where, when the rider pushes down one of the handle, it will cause the wheels on different sides of the personal transporter to turn at different speeds. When this happens, turning will occur effortlessly. In another words, like its predecessor, turning is done by electronically controlled motors rotating at different speeds - Please refer to the article *Combination Segway Ski-Stroll Scooter* [5] for more information. **Figure 4** below shows a picture of Segway personal transporter with skiing steering mechanism.

Figure 4: Segway Personal Transporter with Skiing Steering Mechanism

2.1.2 Car steering mechanism

Car steering mechanism is a good mechanism to be taken into consideration for the design of this project's steering mechanism in the sense that it is very established and there are a few design options to be based on. The following sections show the possible steering box designs of car steering mechanism that could be based on in designing the steering mechanism for the new personal transporter to be designed.

Rack and pinion

Rack and pinion is the system predominantly used in road vehicles today. A pinion is connected by the steering column to the steering wheel. When the steering wheel is rotated, it turns the pinion which is meshed with the mating rack teeth. **Figure 5** in the next page shows a picture of the Rack and Pinion steering box.

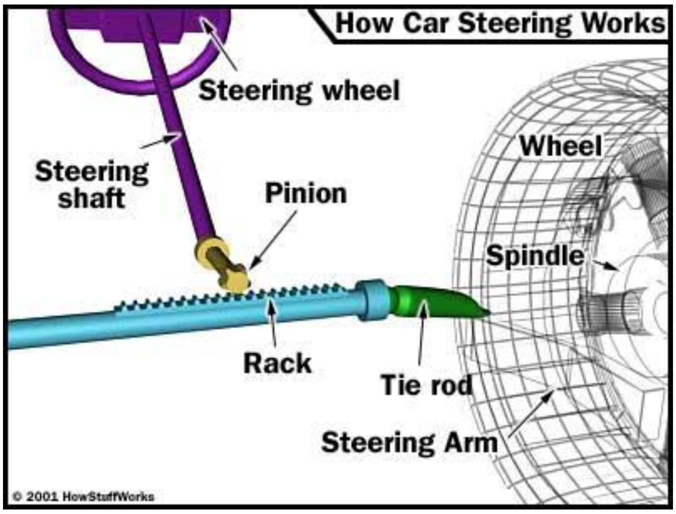


Figure 5: Rack and Pinion Steering Mechanism

The pinion rotation is converted to linear movement by the rack which is supported at one end by a plain bush bearing and at the other end by an adjustable half bearing support yoke opposite the pinion gear. It is adjusted so that it pushes the rack into mesh with the pinion gear and minimizes backlash between the two gears. The circular pitch of the pinion must equal the linear pitch of the rack for correct operation. This linear movement is relayed through the tie-rod to the track rod arms and stub axles to the road wheels, which then causes the vehicle to turn the corner - Please refer to the article *How Car Steering Works* in the *Rack and Pinion Steering Mechanism section* [6] for more information on this steering mechanism. See **Figure 6** in the next page for a picture of steering linkages with a rack and pinion steering mechanism.

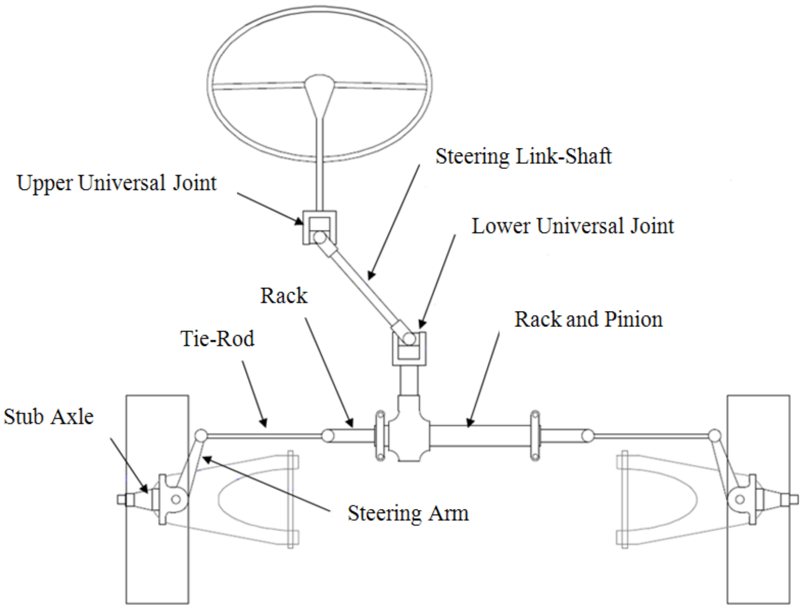


Figure 6: Steering Linkages with a Rack and Pinion Steering Mechanism

Early pinion gears were simple straight spur gears but these have been replaced by helical-toothed pinions. This is because straight cut teeth will mesh with only one pair of teeth in contact at any one time. Uneven movement of the rack results from this arrangement as the steering load is transferred from one pair of teeth to the next.

Helical cut teeth eliminate this problem by having more than one tooth in contact at any one time which leads to the advantage such as (i) ability to take higher loads, (ii) quieter and (iii) smoother.

Pinion axis is usually tilted as shown in **Figure 7** in the next page from the perpendicular line to rack as this will increase the effective pitch-radius which allow fewer and stronger pinion teeth to be used. This will means larger gear-ratio reductions are possible for a given rack travel. It also increases friction which helps to reduce the amount of load shock that is transmitted back to the steering wheel and therefore to the driver.

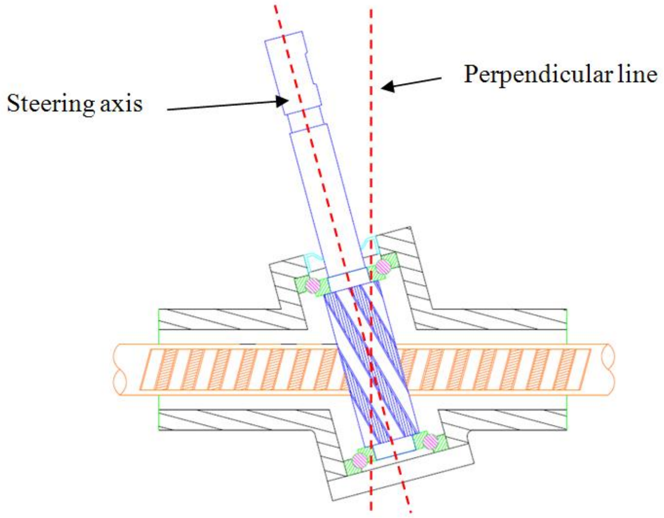


Figure 7: Tilted from Perpendicular Pinion axis to the Rack

The advantages and disadvantages of rack and pinion steering mechanism are as shown in **Table 1**: Advantages and Disadvantages of Rack and Pinion Steering Box.

Advantages	Disadvantages
- Light compared to other systems - Cost less than other systems - Take up a smaller amount of space than other systems - Provides good steering response	- Only efficient on small, light vehicle

Table 1: Advantages and Disadvantages of Rack and Pinion Steering Box

<u>Recirculating ball</u>

Another system that is commonly being employed in car steering system is the recirculating ball steering. The steering column shaft is connected to a worm gear inside the steering box. The worm gear acts like a screw and moves the balls back and forth as the worm gear rotates either one way or the other. The ball nut is held from rotating so that it moves along the worm gear as it rotates. This movement rotates a sector gear using teeth on the side of the ball nut, which in turn moves the pitman arm which causes linear motion on the steering linkages to turn the front wheels - Please refer to the article *Recirculating-ball Steering* in *How Car Steering Works* [7] for more information on how this steering box works. See **Figure 8** in the next page for a figure of recirculating steering box.

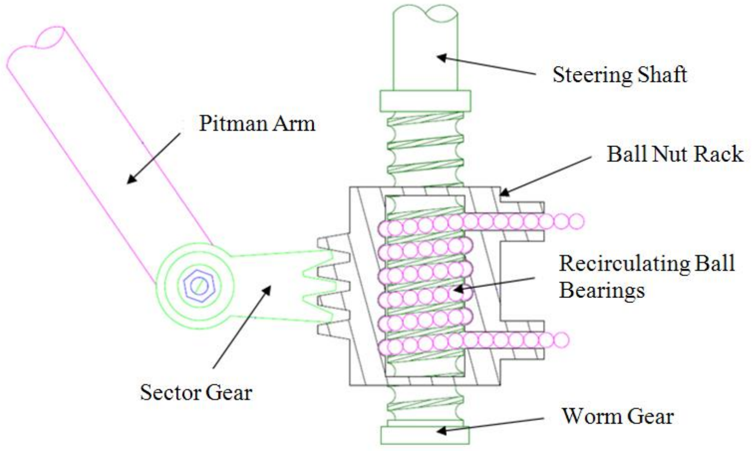


Figure 8: Recirculating Steering Box

Ball bearings and grease are placed between the ball nut and worm gear to reduce the friction. Thrust washers or spaces are used to adjust internal clearances between all internal parts. Accuracy in setting these clearances is critical otherwise there is either free-play in the steering if set too loose, or the systems will bind and have excessive wear if set too tight.

The advantages and disadvantages of recirculating ball steering box are as shown in **Table 2**: Advantages and Disadvantages of Recirculating Ball Steering Box.

Advantages	Disadvantages
- Very compact in design - Very low friction	- Not well suited to front wheel drive applications because of its use of a parallelogram steering linkage which is extremely hard to fit in a small space available

Table 2: Advantages and Disadvantages of Recirculating Ball Steering Box

<u>Worm and sector</u>

The pitman arm shaft carries a sector gear that meshes with a worm gear connected to the steering shaft. Because it only turns through an arc of about seventy degrees, only a sector of gear is needed. When the steering wheel is turned it turns the worm which rotates the sector. This in turn is connected to the pitman arm on a shaft. An adjusting nut is provided to adjust end play on the worm which rotates on tapered roller bearings. See **Figure 9** below for a figure of worm and sector steering box.

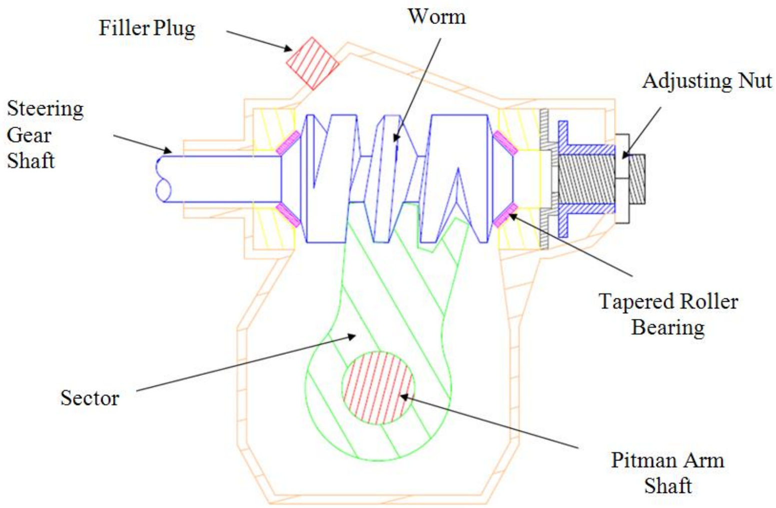


Figure 9: Worm and Sector Steering Box

<u>Worm and roller</u>

This system is more or less the same as the worm and sector except there is a roller in place of the sector. The roller rotates on bearings which reduces friction. When the steering wheel is moved it turns the worm which rotates the roller which causes the pitman arm to rotate at the other end of the shaft to the roller. The worm has an hourglass shape which produces good contact in all positions and also provides a variable steering ratio. Please refer to **Figure 10** in **Appendix 10** for a figure of worm and roller steering box.

