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Bicycle Applications for On-Board Solar Power Generation System Adaptation

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A shift away from conventionally-fueled land transportation vehicles towards greater use of renewable energy fuel sources is needed to manage increasing vehicle usage and associated adverse environmental and human health impacts. Power assisted electric bicycles (PAEBs) provide a means to reduce vehicle emissions within urban areas. PAEBs can utilize electrical power generation from solar energy, reducing the demand from power generating stations using non-renewable fuel sources. While applications of solar energy charging stations for electric vehicles exist, the use of on-board solar power generation on a PAEB has received little focus and warrants further design and experimentation. An analysis of solar power production from an on-board solar panel in various bicycle riding conditions was conducted. Bicycle performance equations combined with Elora Research Station (ERS) solar irradiance and meteorological data were utilized in this analysis to identify riding conditions where greater than 25% of the total required power for propulsion can be supplemented by the solar panel. The on-board solar panel was not able to provide adequate power to the PAEB except under significantly controlled riding conditions not representative of the dynamic nature of typical bicycle riding. Recharging the system battery during summer daytime hours can replenish the battery charge by 42% over the course of one day, making it a feasible alternative to direct use of on-board solar power generation. A separate analysis determined that increasing the solar collector area to 0.5 m^2 could supply over 25% of the total required power and a collector area of 2 m^2 would allow the PAEB system to be completely powered by on-board solar power generation.

Nomenclature

A	=	frontal area
C_d	=	drag coefficient
D	=	density of air
G	=	slope grade
g	=	acceleration due to gravity
m	=	mass of rider and bicycle
P_{Total}	=	total Power
P_{Drag}	=	power for overcoming air drag
$P_{Friction}$	=	power for overcoming friction
P_{Slope}	=	power for overcoming terrain slope
R_c	=	rolling coefficient
V_g	=	ground speed
V_w	=	head wind speed

I. Introduction

Urban transportation around the world is on the rise. As of 2007, over 50% of the world's population lives in urban environments (Loutan et al, 2008). Mobility within these expanding urban environments increasingly relies on personal transportation vehicles instead of walking. Traditionally, these vehicles have been predominately powered by fossil fuels. The emergence of power assisted electric bicycles (PAEBs) provides an alternative means of personal transport. Other forms of power assist bicycles use small conventional gasoline and diesel motors. However, for the purpose of this paper, the vehicles of focus are those that are electrically driven. PAEBs use an on-board electric motor and battery system, which supplements rider pedaling to extend trip durations or aid the rider in ascending steeper terrain (Hendriksen et al, 2008). PAEBs typically do not generate electricity during use; rather they use stored energy from an on-board battery.

The goal of this paper is to review PAEBs and solar power generation, and investigate the potential of assisting bicycle propulsion using on-board solar power generation. The increase in PAEB use in various parts of the world has shifted emissions from vehicle tailpipes in dense urban environments to electrical power generating stations, some of which rely solely on fossil fuels. Incorporating on-board solar power generation onto PAEBs shifts energy consumption from fossil fuels to renewable energy from the sun, ultimately reducing peak energy loading and the pollution associated with non-renewable energy production. In addition, on-board solar power generation also allows for PAEBs to be charged in locations where conventional electricity is inaccessible.

The structure of this paper consists of a review of current literature on the current environmental impact of conventional personal vehicle transportation, recent shifts toward PAEB use, governing equations for bicycle performance, and existing solar powered land vehicle technology. Once a basis for the current state of the art technology has been established, an investigation analyzing the feasibility of bicycle propulsion using on-board solar power generation is presented.

II. Impact of Conventional Personal Land Transportation

Air pollution resulting from vehicle emissions contributes to poor urban air quality. These emissions include carbon dioxide, carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter, some of which are known carcinogens and greenhouse gases that contribute to global warming (USEPA, 2007).

It is important to distinguish between how such pollution is affecting both the developed and developing world. Adverse effects to human health due to urban air quality are not as prominent in the developed world compared to the developing world. Various government-run programs established throughout the developed world aid in reducing vehicle emissions to some extent through vehicle emission testing and driver education and outreach (Environment Canada, 2004). Lack of infrastructure for creating and implementing such programs in the developing world has caused significantly higher health implications. An estimated 650,000 premature deaths were associated with poor urban air quality in developing countries in the year 2000 (Gwilliam et al., 2004).

One factor influencing poor urban air quality is increased vehicle use in both the developed and developing countries. In developed nations, dependence on cars for personal transportation has resulted in an increase in total passenger kilometres (Corp and Lewin, 2010), single-occupant trips in multiple occupancy vehicles (Ferguson, 1997), and subsequent emissions as a result of these activities. Vehicle ridership in the developing world is also expected to continue to increase. A report issued by the United Nations Centre for Human Settlements (2001) estimates the developing world's share of cars will rise from 25% in 1995 to 48% by 2050.