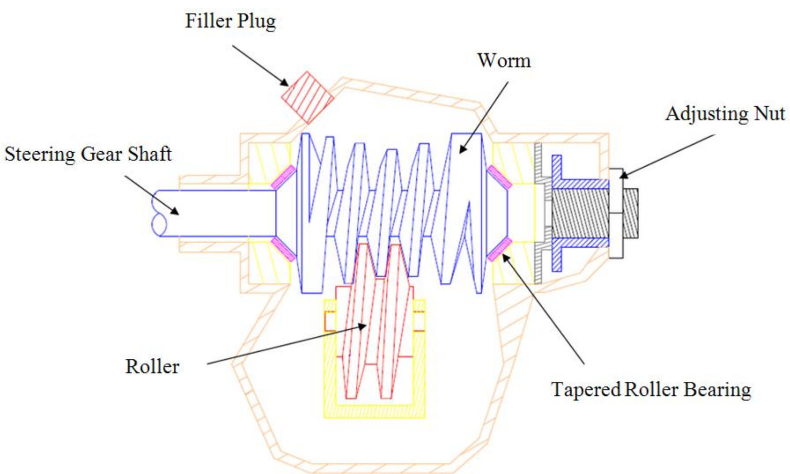


Figure 10: Worm and Roller Steering Box

2.1.3 Recumbent Trike Steering Mechanism

Strictly speaking, a recumbent trike is not considered a personal transporter in the sense that it is not motorized and is driven by means of human feet peddling the peddle. Its steering mechanism, however, provides a good design for the author's consideration. Where its steering mechanism is relatively simple to design and is very unique. The steering itself is very simple to operate, where a joystick is attached to a universal joint that allows the joystick to move to more or less any position without effecting the steering. The steering action is made by twisting the joystick and hence the universal joint. There is a need to have a steering mechanism that can be operated at strange angles because when taking a corner at a rather rapid pace, there is a need to lean into the corner to get a smooth turn - Please refer to the review by Rickey M. Horwitz in his article on *Thunderbolt Design Review* [8] for more information on trike's steering mechanism. See **Figure 11** below for a picture of recumbent trike.

Figure 11: Recumbent Trike

2.1.4 Motorbike & Bicycle Steering Mechanism

Motorbike and bicycle have more or less the same steering mechanism with motorbike's steering mechanism having slightly more features to accommodate the force, vibration and speed that it needs to support. The steering mechanism of motorbike and bicycle are relatively simple to design in the sense that there is less linkages and components if compared to a car steering mechanism. The steering handle is connected directly to the front wheel and the movement is provided by bearings which are in between of the front wheel and the steering handle - Please refer to *Bicycles & Tricycles: A Classic Treatise on Their Design and Construction* [9] by Achibald Sharp and *Motorcycle Handling and Chassis Design* [10] by Tony Foale for more information on the steering mechanism for bicycles and motorcycles respectively.

Despite the availability of many different designs of steering mechanism, focus will be given to steering mechanism that is effective and simple to be design in order to ensure that the author's goal of designing a steering mechanism that provides effective turning and low in maintenance cost is achievable.

2.2 MAJOR DESIGN PARAMETERS OF STEERING MECHANISMS

There are a few basic theories that one needs to know before starting to design any steering mechanism. The basic theories mentioned are as follow:

2.2.1 Two Wheels-based Steering Mechanism

Toe-in and Toe-out

Toe is the symmetric angle that each wheel makes with the longitudinal axis of the vehicle, as a function of static geometry, kinematic and compliant effects. Positive toe or toe in is the front of the wheel pointing in towards the centerline of the vehicle; while negative toe or toe out is the front of the wheel pointing waway from the centerline of the vehicle. Toe angle is important to ensure that the front wheels are parallel as a vehicle is moving forward. This is to ensure that there will be no excessive wear and thus a longer life of front wheels. See **Figure 12** in the next page for a picture of toe in and toe out.

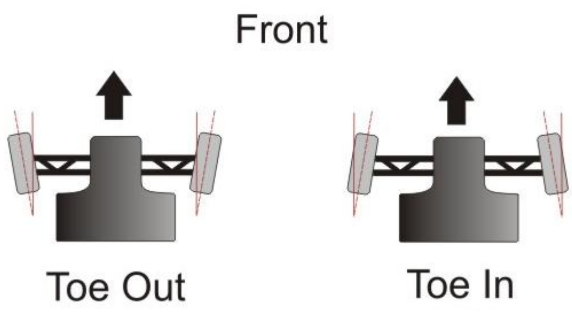


Figure 12: Toe In & Toe Out

Camber Angle

This is the angle as viewed from the front of the car, between the plane of the front wheels and a vertical plane, and is called positive when the top of the wheels leans outward from the body of the car. A slight positive camber reduces the cornering power at the front and normally results in an understeering car. Besides, camber angle is also important for weight adjustment to avoid tire wear. See **Figure 13** below for a picture on how camber angle is measured.

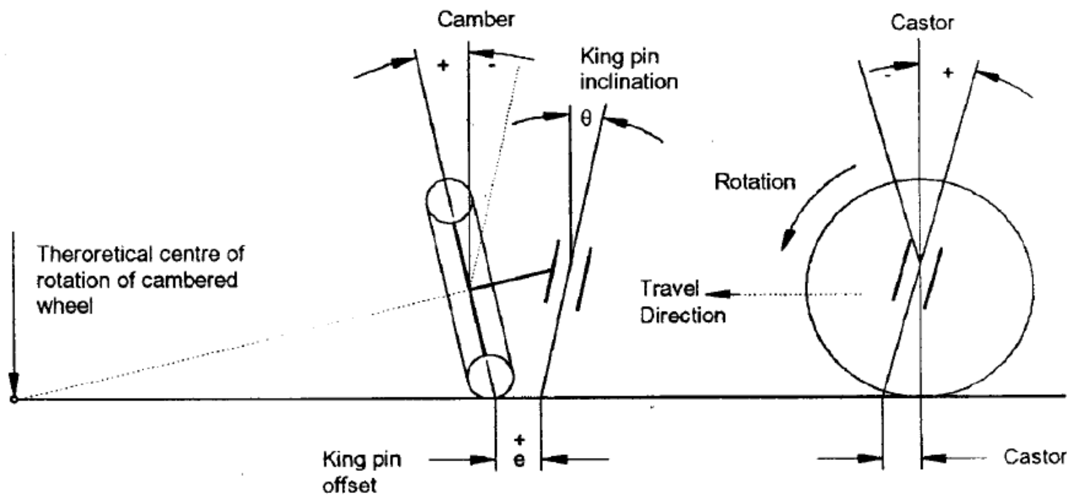


Figure 13: Camber Angle, Caster Angle & Kingpin

Caster Angle

It is the angle between the pivot line (in a car – an imaginary line that runs through the center of the upper ball joint to the center of the lower ball joint) and the vertical line. Caster angle introduces a self-centering torque when the car is traveling forward if it is designed properly - which is achieved by the positive offset as shown in **Figure 13** in the previous page where the contact of the tire on the road trails behind the king pin axis.

King Pin Inclination

It is the traverse angle of the swivel axis of the front wheel and its stub axle. The effect of the inclination is usually discussed in terms of the king pin offset which determines the self centering torque when the steering is turned for cornering.

Although many cars have a positive value of offset which tends to return the wheel to the straight ahead position, some modern cars have a negative offset to improve stability when the tire blows or the brake fails on one front wheel. Please refer to **Figure 13** in the previous page for a picture on how king pin inclination is measured.

Please Refer to *Car Suspension and Handling* [11] by Donald Bastow, Geoffrey Howard and John P. Whitehead for more details on the concepts just presented by author.

Ackermann steering geometry

Ackermann steering geometry is a geometric arrangement of linkages in the steering of a car or other vehicle designed to solve the problem of wheels on the inside and outside of a turn needing to trace out circles of different radii.

A simple approximation to perfect Ackermann steering geometry may be generated by moving the steering pivot points inward so as to lie on a line drawn between the steering kingpins and the centre of the rear axle as shown in the **Figure 14** in the next page. With perfect Ackermann, at any angle of steering, the centre point of all of the circles traced by all wheels will lie at a common point. In practice, however, this may be difficult to achieve with simple linkages arrangement. Please refer to the article *The Ackermann Steering Geometry* [12] for more information on Ackermann steering geometry.

Modern cars do not use pure Ackermann steering, partly because it ignores important dynamic and compliant effects, but the principle is sound for low speed maneuvers. Some race cars use rever*se* Ackermann geometry to compensate for the large difference in slip angle between the inner and outer front tires while cornering at high speed. The use of such geometry helps reduce tire temperatures during high-speed cornering but compromises performance in low speed maneuvers.

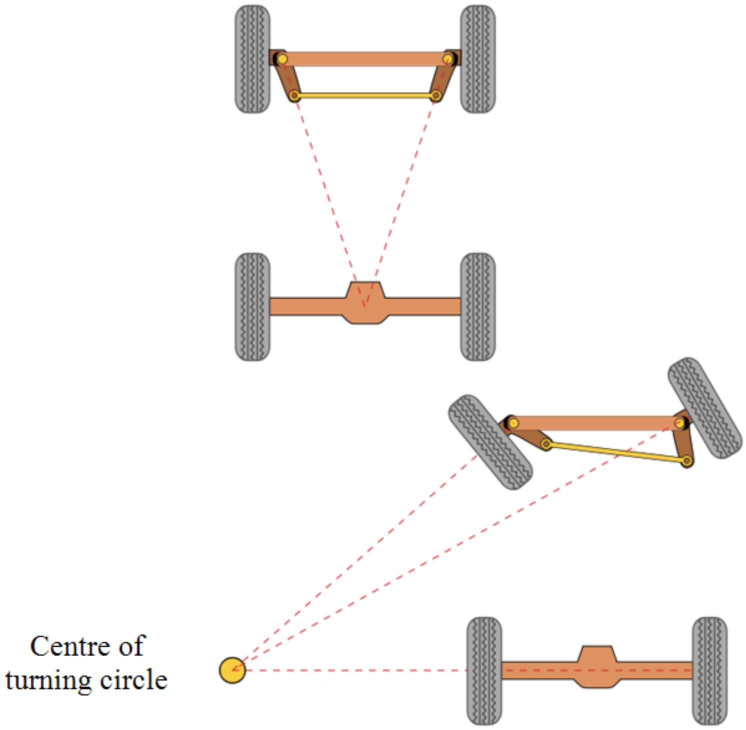


Figure 14: Simple approximation to Ackermann Steering Geometry

2.2.2 One Wheel-based Steering Mechanism

Trail

Is the horizontal distance from where the steering axis intersects the ground to where the front wheel touches the ground. The measurement is considered positive if the front wheel ground contact point is behind (towards the rear of the bike) the steering axis intersection with the ground. Large trail values will cause the bike to be more stable but hard to turn due to large centering force acting on the front wheel. Thus, care has to be taken when designing a one wheel-based steering mechanism to ensure that a balance is strike between stability and cornering effort to ensure a good steering handles. Please refer to **Figure 15** in the next page for a clearer picture on how trail is measured.

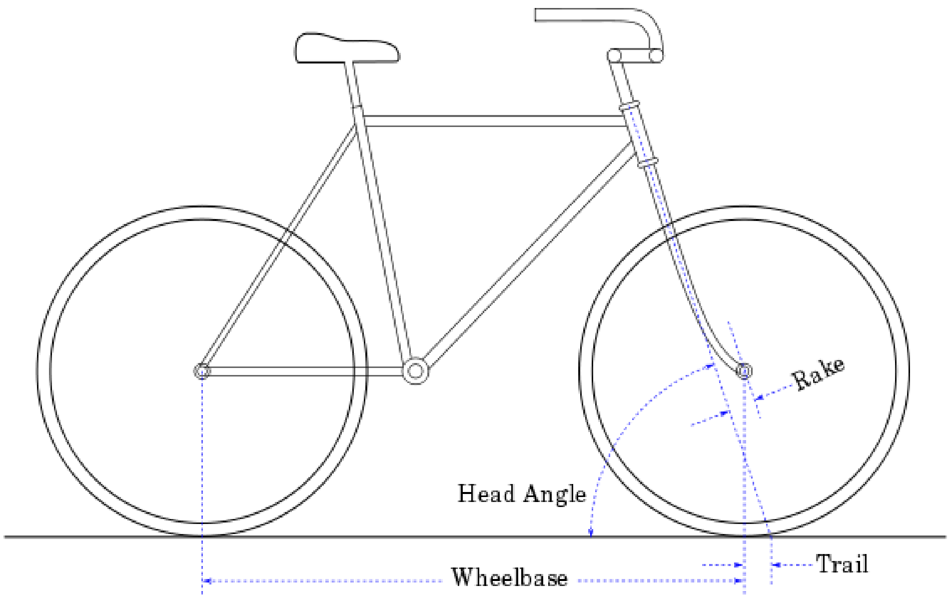


Figure 15: Trail, Head Angle, Rake and Wheelbase

Steering Axis Angle

The steering axis angle, also called caster angle, is the angle that the steering axis makes with the horizontal or vertical, depending on convention. The steering axis is the axis about which the steering mechanism (fork, handlebars, front wheel, etc.) pivots. The steering axis angle usually matches the angle of the head tube.

In bicycles, the steering axis angle is called the head angle and is measured clock-wise from the horizontal when viewed from the right side. A 90° head angle would be vertical. Please refer to **Figure 15** as shown above for a clearer picture on how head angle is measured.

In motorcycles, the steering axis angle is called the rake and is measured counter-clock-wise from the vertical when viewed from the right side. A 0° rake would be vertical. Please refer to **Figure 16** in the next page for a clearer picture on how rake angle is measured.

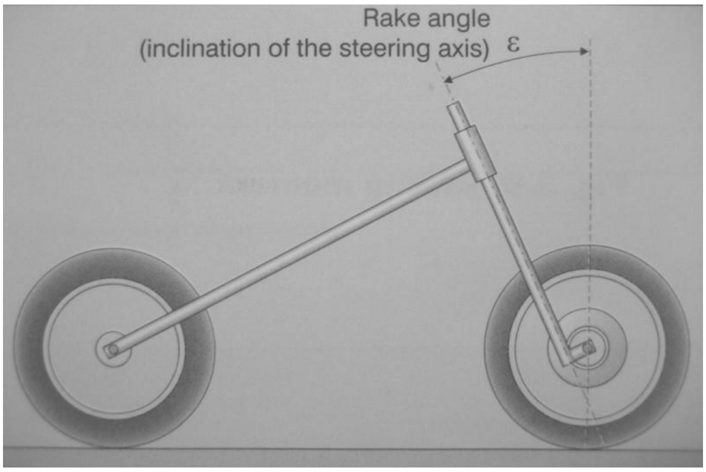


Figure 16: Rake Angle on Motorcycle

Wheelbase

Wheelbase is the horizontal distance between the centers (or the ground contact points) of the front and rear wheels. Wheelbase is a function of rear frame length, steering axis angle, and fork offset. It is similar to the term wheelbase used for automobiles and trains. Wheelbase has a major influence on the longitudinal stability of a bike, along with the height of the center of mass of the combined bike and rider. Short bikes are much more likely to perform wheelies and stoppies. Please refer to **Figure 15** in the previous page on how wheelbase is measured.

Fork Offset

Fork offset is the perpendicular distance from the steering axis to the center of the front wheel. Its purpose is for shock absorption.

In bicycles, fork offset is also called fork rake. Virtually all road racing bicycle forks have almost-standard frame geometry and wheels, so racing forks are widely interchangeable. Today, some fork blades are straight, having their offset introduced by an angled fork crown. Before most roads were paved, fork rake had a lower angle so the fork would be loaded axially on rougher surfaces. As most roads became paved, bicycles forks were made steeper, which also gave lighter steering. Please refer to **Figure 15** in the page 18 on how rake is measured.

In motorcycles with telescopic fork tubes, fork offset can be implemented by either an offset in the triple tree, adding a rake angle (usually measured in degrees from 0) to the fork tubes as they mount into the triple tree, or a combination of the two. Other, less-common motorcycle forks, such as trailing link or leading link forks, can implement offset by the length of link arms. Please refer to **Figure 17** in below on how Offset is measured on motorcycle.

Please refer to *Bicycles & Tricycles: A Classic Treatise on Their Design and Construction* [9] by Achibald Sharp and *Motorcycle Handling and Chassis Design* [10] by Tony Foale for more information on the concepts just presented

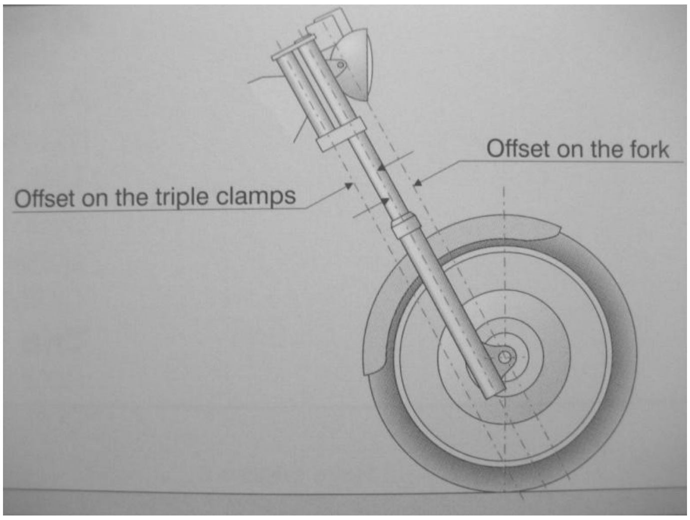
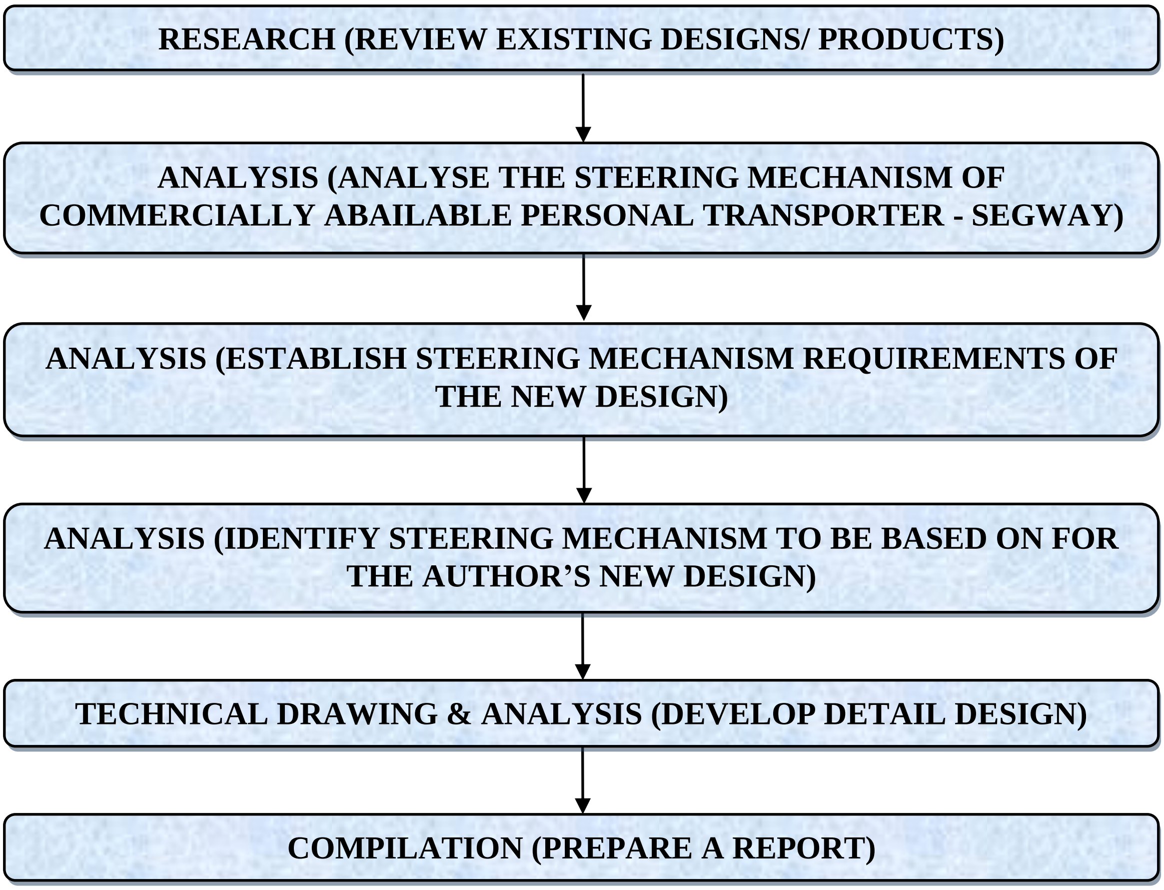


Figure 17: Offset on the Triple Clamps

CHAPTER 3

METHODOLOGY

To achieve the objectives of this project, the author has developed a flowchart as shown in **Flowchart 1** below to serve as a guideline in order for him to get the project done within the given time frame.



Flowchart 1: Activities to be carried out in order to achieve the objectives of this project

There are several activities to be carried out in each step in **Flowchart 1**; the activities to be carried out are as the following:

<u>Research (Review existing designs/products)</u>

- Gather information on the various types of steering mechanisms that could be employed on personal transporter after being re-designed.

- Read journals to find out if there is any new yet simple steering technology that could be incorporated into the author's project.
- Gather information of the steering mechanism of commercially available personal transporter – Segway personal transporter.

Analysis (Analyze the steering mechanism of commercially available personal transporter - Segway)

- Study the advantages and disadvantages of the steering mechanism of commercially available personal transporter - Segway.
- Identify the reasons on why commercially available personal transporter like Segway is not popular in developing countries.
- Study the advantages and disadvantages of each type of steering mechanism identified in the previous stage.

Analysis (Establish steering mechanism requirements of the new design)

- Set the requirements that need to be achieved by the new design.
- Factors such as size, effectiveness, simplicity, maintainability and cost shall be considered in this stage.

Analysis (Identify steering mechanism to be based on for the author's new design)

- Indentify the best steering mechanism that the new design could be based on.
- Emphasize will be given to steering mechanism that is easy to maintain, low in cost, simple and effective.

Technical drawing & analysis (Develop detail design)

- Identify the best steering geometry by means of calculations.
- CAD drawing of the conceptual design of the new steering mechanism.
- Force analysis on the new design of steering mechanism for safety purposes.

Compilation (Prepare a report)

- Compilation of findings, designs and results into a report for future reference.

On top of the flowchart prepared earlier, Gantt charts are also developed to ensure that all the tasks are performed and finished within the timeline give. Timeline might be altered from time to time to accommodate additional work scope if deemed necessary. Please refer to **Table 3** below and **Table 4** in the next page for the Gantt charts developed by the author.