Increasing ridership creates a larger energy demand to power these vehicles. Despite PAEBs having zero direct emissions, the electricity used to power PAEBs originates at power generating stations, which can emit a variety of pollutants or have other negative environmental impacts. As discussed in Sawin and Martinot (2010), global energy consumption derived from renewable energy sources is growing, yet 78% of the global energy market is still largely comprised of fossil fuel based technologies. Using renewable energy to power PAEBs would reduce urban air pollution, point source pollution emitted from non-renewable energy based power generating stations, and the overall dependence on fossil fuels.

The compounding effects of increasing personal vehicle use and the deterioration of urban air quality from fossil fuel based transportation vehicles has resulted in a shift to seek alternative modes of transportation and energy sources for powering land transportation vehicles, including PAEBs.

III. PAEBs Worldwide Usage

The design, manufacture, and use of PAEBs is growing worldwide, with particular interest in China, Europe, Japan, Taiwan, and to a lesser extent the United States (Muetze and Tan, 2007). Reasons for using PAEBs vary between developed and developing nations. In developed nations, PAEBs are generally used for leisurely rides, small errands, or short daily commuting to the workplace (Muetze and Tan, 2007; Transport Canada, 2007). Contrastingly, the growing use of PAEBs in mega cities of developing countries is attributed to an increasing standard of living. According to Weinert et al (2007), as disposable family income in China increased 82% between 1997 and 2004, sales of electric bicycles (i.e., PAEBs and scooter-style electric bicycles) grew from 40,000 in 1998 to 10 million in 2005.

IV. Review of Solar Power Generation for Vehicles

Experimentation using photovoltaic devices for the propulsion of wheeled land transportation vehicles has been ongoing since the 1980s (USDOE, ND). Despite vast improvements in photovoltaic technologies, vehicles using internal combustion engines have remained the primary method of land-based transportation. The development of solar vehicles as a practical alternative to gasoline and diesel fuel vehicles is currently not feasible due to significant limitations of solar technology (Sorrentino et al, 2010). The low energy density of solar power and the unpredictability of solar irradiation due to transient weather effects are both significant drawbacks faced by solar power vehicle researchers (Arsie et al, 2006). Research by Sorrentino et al (2010), however, shows the viability of integrating solar panels into hybrid-electric vehicles to supplement energy production.

Literature surrounding solar power vehicle propulsion has been predominantly conducted for highly specialized vehicle applications (Arsie et al, 2006) such as speed-optimized racing. For example, international solar vehicle racing competitions such as the World Solar Challenge, require participants to design solar powered vehicles to travel across the Australian continent (World Solar Challenge, 2010). With the limitations in solar energy production, performance of these racing vehicles depends greatly on improving vehicle aerodynamics and reducing vehicle mass. For applications where a more practical commuter vehicle is desired, optimizing these parameters in the same way may not be feasible due to concerns of vehicle safety. Although limited in performance, a compact electric car manufactured in China was retrofitted with rooftop solar panels. The car is estimated to travel up to 90 miles on a 30-hour charge from the sun (RideLust, ND), although verification of this data by reputable academic sources could not be obtained.

A search of current literature did not find direct uses of on-board solar power specifically for PAEBs beyond a few hobbyist do-it-yourself bicycle modification kits. These solar-electric modification kits claim to produce self-sufficient power from the sun, but reproducible experiments and data could not be obtained. An example of one such solar power modification kit includes the use of photovoltaic panels built into the wheels of the bicycle (Treehugger, ND)

Cases of using external solar panels for charging PAEBs have been observed in various parking lot applications. The Japanese company Sanyo has developed solar parking lots for recharging PAEBs for employees (Sanyo, 2010).

V. Performance Equations for Bicycles

The performance of a PAEB is governed by the same equations as those for conventional bicycles. The performance equations relating power input to bicycle speed were obtained from Muetze and Tan (2007):

$$P_{Total} = P_{Drag} + P_{Slope} + P_{Friction} \quad (1)$$

$$P_{Drag} = \frac{C_D D A}{2}\left(V_g + V_w\right)^2 V_g \quad (2)$$

$$P_{Slope} = gGV_g m \quad (3)$$

$$P_{Friction} = gmR_c V_g \quad (4)$$

The total required power, P_{Total}, is the sum of the power needed to overcome aerodynamic drag P_{Drag}, climb sloped terrain P_{Slope}, and overcome frictional rolling resistance $P_{Friction}$. Equations (1) through (4) are used to calculate these power loss parameters, where C_D is the drag coefficient, D is the air density, A is the frontal area, V_g is the ground speed, V_w is the headwind component of wind speed, g is the acceleration due to gravity, G is the slope grade expressed as a ratio of the rise and run of the terrain, m is the mass of the rider, bike, and all accessories, and R_c is the rolling coefficient. According to Wilson (2004), typical values for an upright commuter bicycle were found to be $C_D = 1.15$, $A = 0.55$ m^2, and $R_c = 0.0060$.