No.	Detail/ Week	1	2	3	4	5	6	7	8		9	10	11	12	13	14
1	Feasibility study on the project	■	■							Mid-semester break						
2	Preliminary research work on different kinds of steering mechanisms		■	■	■											
3	Compilation of findings into progress report				■											
4	Continue research on different kinds of steering systems				■	■	■									
5	Study on the advantages & disadvantages of each steering mechanism				■	■	■									
6	Study in detail on the Segway's steering mechanism					■	■	■	■		■	■	■	■		
7	Study in detail on the various types of alternative steering mechanism								■		■	■	■	■	■	■
8	Compilation of findings into progress report								■							
9	Preparation of slides for Seminar								■							
10	CAD drawing on steering mechanism (most suitable one)								■			■	■	■	■	
11	Compilation of findings into Interim report															■
12	Preparation of slides for oral presentation															■

Table 3: Gantt chart (4^{th} year, 1^{st} semester)

No.	Detail/ Week	1	2	3	4	5	6	7	8		9	10	11	12	13	14
1	Calculations to get the most suitable dimension of steering linkages	■	■	■	■					Mid-semester break						
2	Calculations on the forces applied on the steering mechanism	■	■	■	■											
3	Compilation of findings into progress report 1				■											
4	Detailed drawing of design in Auto CAD				■	■	■	■								
5	Compilation of findings into progress report 2								■							
6	Preparation of slides for Seminar								■							
7	Stress analysis on Ansys										■	■	■			
8	Simulation of the steering mechanism in Adams													■	■	■
9	Preparation of slides for oral presentation															■
10	Compilation of findings and results into Dissertation report															■

Table 4: Gantt chart (4^{th} year, 2^{nd} semester)

CHAPTER 4

RESULTS AND DISCUSSION

After reviewing the steering mechanisms that could be employed on personal transporter, the author shall then identify the best steering mechanism to base his design on. Design criteria and specifications have to be established before decision could be made and they are as the following:

Design criteria that should be met by the steering design are as shown in **Table 5**: Design Criteria.

Criteria	Description
Low Cost	Contributes to the overall low cost of the final design.
Simple Design	Technologies available in developing countries.
Easy to Maintain	Replacement components available in developing countries.
High Effectiveness	Provides good turning and stability to the personal transporter.
Small in Size	Take up little space to ensure compact overall design.

Table 5: Design Criteria

While the design specifications that should be met by the design are as the following:

i) Provides stable cornering capability to personal transporter traveling at a speed range of 0.0 km/h -20.0 km/h.
ii) Its structure should be able to support up to 120.0 kg of weight.
iii) Provides ground clearance of at least 7.5 cm
iv) Footprint of 48.0 cm x 60.0 cm
v) Turning radius of less than 4.5 m

The designs specifications above are set above are based on commercially available personal transporter – Segway personal transporter. Design specifications are subjected to change from time to time depending on requirements and new design specifications will be added should the needs arise. Having set the design criteria and specifications, author has come out with three conceptual designs as shown in the following pages.

4.1 CONCETUAL DESIGNS

<u>Conceptual Design 1</u>

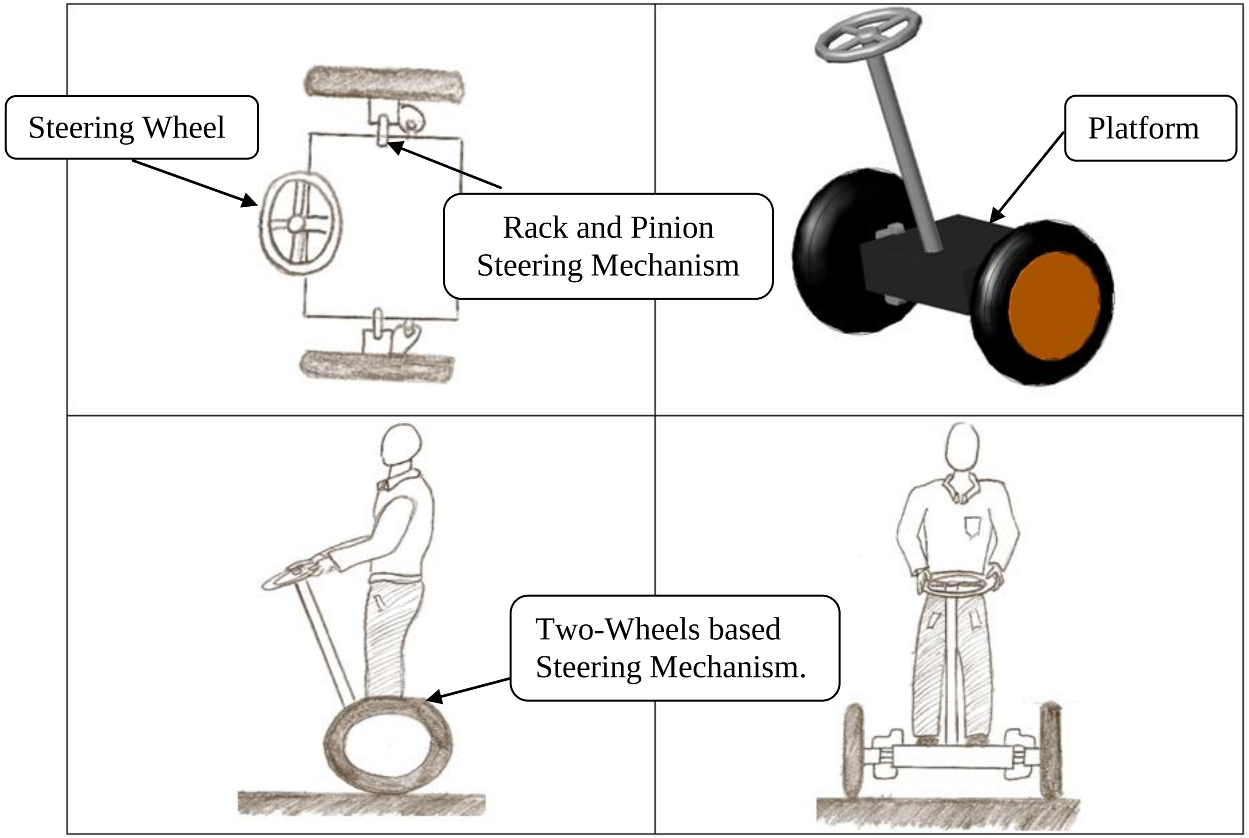


Figure 18: Conceptual Design 1

Conceptual Design 2

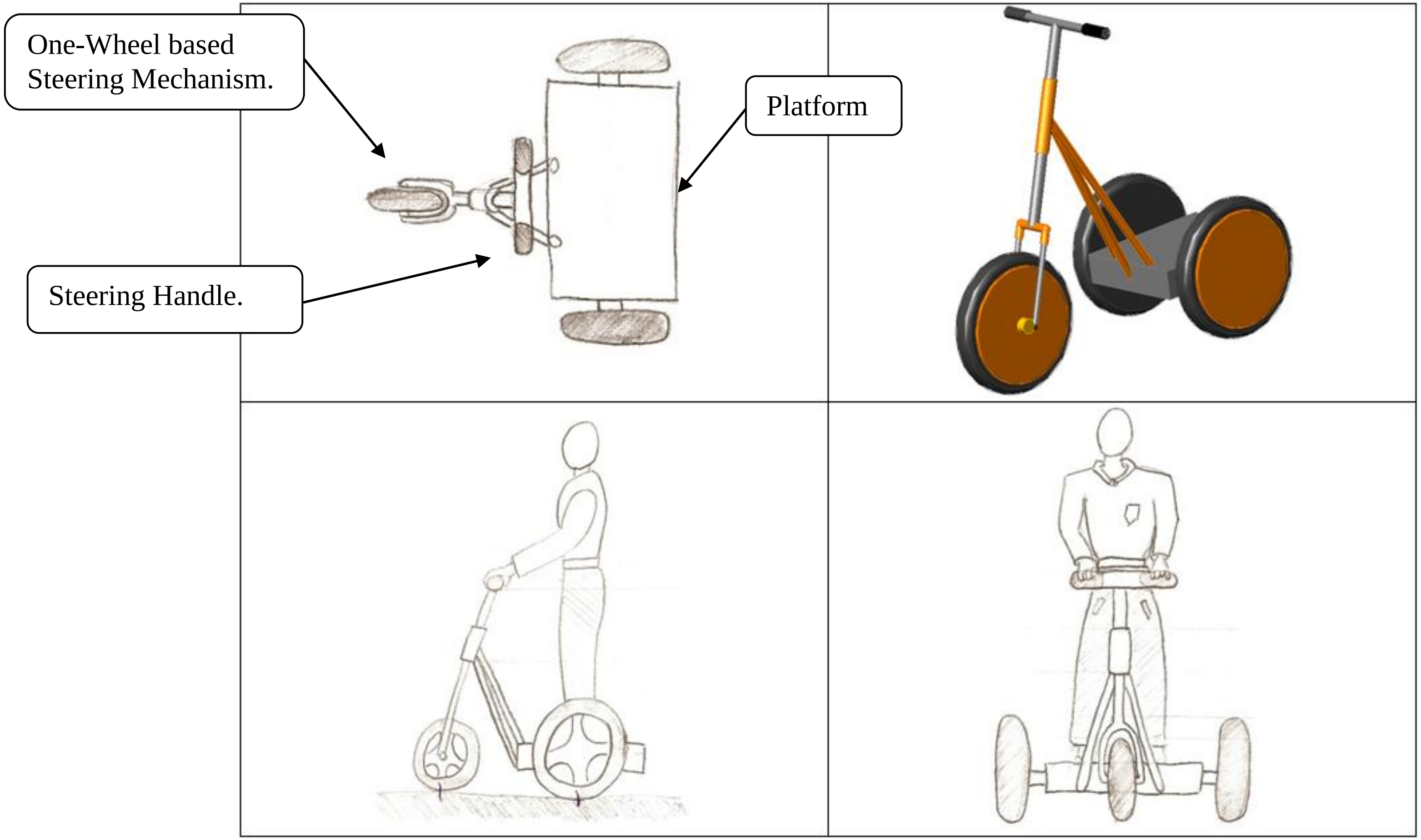


Figure 19: Conceptual Design 2

Conceptual Design 3

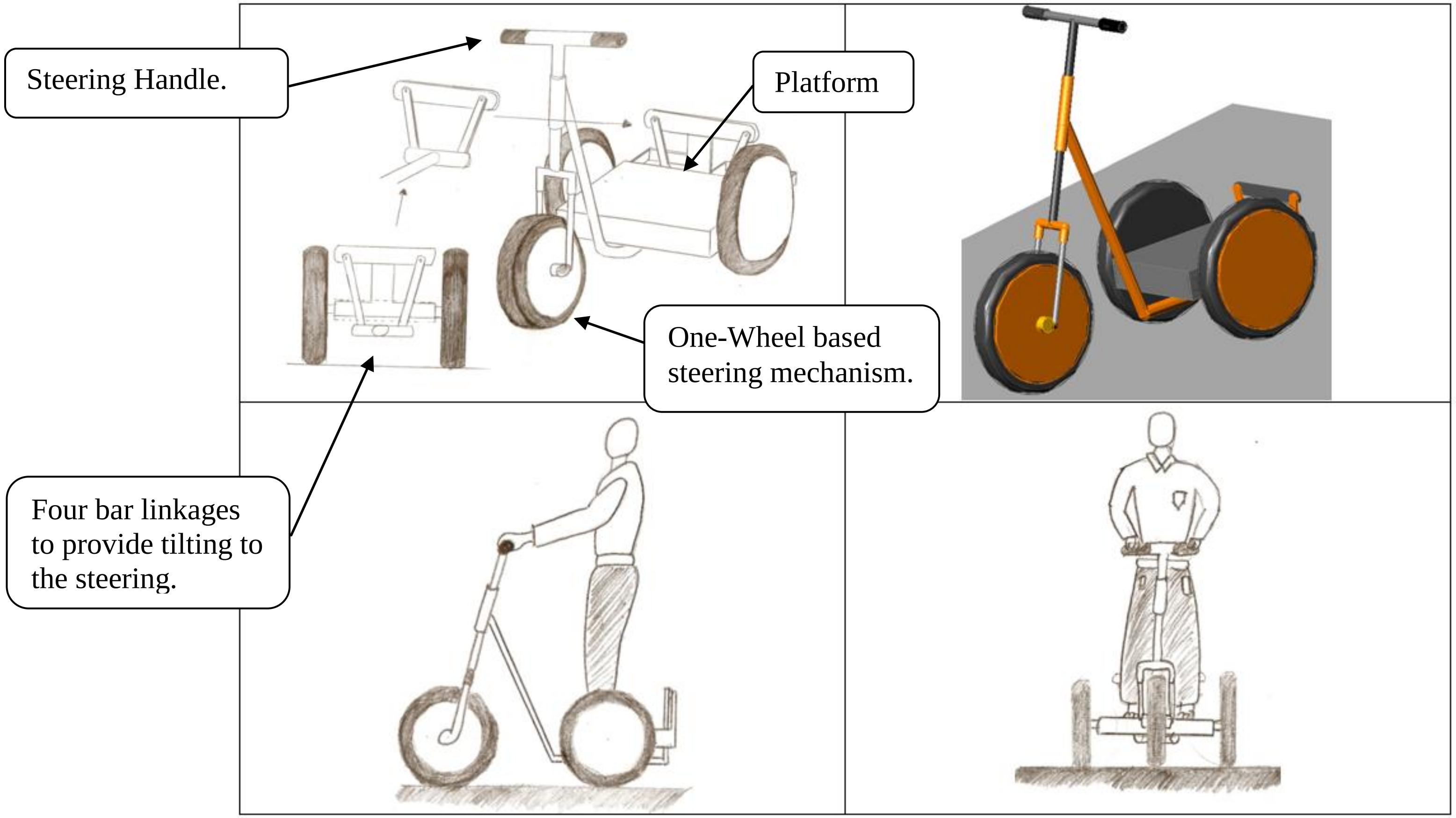


Figure 20: Conceptual Design 3

4.2 CONCETUAL DESIGN DETAIL DESCRIPTIONS

<u>Conceptual Design 1</u>

This conceptual design has only two wheels which mean maneuvering and power drive are carried out by the same two wheels. There will be a need for self-balancing system in order for this conceptual design to work. The steering mechanism being employed on this conceptual design is the rack and pinion steering mechanism. The maneuvering for this is done by the rider turning the steering wheel which in turn rotates the steering shaft which is connected a universal joint which ultimately turns the pinion that is connected to the rack of steering mechanism. **Flowchart 2** below summarizes how turning is done on conceptual design 1:

Rider turns the steering wheel → Steering shaft is turned → Pinion which is connected to the steering shaft via a universal joint is turned → Rack is moved by the turning pinion and maneuvering is achieved by the turning wheels which are connected to the rack.

Flowchart 2: Working Principle of Conceptual Design 1's Steering Mechanism

Figure 21 below shows the steering mechanism of this conceptual design:

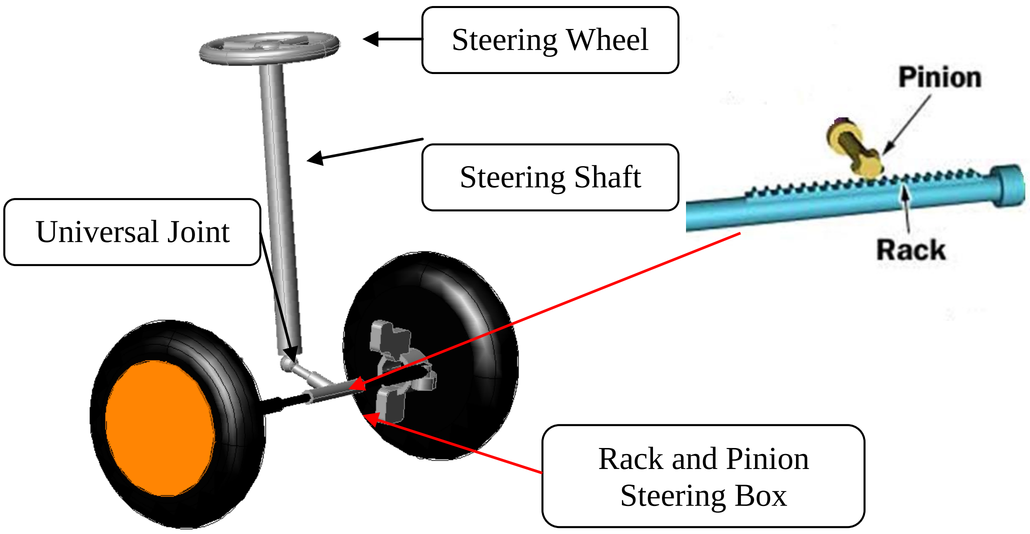


Figure 21: Steering Mechanism for Conceptual Design 1

Conceptual Design 2

This conceptual design has three wheels as shown previously in page 26 - **Figure 19**, **w**here two wheels are installed at the platform and one at the front. Maneuvering is done by the front wheel via motorbike/ bicycle based steering mechanism. Simple enough, the maneuvering is done simply by turning the steering handle which is connected directly to the front wheel. This steering mechanism gives turning ratio of 1:1. **Figure 22** below shows the steering mechanism of this conceptual design:

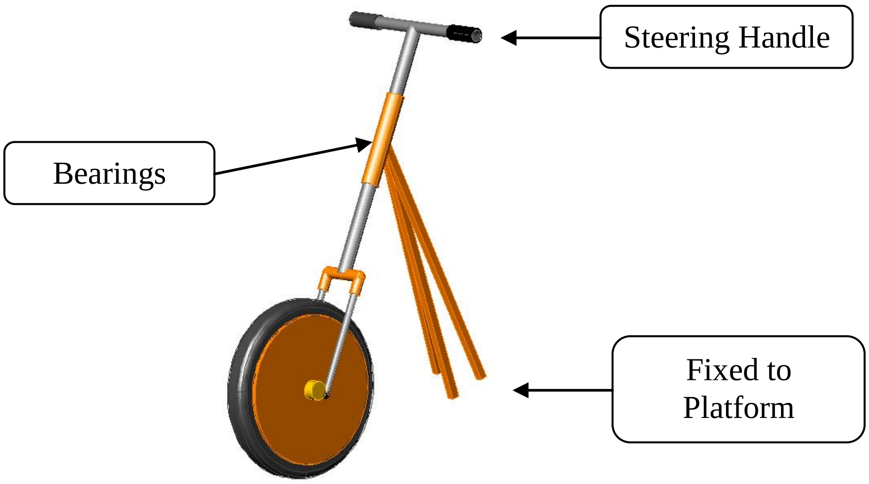


Figure 22: Steering Mechanism for Conceptual Design 2

Conceptual Design 3

Like conceptual design 2, this conceptual design also has three wheels. Namely, two wheels at the platform and one at the front as shown in page 27 – **Figure 20**. Besides, this conceptual design also has a steering mechanism which is based on motorcycle/ bicycle. What set it apart from conceptual design 2 is the fact that it is equipped with a four bar linkages system which make it possible for the steering mechanism to tilt during turning. The tilting effect that is achieved by the four-bar linkages during turning will definitely increase the stability during turning by a great margin - Please refer to the technical report titled *Development of a Novel Three-Wheeled Vehicle* [13] by V. Cossalter, N. Ruffo, F. Biral, R. Berritta from Department of Mechanical Engineering, University of Padua for more information on the four bar linkages system presented. **Figure 23** in the next page shows the steering mechanism for this conceptual design.

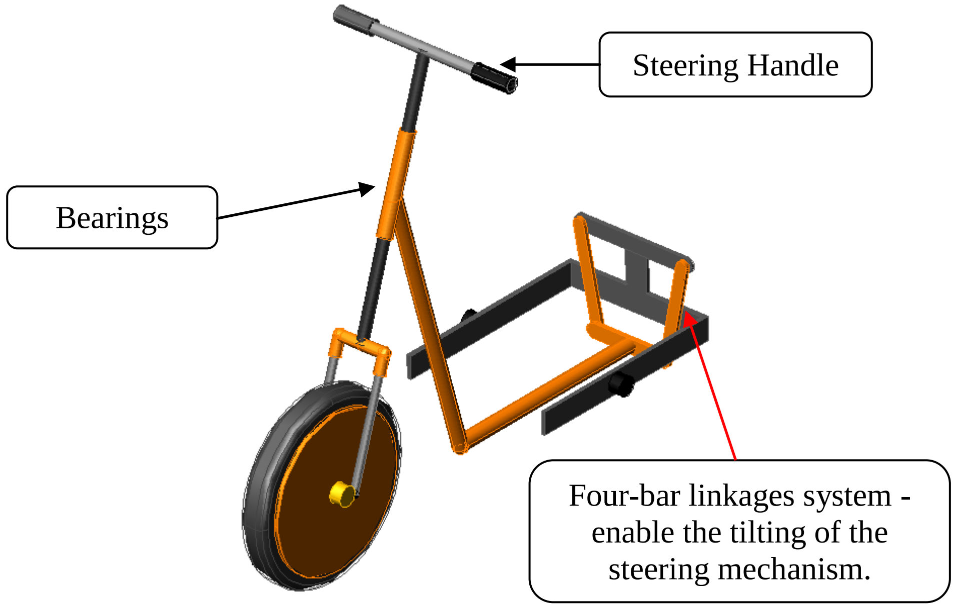


Figure 23: Steering Mechanism for Conceptual Design 3

While **Figure 24** below shows the four bar linkages positions during 29 degrees tilting of the steering mechanism on both sides:

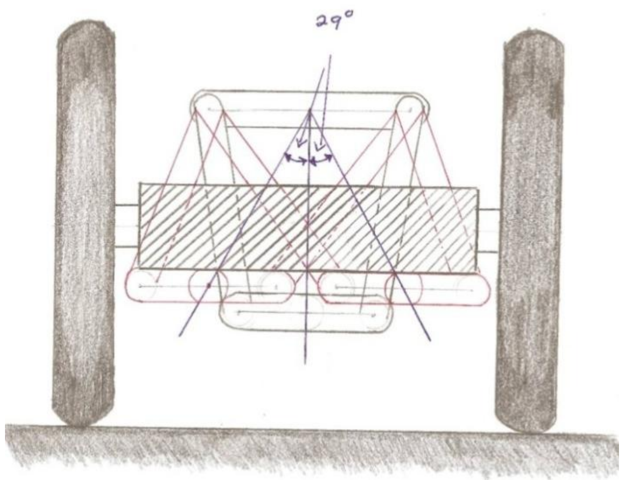


Figure 24: Four Bar Linkages Position during 29 degrees Tilting on Both Sides

Having discussed the steering mechanism for each conceptual design, the pros and cons of each design are analyzed and presented in **Table 6** in the next page:

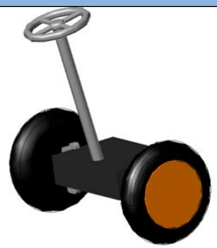
Design / Items	Conceptual Design 1	Conceptual Design 2	Conceptual Design 3
CAD Drawing			
Pros	i) Low cost – established steering design. ii) Simple steering mechanism – rack and pinion steering mechanism. iii) Easy to maintain. iv) Compact design.	i) Low cost – established steering design. ii) Simple steering mechanism – motorbike/ bicycle steering mechanism. iii) Easy to maintain.	i) Low cost – established steering design. ii) Simple steering mechanism – motorbike/ bicycle steering mechanism. iii) Easy to maintain. iv) Effective –availability of the four bar linkages that provide tilting to the steering mechanism.
Cons	i) Need self balancing system – Expensive and thus cancel out the benefit of low cost steering mechanism. ii) Unstable turning due to all the weight components are acting on top of the steering mechanism.	i) Takes up larger space than conceptual design 1. ii) Not stable during turning due to the incapability of the steering mechanism to provide tilting.	i) Takes up larger space than conceptual design 1. ii) Improper design might cause improper weight distribution which will cause the personal transporter to be unstable.

Table 6: Pros and Cons Analysis of the Conceptual Designs

From the pros and cons analysis of the three conceptual designs, it is obvious that conceptual design 1 has the advantage of being a compact design. Yet, the facts that conceptual design 1 only has two wheels and that all the weight components are acting on its steering mechanism have caused it to be extremely unstable during cornering. Not to mention the requirement of a self-balancing system which is expensive that will cancel out the compact benefit of conceptual design 1.