The proportion of overall power lost due to P_{Drag}, P_{Slope}, and $P_{Friction}$ varies based on riding conditions. According to Wilson (2004), three riding scenarios best describe the effects of P_{Drag}, P_{Slope}, and $P_{Friction}$. Firstly, at riding speeds less than 3 m/s on smooth, flat pavement, $P_{Friction}$ accounts for the greatest proportion of P_{Total}, with resistance mostly attributed to the frictional forces between bicycle tires and the road. Secondly, as riding speed increases beyond 3 m/s on smooth, flat pavement, P_{Drag} accounts for an increasingly larger proportion of P_{Total}. This relationship can be attributed to P_{Drag} being proportional to the square of V_g as shown in Eq. (2). Thirdly, as terrain slope increases and power input remains constant, riding speed decreases to a point where P_{Slope} overcomes P_{Drag} and accounts for the greatest proportion of P_{Total}.

In addition to different riding conditions it is important to note the effects of mass and frontal area when using Eqns. (2) through (4). Making PAEB system components such as motors, batteries, and controllers lighter will reduce overall mass and result in less frictional and slope resistance. Similarly, decreasing the frontal area and improving aerodynamics will result in less aerodynamic drag resistance.

Measuring human power output for use in bicycle propulsion is very difficult, as "people vary widely in performance, and unless very many are tested (as has seldom been the case), the data obtained through testing cannot be generalized to the whole of humanity" (Wilson, 2004). However, according to Rohloff and Greb (2004), "low speed commuting [is] normally less than 150 watts…200 watts average power is sufficient to propel a bicycle at over 32 km/h on level ground with no wind." This is consistent with the bicycle classifications presented by Muetze and Tan (2005), show in Figure 1.

"SPECIAL-PURPOSE BICYCLES"
City bicycle Fast acceleration, frequent stops Average power 150 W Average speed 17.6 km/h (11mph)
Hill bicycle High torque capability, Maximum power 300 W at 12.8 km/h (8 mph) for a short time corresponding to a (4 % slope grade)
Distance bicycle Designed for traveling at constant and comparatively low speed, but for a longer distance For example average speed 16 km/h (10 mph) at average power 100 W
Speedy bicycle Fast acceleration capability High speed capability 29km/h (18mph), Average power 200 W For example: guide bicycle in cycling competitions, vehicle for law enforcers

Figure 1. Comparison of bicycle types and average human input power and speed output. Adapted from Muetze and Tan (2007).

The current literature suggests a need to move away from fossil fuel based personal transportation technologies due to contributions to global warming and adverse human health impacts in urban environments. While the implementation of a practical urban transport vehicle powered completely by solar energy is not yet feasible, the integration of PAEBs with on-board solar power generation, and solar powered charging stations presents a promising outlook for future research and design.

VI. Method for Analyzing On-board Solar Power Generation

Based on the limited amount of reputable and reproducible experiments for this area of research, an investigation into the incorporation of solar power generation onto a typical bicycle was conducted. The basis of this investigation was to assess the solar power generating capability of an on-board solar panel for assisting the propulsion of a PAEB. The location of study chosen for this analysis was Elora, Ontario (Latitude = 43.68°, Longitude = 80.43°). Meteorological and solar irradiance data collected in 2006 from the Elora Research Station (ERS) was used to estimate the power generation capability of the solar panel used in the analysis.

The performance equations for bicycles discussed in Section V were used to establish the total power required, P_{Total}, for various riding conditions (i.e., various combinations of P_{Drag}, P_{Slope}, and $P_{Friction}$). This required power represents the power needed to maintain a determined ground speed (V_g). This power is a combination of human input and supplementary power provided by the on-board solar power generation system. An assumption was made that a minimum of 25% of the P_{Total} was to be supplied through on-board solar power generation in order for the system to be considered a worthwhile investment for existing PAEB users. Most PAEB modification kits are capable of providing 100% of P_{Total}, and a 25% increase in performance (e.g., speed, battery life per charge) would be considered desirable for existing PAEB users. This assumption was used throughout the analysis under differing riding conditions.

Section VII outlines definitions, provides clarification on system components used in the analysis, and states assumptions pertaining to these system components where information gaps exist. Section VIII analyzes the impacts of seasonal variation in ERS solar irradiance data and as well as identifies riding conditions conducive to increasing PAEB performance by at least 25%. In addition to determining favourable conditions for the designed solar system, Section IX presents methods for improving solar power generation.