While for conceptual design 2, it has the advantage of being more stable than conceptual design 1 due to the addition of a third wheel in front of the platform. On top of that, it has a lower overall cost of production than conceptual design 1 since it does not require self-balancing system. This design, however, is still not good enough in the sense that the steering mechanism could not tilt during cornering which make it still not very stable during cornering.

For conceptual design 3, it has all the advantages of conceptual design 2. What makes it stands out from the rest is its four-bar linkages system which allows its steering mechanism to tilt during cornering for stability. This has made it the most feasible design that meet the author‘s needs of designing a steering mechanism for personal transporter that is low in cost and provides effective turning.

4.3 DECISION MATRIX

In the previous section, it is obvious that conceptual design 3 is the best design function wise – without taking into consideration of currently existing personal transporters in the market such as Segway personal transporter and Yike bike. Yet, more considerations and studies have to be done before final decision could be made on which design is the best as there are few factors that the author needs to look into such as cost, simplicity of design, maintainability and effectiveness.

To ensure that the final design chosen meets all the design criteria set earlier, the author decided to employ decision matrix to compare between the conceptual designs and currently available personal transporter on the market like Segway and Yikebike personal transporters. Besides, the author also employed decision matrix to compare between one-wheel based steering mechanism and two-wheel based steering mechanism.

It should be bear in mind that the project's main focus is to develop a steering mechanism that is low in cost yet effective so that the overall cost of a new personal transporter to be developed is low and thus affordable to citizens living in cities in developing countries.

Table 7 in the next page shows the decision matrix to choose the steering mechanism that best suits all the design criteria set earlier. While **Table 6** in page 35 shows the decision matrix to choose between one-wheel based steering mechanism and two-wheel based steering mechanism.

		Decision Making Criteria					
Options	Criteria / Options	Cost	Design Complexity	Maintainability	Effectiveness	Size	Total
	Segway	5	2	4	9	9	29
	Yikebike	5	3	4	9	9	30
	Conceptual Design 1	7	7	8	2	7	31
	Conceptual Design 2	9	9	9	3	4	34
	Conceptual Design 3	8	8	9	7	4	36

Table 7: Decision matrix to choose the best steering mechanism

Note: The rating is in the range of 1 – 10, where 10 represent the best and 1 represents the worst.

Ex: Complexity of design

10 **= Very simple design**

1 **= Very complex design**

From the decision matrix analysis, it becomes immediately apparent that conceptual design 3 is the best in terms of serving the objectives set earlier in this project, which is to develop a low cost personal transporter that is affordable to people living in developing countries which ultimately leads to the easing of pollutions and congestion problems in cities. Despite this design has the disadvantage of being relatively larger in size, it serves the other design criteria of this project nicely. This is mainly due to its four-bar linkages system that gives it the advantage of being more stable than conceptual designs 2 and 1 during cornering.

While the second design that best suits the design criteria of this project is conceptual design 2. Despite its relatively low stability during cornering (low effectiveness), it achieves the other design criteria of this project nicely - low cost, easy to maintain and simple design. Conceptual design 1 comes next after conceptual design 2 as the steering mechanism that best suits the design criteria set. Again, despite its low effectiveness, it manages to achieve the other design objectives better than the Segway and Yikebike personal transporters.

Last but not least, the least favorable options in terms of achieving the design criteria of this project are the Segway and Yikebike steering mechanisms. Despite their highly sophisticated technology and designs, they failed to fair in this project because the project's main concerns are low cost, simple design and easy to maintain which are not the strong points of the two products.

4.4 CALCULATIONS

4.4.1 Calculations for Steering Geometry

With the design criteria, specifications and conceptual design decided upon. Calculations were performed in order to get the geometry of the new steering mechanism to be designed.

In the following pages, the author presented on how parameters that are important for the stability and maneuvering of his steering mechanism design, namely, (i) fork offset, (ii) trail and (iii) caster angle were determined and decided upon. Radius of steering wheel to be used in the author's design is also fixed later on as it will affect the values of trail and caster angle.

Fork Offset

As mentioned in the theory part, offset is important for shock absorption. There is no specific limitation though on what is the range that offset value should be in. In industrial practice, prototypes at a range of fork offset values are tested in lab to see the amount of stress that steering at various fork offset could withstand before it fails. The best offset value is then selected to be used in the final design of their product. In the author's case, however, an offset value will be selected from a range that is generally employed on motorcycles and bicycles (0.036m – 0.05m) due to the unavailability of budget to produce prototypes at various fork offset values for testing purposes.

The fork offset value to be employed in the author's design is not very critical in the sense that personal transporter is designed to be used in cities where the roads are properly paved and there will not be much vibration experienced by the wheels. Thus, the author decided to fix the fork offset value of the steering mechanism to be designed to 0.0036m.

Trail and Caster Angle

Trail and caster angle are closely related to each other, where an increase in trail will be accompanied by an increase in caster angle for stability. In fact, trail and caster angle are related to each other through the following formula:

$$a = R_f \times \tan\varepsilon - \frac{d}{\cos\varepsilon}$$

Where:

a is the trail

R_f is the radius of the front wheel

d is the fork offset

ε is the caster angle

There is large combination of trail and caster values that the author can use as any change in the front wheel radius, R_f and fork offset, d will lead to another set of trail and rake angle combination. To reduce the variables in designing the steering mechanism, the author has decided to use a wheel with a radius of 24cm (Please refer to "fixed design parameters" section in the next page for justification of using 24cm wheel radius) for his design. Besides, to get some guidelines in designing his steering mechanism, the author has done researches on the trail and caster angle combination of motorcycle and bicycle available nowadays. **Tables 8** and **9** in the next page show the general combination of trail and caster angle for motorcycles and bicycles respectively:

Motorcycle Category	Caster angle range (deg)	Trail range (mm)
Competition	19-21	75-90
Touring and sport	21-24	90-100
Purely for touring	27-34	≥120

Table 8: Caster angle and Trail Combinations of Motorcycles

Bicycle Category	Head angle range (deg)	Equivalent Caster angle range (deg)	Trail range (mm)
Racing	73-74	16-17	28-45
Track	71-74	16-19	52-69
Touring	72-73	17-18	43-60

Table 9: Caster angle and Trail Combinations of Bicycles

Note that motorcycle and bicycle steering mechanisms are the same, just that some parameters are represented differently which make the formula employed different (The author employed motorcycle's formulas throughout his design). Also, equivalent caster angle for bicycle can be obtained simply by using the following formula:

$$\textbf{Equivalent Caster Angle} = \textbf{90 deg} - \textbf{Head Angle}$$

Having set the guidelines, the author shall calculate all the necessary design parameters by using the following steps:

Fixing design parameters:

There are two parameters that were fixed previously for their own reasons, namely, wheel radius and fork offset. The values fixed for each are as the following:

Wheel Radius = 0.24 m

Fork Offset = 0.036 m

The wheels radius is actually based on the Segway personal transporter wheels radius. The reason why it is selected is because a research has been done by Segway which states that this is the optimum wheel radius that will provide a ground clearance of at least 7.5cm at most conditions which enable the personal transporter to travel though water puddle that you might come across in cities roads safely without spoiling the electrical components in the personal transporter.

While the fork offset value is selected for the reason mentioned in the “fork offset” part in page 37 of this report.

Employ trail equation to calculate possible caster angle and trail combinations:

Microsoft excel has been employed to speed up the calculation process as well as to reduce human error. Please refer to the **Table 10:** Possible Caster Angle and Trail Combinations below for the possible combinations:

Caster Angle (˚) , ε	Trail (m) ,a	Trail (mm), a
16	0.031	31.37
17	0.036	35.73
18	0.040	40.13
19	0.045	44.56
20	0.049	49.04
21	0.054	53.57
22	0.058	58.14
23	0.063	62.76
24	0.067	67.45
25	0.072	72.19

Calculations are only done on caster angle in the range of 16 – 25 degree as the author is striving for small value of caster angle which enable a more compact design. Of all the possible combinations above, the author has decided to use the following combinations of caster angle = 19 degree and trail = 44.56mm.

Caster Angle, ε = 19 degree

Trail, a = 44.56mm

The reason why the author choose this combination despite saying that smaller caster angle is better is that there is another factor to consider. That is, the stability of the overall design. Too small caster angle will cause the wheelbase to be too small and thus affect the longitudinal stability. Therefore, an average caster angle is selected.

Here is the example on how the caster angle and trail combination selected could be calculated manually:

By employing formula presented earlier in "Trail and Caster Angle" section in page 38:

$$a = R_f \times \tan\varepsilon - \frac{d}{\cos\varepsilon}$$

Where:

$R_f = 0.24$ m

$d = 0.036$ m

Substituting parameter values that have been set earlier as well as caster angle of 19 degree into the formula, the trail value can be obtained as the following:

$$a = 0.24 \times \tan(19°) - \frac{0.036}{\cos(19°)}$$

$$a = 0.24 \times 0.3443 - \frac{0.036}{0.9455}$$

$$\underline{a = 0.044556\text{m} \approx 44.56\text{mm}}$$

After determined based on the preceding calculations. A summary of the parameters is shown in **Table 11:** Summary of parameters determined by calculations:

Parameters	Values
Wheel Radius, m	0.24
Fork Offset, m	0.036
Caster Angle, deg	19
Trail, mm	44.56

The rest of the parameters are automatically known with the determination of the parameters of the steering mechanism and design specifications set earlier. The perpendicular distance between the steering handle and the center of the platform where the rider stands is set to be 40cm for the comfort gesture of the rider. Please refer to *Bicycles & Tricycles: A Classic Treatise on Their Design and Construction* [9] by Achibald Sharp and *Motorcycle Handling and Chassis Design* [10] by Tony Foale for more information on the generally employed values, formulas and design considerations presented in this section. Please refer to the sketch below for the overall parameters of the whole personal transporter:

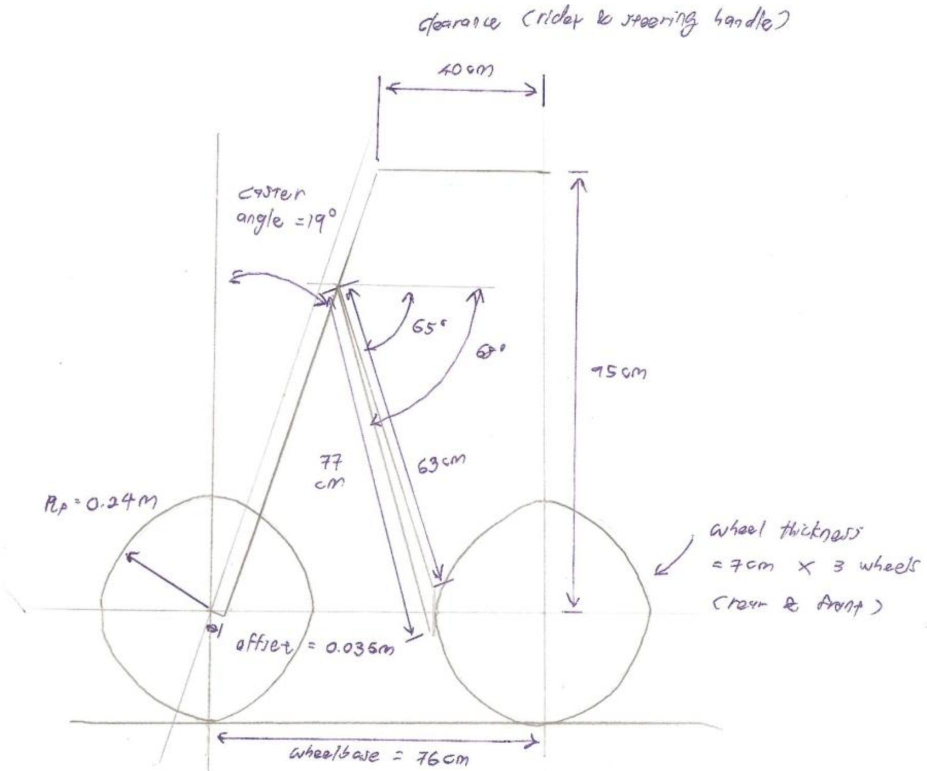


Figure 25: Sketch with important overall parameters

Having determined all the important parameters for the steering mechanism, as well as the parameters decided earlier such as footprint of 48.0 cm X 60.0 cm for the platform on which the rider stands, the author had drawn an AutoCAD drawing of his design to scale as shown in the next page.