VII. Parameter Definition and Assumptions for Analysis

Due to the vast range of parameters used in the performance equations, the detail of the ERS data, and the clarification of system components, various assumptions were made in addition to those documented in Section V to simplify this analysis.

A. PAEB Modification Kit

The eZee Bike Conversion Kit (PAEB modification kit) sourced from Grin Technologies Ltd. was chosen for this analysis. Unlike other PAEB systems, the eZee system allows for freewheeling (i.e., coasting without having to operate pedals). While this eliminates the possibility of incorporating regenerative breaking into the PAEB system, it provides no resistance during times where the electrical assist is turned off or not needed (e.g., downhill riding conditions). This modification kit was also chosen due to its adaptability to any bicycle and contains the following components (Grin Technologies Ltds., 2010):

- 400 W internally geared eZee brushless hub motor (3.72 kg)
- 20 amp motor controller (0.32 kg)
- 37 V 9 Amp-hour Lithium-Manganese battery (4.53 kg)

Ontario regulations governing power-assisted bicycles require the total system power to be less than 500 W and the total system mass (bicycle and accessories) to be less than 120 kg (MTO, 2010). All components of the PAEB modification kit comply with these regulations. The purpose of sourcing an existing PAEB modification kit was to accurately represent additional mass that would be added to the bicycle system. The frontal area of the PAEB modification kit was deemed to have a negligible impact on system performance based on the location of the components being within the existing bicycle frame or behind the rider. The PAEB modification kit used a lithium-ion (Li-Mn) battery, which is light in comparison to other battery types (e.g., lead-acid, nickel-metal hydride). Although the lighter mass of the lithium ion batteries helps reduce $P_{Friction}$, the higher cost of these batteries make their use less economically feasible.

The specific details of integrating the electronic components of the PAEB modification kit and the on-board solar panel were not analyzed in-depth. Beyond the requirements of a controller for both types of systems, it was generally assumed that the internal workings of these components would be compatible for applying propulsion to the PAEB through battery discharge and receiving solar energy through battery recharge. It should also be noted a bicycle is an extremely efficient energy converter of applied power to forward motion (Wilson, 1973). On this basis, inefficiencies of the bicycle itself were excluded from this analysis.

B. On-board Solar Power Generation

The solar panel chosen for this analysis was a SunWize SolCharger 24W panel ("solar panel" herein). This solar panel is commonly used for charging remote electrical devices, and is weather and impact resistant (SunWize Technologies, 2010). As such, the chosen solar panel was considered to be suitable for retrofitting a bicycle. The dimensions of the solar panel are 0.54 m by 0.34 m with a resulting surface area of 0.18 m^2. The maximum frontal area of the panel, 0.003 m^2, was calculated based on a panel thickness of 0.005 m and the longest panel dimension of 0.54 m. As such, the frontal area of the panel is not expected to impact system performance. The size of the solar panel was deemed feasible for attaching to a typical bicycle back rack in a horizontal position with minor modifications.

The ERS data contains only horizontal irradiance. As such, this analysis is limited to horizontal solar power production without consideration for changing solar panel slope (β) for increased exposure to solar radiation. Changes in bicycle orientation due to variable terrain slope or shading of the panel by the bicycle rider were not considered for this analysis. A solar panel efficiency of 13% was obtained from manufacturer specifications (SunWize Technologies, 2010). Potential system losses resulting from transfer inefficiencies between the solar panel, controller, and battery are acknowledged yet are excluded from this analysis.

C. Elora Research Station Irradiance and Meteorological Data

The 2006 ERS data used for this analysis consisted of irradiance data for a horizontal collection surface (i.e., slope ($\beta = 0$), and average wind speed (measurements taken at 2 m height). ERS solar irradiance was recorded using a pyranometer. Average hourly irradiance data was used for this analysis. Although obstacles present in bicycle riding environments may obstruct irradiance, all irradiation reported in the ERS data was assumed to be available for solar power production. As such, only the efficiency factor obtained from the manufacturer specifications was applied to the solar panel and used in this analysis.

Seasonal variations affect the amount of available solar energy. This limits the amount available for supplementary solar power generation used in bicycle propulsion. Assuming 13% of incoming solar radiation is converted to electrical energy by the 0.18 m^2 SunWize panel, the average hourly daytime solar power production was predicted for summer (June 1, 2006 – August 31, 2006) and winter (December 1, 2006 – February 28, 2006) (Figure 2). In addition, hourly solar production for June 21, 2006 (summer solstice) and December 21, 2006 (winter solstice) are also shown in Figure 2 to depict times of extended and shortened exposure to the sun based on solar position. The average daytime solar power generation was 9.87 W for the summer and 2.85 W for the winter. It is important to consider transient weather effects (e.g., cloud cover) when looking at individual days, as they can have a significant impact on solar irradiance received by the solar panel at a specific time. This may explain the significant drop in power production on the summer solstice as this time of year is expected to have the longest exposure to the sun throughout the year. The average solar power generation on the summer solstice was 8.35 W, lower than the summer average power generation. The analysis in the following sections uses the average summer daytime irradiance values for estimating potential solar power generation unless otherwise noted.