DESIGN CONCEPT

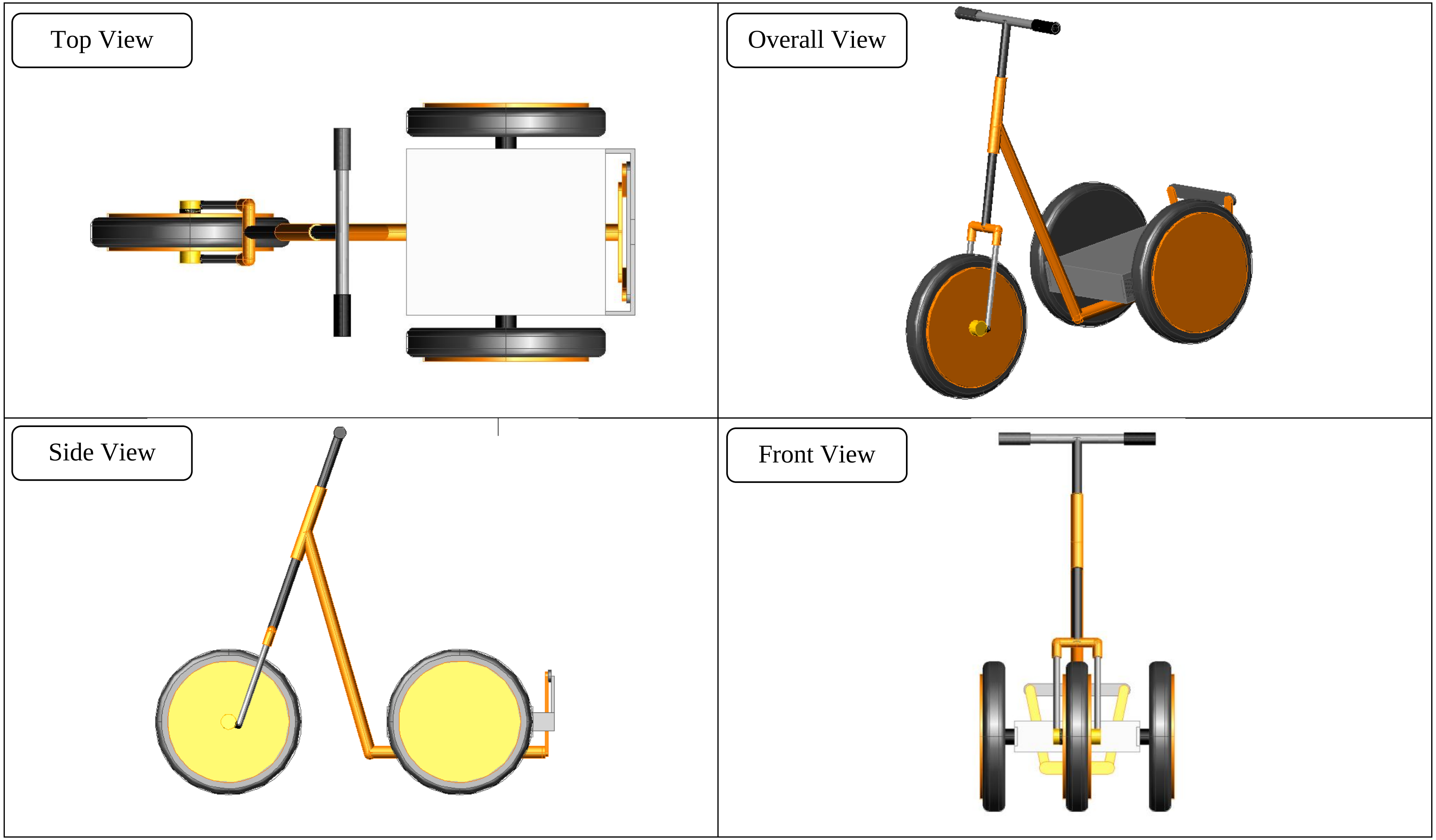


Figure 26: Auto CAD Drawing of the Conceptual Design (Drawn to real Dimension)

4.4.2 Calculations for Stability Analysis

Having decided upon the parameters of the steering mechanism as well as the dimensions of the overall personal transporter, it is time to analyze the stability of the overall design. The design's primary stability concern will be its turning stability. To analyze the turning stability, the following assumptions and calculations are performed:

To simplify the analysis, the author has made the following assumptions:

- The steering wheel is the driving wheel.
- The rear wheels are mounted independently on the axle. (So that they will rotate at their respective proper speeds during turning automatically.)
- Rider's weight = 80 kg. (The weight could be any reasonable value as it will not affect the final results.)
- Personal transporter's overall weight is 50 kg
- Right cornering at a turning radius of 2 m from the rider's point of view.
- Cornering is done at 50% of the maximum velocity, namely10 km/h.

The free body diagram of the personal transporter designed is shown in **Figure 27**:

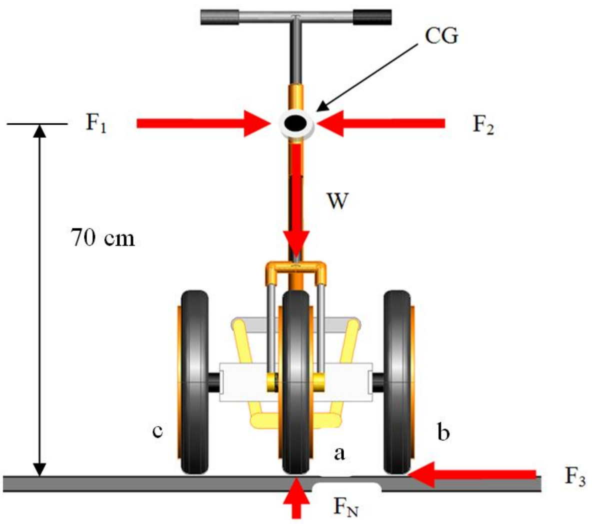


Figure 27: Free Body Diagram

Where,

CG – Center of Gravity

F_1 – Centrifugal Force

F_2 – Centripetal Force

W – Overall Weight

F_3 – Overall Frictional Force

While **Figure 28** below shows denotations that are important for the stability analysis later on:

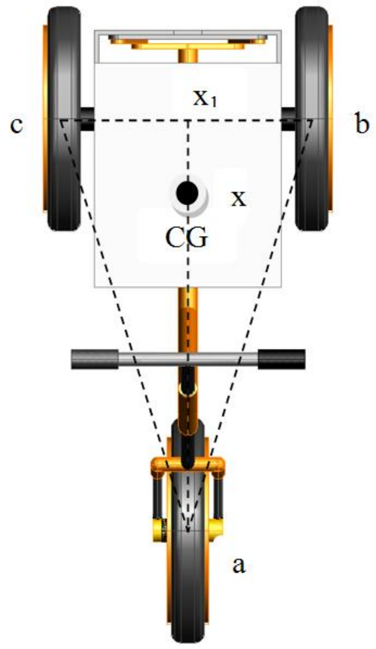


Figure 28: Free Body Diagram

First, all the important unknown forces are calculated as the following:

F1 and F2 are centrifugal and centripetal forces respectively, they have the same magnitude but different directions as shown in **Figure 19** in the previous page. Their magnitude may be calculated by using the following formula:

$$F_{1,2} = \frac{mV^2}{r}$$

$$F_{1,2} = \frac{(80\ \mathrm{kg} + 50\ \mathrm{kg}) \times (10\ \mathrm{km/h} \times \frac{1000\ \mathrm{m}}{1\ \mathrm{km}} \times \frac{1\ \mathrm{h}}{3600\ \mathrm{s}})^2}{2}$$

$$\underline{F_{1,2} = 482.54\ \mathrm{N}}$$

W is the overall weight of the personal transporter and rider, it can be calculated as the following:

$$W = (\text{Rider}'\text{sMass} + \text{Personal Transporter}'\text{sMass}) \times \text{gravitational Acceleration}$$

$$W = (80\text{ kg} + 50\text{ kg}) \times 9.81\ {}^{\text{m}}/_{\text{s}^2}$$

$$\underline{W = 1275.30\text{ N}}$$

Now, F_3 shall be calculated as the following:

- Since F_3 is the overall frictional forces due the contact points of the three wheels at a, b and c. The author's shall first find the weight at each of the wheel by using principle of moments as the following:
  To find weight on wheel a, the author uses the equation of equilibrium of moments around axes b and c as the following:

$$W \times xx_1 = w_a \times ax_1$$

$$(50\text{ kg} + 80\text{ kg}) \times 9.81\ {}^{\text{m}}/_{\text{s}^2} \times 36\text{ cm} \times \frac{10^{-2}\text{ m}}{1\text{ cm}} = w_a \times 88\text{ cm} \times \frac{10^{-2}\text{ m}}{1\text{ cm}}$$

$$\underline{w_a = 521.71\text{ N}}$$

  While to find weight on wheels b and c, the author uses the equation of equilibrium of moments around axes a as the following:

$$W \times xa = w_{b\&c} \times ax_1$$

$$(50\text{ kg} + 80\text{ kg}) \times 9.81\ {}^{\text{m}}/_{\text{s}^2} \times 52\text{ cm} \times \frac{10^{-2}\text{ m}}{1\text{ cm}} = w_{b\&c} \times 88\text{ cm} \times \frac{10^{-2}\text{ m}}{1\text{ cm}}$$

$$w_{b\&c} = 753.59\text{ N}$$

$$w_b = w_c = \frac{753.59\text{ N}}{2} = 376.79\text{ N}$$

- F_3 is simply the summation of the frictional forces at each of the wheels as the following:

$$F_3 = \mu w_a + \mu w_b + \mu w_c$$

Where

μ is the coefficient of friction and is assumed to be 1.7 for tire and concrete contact under good condition

$$F_3 = 1.7 \times 521.71\text{ N} + 1.7 \times 376.79\text{ N} + 1.7 \times 376.79\text{ N}$$

$$\underline{F_3 = 2167.99\text{ N}}$$

Having obtained all the important forces, the author tested the turning stability of his design by using the principle presented in *chapter XVII – Stability of Cycles* in the book titled "*Bicycles &Tricycles: A Classic Treatise on Their Design and Construction* [9] by Archibald Sharp" which states that if the resultant force, R of W and F_1 cut the ground at point p, (as shown in **Figure 29** below) outside the wheelbase a, b and c. Then the design will overturn.

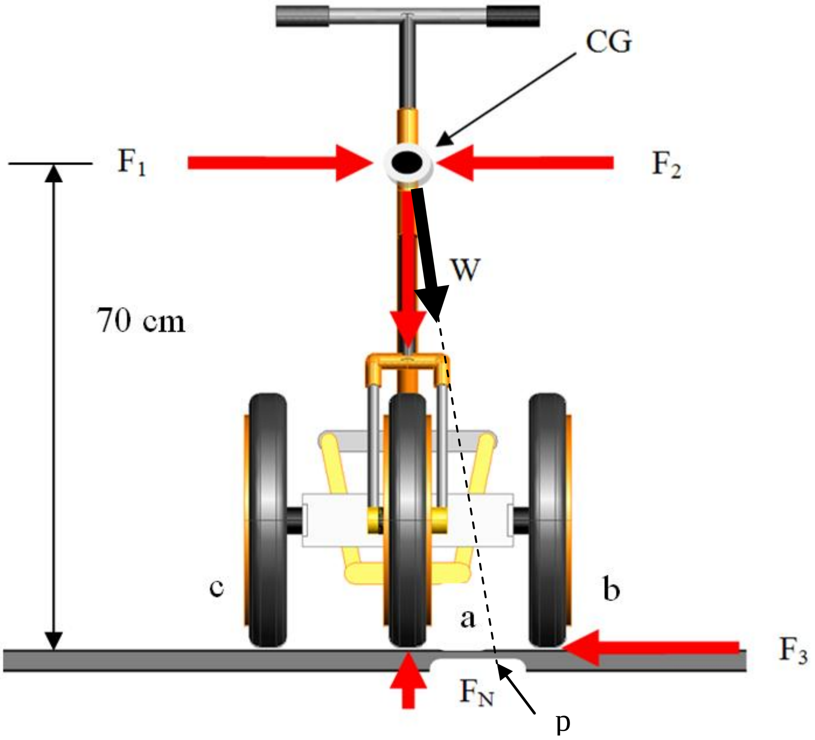


Figure 29: Free Body Diagram

Thus, to check for the turning stability of the author's design. Force analysis is carried out based on the values calculated earlier as shown in the **Figure 30** in the next page.