It is important to note not only the higher power production observed during the summer, but also the longer power generating hours. On average, power is generated during all daytime hours throughout the summer whereas the winter months experience an average of approximately 2.5 power-production hours less per day (Figure 2).

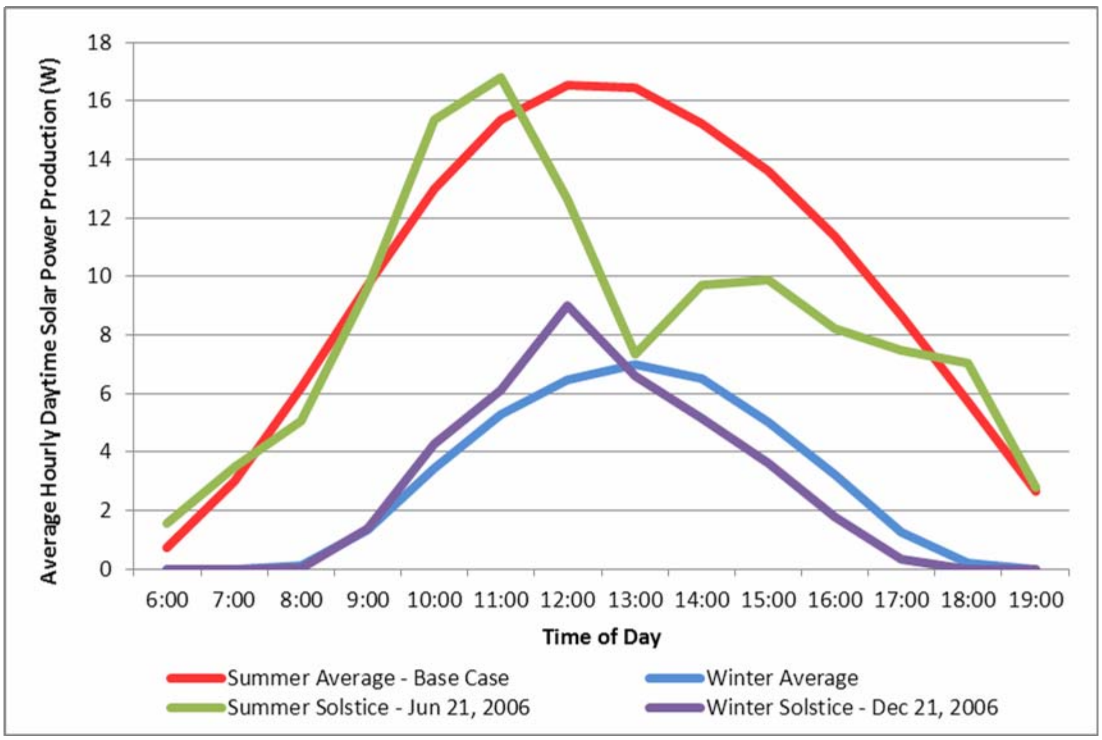

Figure 2. Comparison of expected solar power generation for ERS summer and winter months and for summer and winter solstices

ERS wind speed data was used to determine a typical average wind speed for Elora. Despite winds typically blowing from the southwest (W.D. Lubitz, personal communication, November 11, 2010; Wallace & Kanaroglou, 2007), localized wind effects were assumed to be quite random due to obstructions and the typical timescale of a bicycle ride. The typical average wind speed was applied in the worst-case scenario, where 100% of the wind speed is attributed to headwind to see the effects on the total power required.

An additional environmental parameter that was required for this analysis is the typical air density. Air density was needed to determine power losses due to aerodynamic drag. To obtain the air density, the ideal gas law was rearranged for density and the air was assumed to be dry:

$$\rho = \frac{p}{RT} \qquad (5)$$

The elevation of Elora is 381 metres above sea level (masl). The associated average pressure at 381 masl is 96.8 kilopascals (Engineering Toolbox, 2010). An average daytime temperature for 2006 from the ERS data was calculated to be 9 °C. The resulting air density used for this analysis is 1.20 kg/m^3.