From the force analysis carried out (Please refer to **Figure 30** in the next page), we can see that the resultant force is still within the wheelbase a,b and c of the vehicle. Even though the point p crosses the wheelbase at margin, it is good enough to show that the design is still stable in terms of turning stability if a rider is to turn through a turning radius of 2m at a speed of 10km/h. Besides, it should be bear in mind that the analysis above is carried out without considering the tilting capability of the steering mechanism yet. Thus, the author can conclude that the design is safe to turn through a turning radius of 2 m at a speed of 10km/h.

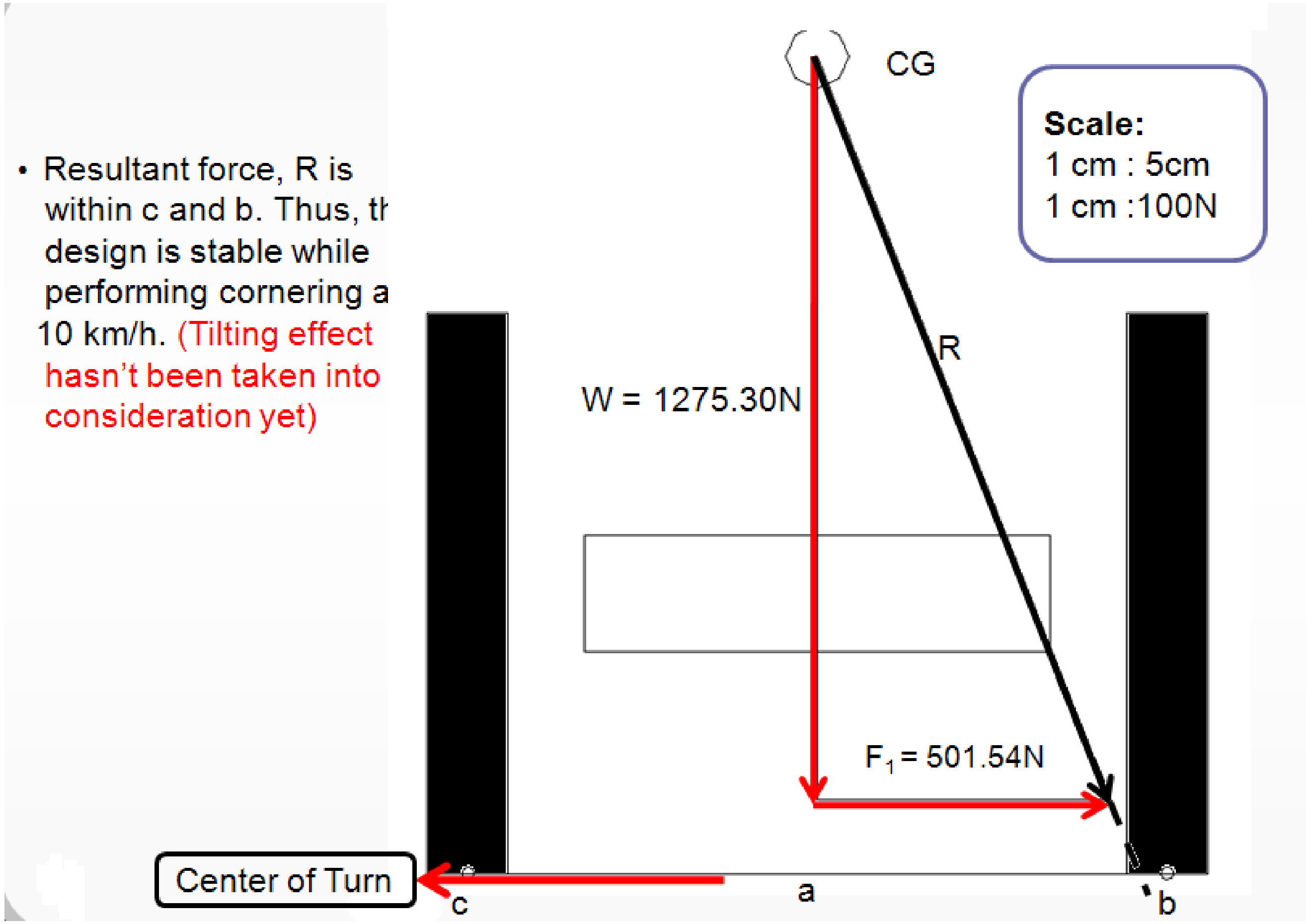


Figure 30: Force Analysis

4.4.3 Calculations for Self-Alignment Moment

In this section, the author shall perform calculations to see the self-alignment moment generated when the vehicle is making a turn at 10km/h. By using the information that has been calculated in section 4.4.2 as well as the assumption made. The self-alignment has been calculated as shown in **Table 12:** Self-alignment moment, with the assistance of Microsoft excel:

Slip Angle (°)	Trail Value, a_t (m)	Self-Alignment Moment, Mz (N.m)
0	0.045	39.91
1	0.042	37.25
2	0.039	34.59
3	0.036	31.93
4	0.033	29.27
5	0.030	26.61
6	0.027	23.95
7	0.024	21.29
8	0.021	18.63
9	0.018	15.96
10	0.015	13.30
11	0.012	10.64
12	0.009	7.98
13	0.006	5.32
14	0.003	2.66
15	0.000	0.00

To illustrate how the self-alignment moment was obtained, the author will show the steps to calculate the self alignment moment for slip angle = 1^{o} below:

By using the following formula, we can get the trail value during slip angle = 1^{o} as the following:

$$a_t = a_{t_0} \times \left(1 - \frac{\lambda}{\lambda_{max}}\right)$$

Where,

a_t – Trail Value during Turning

a_{t0} – Maximum Value of Tire Trail = 0.045 m (Calculated previously)

λ – Centrifugal Force

λ_{max} – Slip Angle at which the trail becomes zero = 15^o

(Experimental value, refer to *Motorcycle Dynamics* [14] by Vittore Cossalter)

$$a_t = 0.045 \times \left(1 - \frac{1}{15}\right)$$

$$a_t = 0.042\text{m}$$

After obtaining the trail value at slip angle = 1^o, the self-alignment moment can be calculated by using the following formula:

$$M_z = a_t \times F_s$$

Where,

M_z – Self Alignment Moment

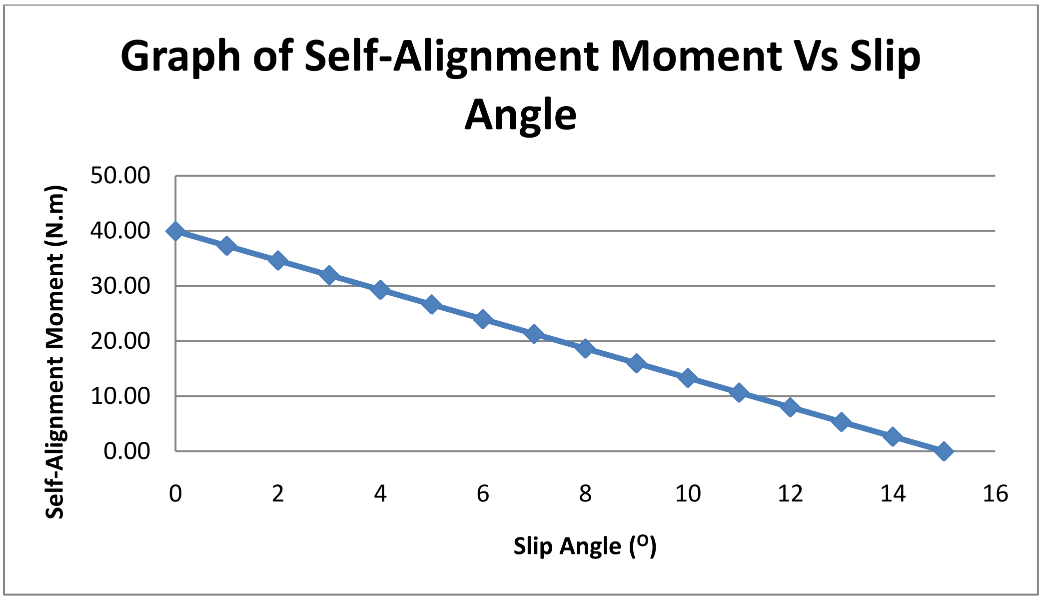
a_t – Trail Value at a Particular Slip Angle (1^o in this case)

F_s – Lateral Force = 886.91N (Calculated previously)

$$M_z = 0.042 \times 886.91$$

$$\underline{M_z = 37.25\text{N.m}}$$

From the data calculated, a graph of self-alignment moment vs slip angle has been plotted as shown in **Graph 1** in the next page. It is clear from the graph that the self-alignment moment gets lesser as the slip angle increases, this is mainly due to the trail value gets smaller as the slip angle increases which causes the moment generated to be less. This is theoretically correct with reference the book *Motorcycle Dynamicp* [14] by Vittore Cossalter. The formula employed in this section to calculate self-alignment moment was also obtained from the same source.



Graph 1: Graph of Self Alignment Moment Vs Slip Angle

Also, from the calculated self-alignment data in the previous page, the author has also calculated the steering force needed to make the turn as shown in **Table 13:** Steering force:

Slip Angle, (°)	Self-Alignment Moment, Mz (N.m)	Steering Force, (N)
0	39.91	79.82
1	37.25	74.50
2	34.59	69.18
3	31.93	63.86
4	29.27	58.54
5	26.61	53.21
6	23.95	47.89
7	21.29	42.57
8	18.63	37.25
9	15.96	31.93
10	13.30	26.61
11	10.64	21.29
12	7.98	15.96
13	5.32	10.64
14	2.66	5.32
15	0.00	0.00

Again, for clarity purposes, the author will show the calculations to get the steering force needed to turn the corner below:

Taking slip angle = 1^o as an example, the steering force can be calculated by using the following formula:

$$F_S = \frac{M_z}{L}$$

Where,

F_S – Steering Force

M_z – Self-Alignment Moment

L – Length of Steering Bar = 0.5m

$$F_S = \frac{37.25}{0.5}$$

$$\underline{F_S = 74.50 \text{ N}}$$

From the calculated values, one can observe that the steering force to initiate the turn is large initially and it gets lower as the turning angle gets successively large due to the reduction in self-alignment moment.

CHAPTER 5
CONCLUSIONS & RECOMMENDATIONS

In a nutshell, a conceptual design which employs a four bar linkage to provide tilting for the steering mechanism is the best design that could serve the objectives of this project. Namely, to design a steering mechanism for a personal transporter that is low in cost, easy to maintain, simple design and provides effective turning to the new personal transporter to be designed sometime in the future. If the overall project is a success, it will not be long before citizens in developing countries can afford a cheap personal transporter that could ultimately help to solve the congestion and pollution problems in cities.

Besides, in order to improve the design. The author would recommend that the successor of this project to do the following items:

- Conduct simulation in Adams to further ensure its stability at various speeds.
- Conduct simulation in Ansys to check for the robustness of the design.
- Come out with a prototype to test ride.

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