D. System Mass

A study conducted between 1999 and 2002 in the United States presented the national mean body masses for adult men and women over the age of 20. The reported mean body masses from the study were 86.1 kg for men and 74 kg for women (Ogden, Fryar, Carroll, & Flegal 2004). For the purpose of determining power losses of a bicycle, the heavier rider mass of 86.1 kg was used for a more conservative estimate. In addition to rider mass, the mass of other previously identified system components such as the bicycle, solar panel, and the PAEB modification kit (i.e., motor, battery, and controller) are required to accurately determine resistances to bicycle propulsion. The standard bicycle used in this analysis was a 21-speed 2009 Norco Mountaineer. This bicycle is designed for light trail and city riding and has a mass of 14.5 kg (Norco Performance Bikes, 2010). The mass of the solar panel is 1.68 kg and was obtained from manufacturer specifications (SunWize Technologies, 2010). The total mass of the PAEB modification kit was 8.57 kg. As such, the mass of the total system is 110.9 kg.

E. System Summary

A summary of system components, parameters, and constants are summarized in Table 1.

Table 1. Summary of PAEB system components

System Parameter	Value	Units
PAEB Modification Kit		
Hub Motor	3.72	kg
Battery	4.53	kg
Controller	0.32	kg
Bicycle		
Norco 2009 Mountaineer	14.5	kg
Solar Panel		
SunWize SolCharger 24W	1.68	kg
	0.18	m^2
Rider		
Average Rider	86.1	kg
Performance Equations for Bicycles		
Drag Coefficient (C_d)	1.15	-
Rolling Coefficient (R_c)	0.006	-
Frontal Area (A)	0.55	m^2
Air Density (D)	1.20	kg/m^3
Gravity (g)	9.81	m/s^2

VIII. Performance Evaluation for PAEB with On-board Solar Power Generation

Based on the defined PAEB system, an analysis of the PAEB solar power generation system can be conducted. The following section establishes a base case riding scenario and investigates the impact of parameter variation on the ability for solar power to provide 25% of P_{Total}.

A. Base Case Riding Conditions

The base case was designed to analyze system performance under as little influence from system parameters as possible. As such, riding conditions were not subject to wind ($V_w = 0$) or uneven terrain ($G = 0$). In addition, the sustained speed by the rider was chosen to be 17.6 km/h, consistent with the typical city riding speed (Muetze and Tan, 2007). The calculated average summer solar power generation was 9.87 W for the 0.18 m^2 solar panel area at a solar panel efficiency of 13%. An average solar power generation for the entire summer was used based on the irregular weather behavior due to cloudiness or other unpredictable conditions on any given day. Daytime refers to values collected between 6 am and 7 pm for each day of the summer. The summer season was chosen to depict a time of the year with most consistent irradiance. Equations (2) through (4) were used with the base case riding conditions to calculate a P_{Total} of 76.24 W. Breaking P_{Total} into its components, 58% of power losses are attributed to P_{Drag} and the remaining 42% to $P_{Friction}$. Table 2 summarizes the base case riding conditions.

Table 2. Summary of base case riding conditions

System Parameter	Value	Units
Ground Speed (V_g)	17.6	km/h
Headwind (V_w)	0	km/h
Rider Mass	86.1	kg
System Mass	24.75	kg
Slope (G)	0	%
P_{Total}	76.24	W
Average Summer Solar Power Production	9.87	W

It can be observed that the power supplemented by the on-board solar panel during the summer months was on average 13% of P_{Total}, with a peak solar power generation of 22% at midday (Figure 3). The time of the day typically used for bicycle commuting, morning and evening received less solar irradiance. On average, the designed PAEB did not attain 25% of P_{Total} on flat terrain, with no wind, while maintaining a sustained city biking speed of 17.6 km/h (Figure 3).

Based on the average base case discussed, limited application exists for on-board solar power generation on a PAEB given the irradiance data for the location. Further investigation for identifying specific riding conditions that satisfy a 25% production of supplementary power was conducted and is presented in Section VII. In addition to real-time solar power generation, the use of the solar panel for daytime charging is discussed in Section IX.

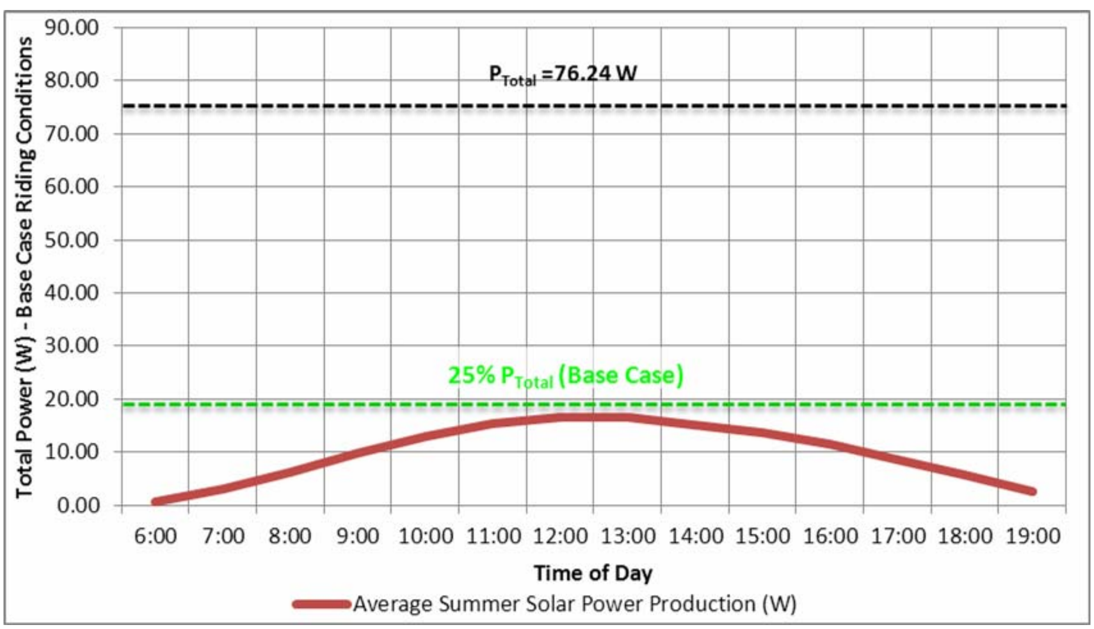

Figure 3. Average summer solar power generation and total required power under base case riding conditions.

B. Sloped Terrain Performance Analysis

Using the base case riding conditions, the effects of terrain slope on P_{Total} were analyzed. Terrain slopes used for this analysis included both uphill and downhill riding conditions, with G values ranging from -1% to 4%. A linear relationship was observed between terrain slope and P_{Total} for the specified G values. As G values increase, P_{Slope} (and subsequently P_{Total}) also increase. The feasibility of solar power production accounting for 25% of P_{Total} only occurs for downhill terrain slopes. For a slope of G = -1%, the on-board solar power generation of 9.87 W supplements 43% of P_{Total} while maintaining the base case riding speed. Any downhill G values representing a slope steeper than or equal to –2% produce significant negative power losses (i.e., power gains), which overcome any losses attributed to P_{Drag} and $P_{Friction}$. The desired slope characteristics that could supply a sufficient proportion of P_{Total} through solar power will not be constant during typical riding conditions, especially on two-way bicycle rides.

C. Ground Speed (V_g) and Headwind (V_w) Performance Analysis

The solar panel was unable to supply 25% of P_{Total} at the base case riding condition of V_g = 17.6 km/h, which is a typical speed for city bicycling. A range of base case riding conditions with reduced V_g values was then analyzed to examine system performance. V_g values larger than 17.6 km/h were also included to observe P_{Total} at the maximum allowable PAEB road speed of 32 km/h in Ontario (MTO, 2010). The results summarizing the effects of V_g on P_{Total} are shown in Figure 4. Figure 4 also depicts the maximum value for P_{Total}, 39.48 W, for which 25% of P_{Total} can be supplied by the on-board solar panel. All V_g values less than or equal to approximately 12.5 km/h have a corresponding P_{Total} less than this threshold value, and thus can provide at least 25% of P_{Total} by solar power generation. Based on this analysis, the designed system was found to be more feasible for lower ground speeds.

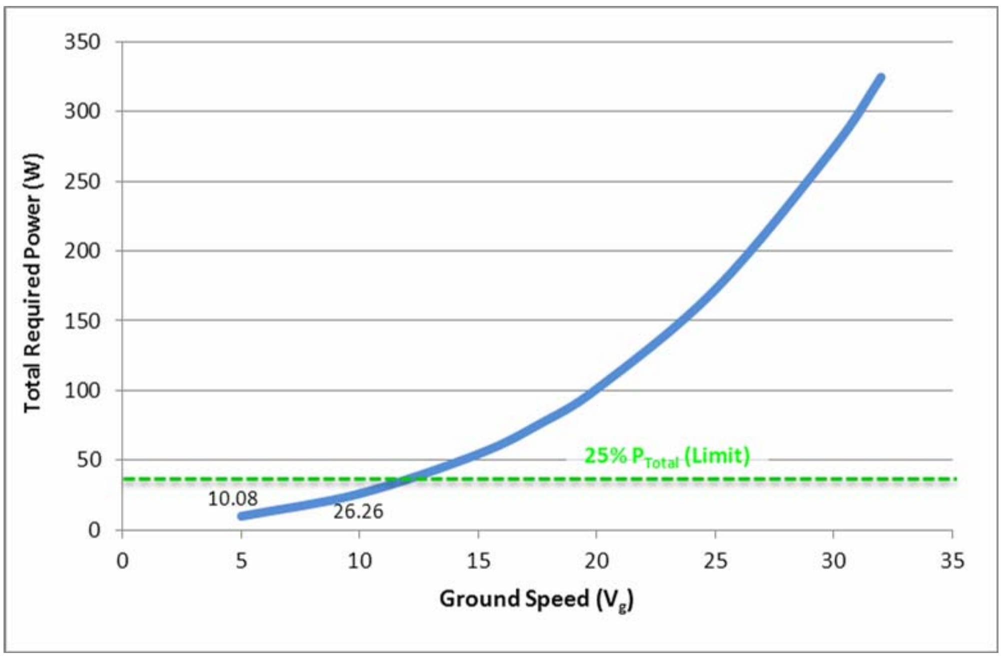

Figure 4. Effect of ground speed (V_g) on base case riding conditions.

Based on Eq. (2), the effect of V_w on the system performance is slightly different compared to V_g. For this analysis, various combinations of V_g and V_w each equaling 5km/h, 10km/h and 15km/h were compared (Figure 5). An average daytime wind speed of 12.6 km/h at a 2 m height was calculated from the ERS data and used for choosing an appropriate range for the aforementioned headwind speeds. It should be noted that localized wind speeds could be quite different than the ERS data used and are likely to be lower due to the effects of obstacles (i.e., trees, cars, buses, buildings, etc.) present during typical city riding conditions. At V_g = 5 km/h, sufficient solar power generation was observed at all V_w values, ranging between 39% and 75% of P_{Total}. At V_g = 10 km/h, sufficient solar power generation was observed for V_w = 5 km/h, comprising of 27% of P_{Total}. P_{Total} at V_g = 15 km/h was not met by sufficient solar power generation for any V_w values. As a result, the designed system has the potential to supply sufficient power through solar generation for various wind speeds at low corresponding ground speeds.

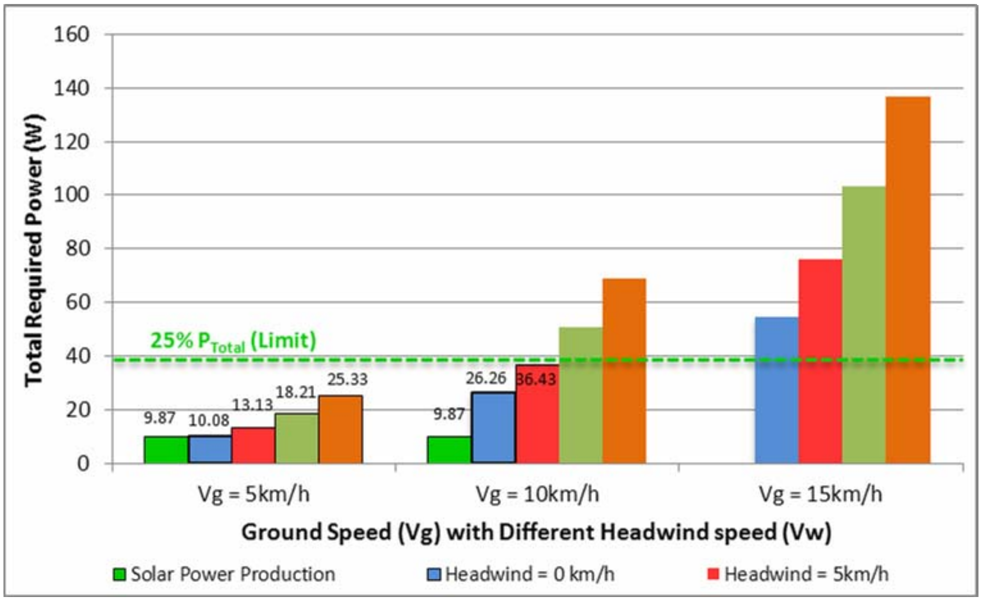

Figure 5. Effects of ground speed (V_g) with differing headwind speeds (V_w).

D. Rider Mass Performance Analysis

The base case riding condition for the total system mass was an 86.1 kg rider and a total PAEB system mass (bicycle, solar panel, and PAEB modification kit components) of 24.75 kg. The effects of altering total system mass between the range of 75 kg and 125 kg were examined at various V_g values. It should be noted that rider mass does influence the frontal area; however, due to the high variability in this system parameter it was omitted for this analysis. Results are presented in Figure 6. At V_g = 5 km/h, sufficient solar power generation was observed at all system masses, ranging between 88% and 138% of P_{Total}. At V_g = 10 km/h, sufficient solar power generation was also observed at all system masses, ranging between 35% and 48% of P_{Total}. P_{Total} at V_g = 15 km/h and the base case ground speed of 17.6 km/h were not met by sufficient solar power generation for any system mass values. Small differences were observed between P_{Total} values at low V_g values and varying system masses. As such, the total system mass has a relatively small effect on P_{Total} compared to the effects of P_{Drag}, which increases as V_g values increase.

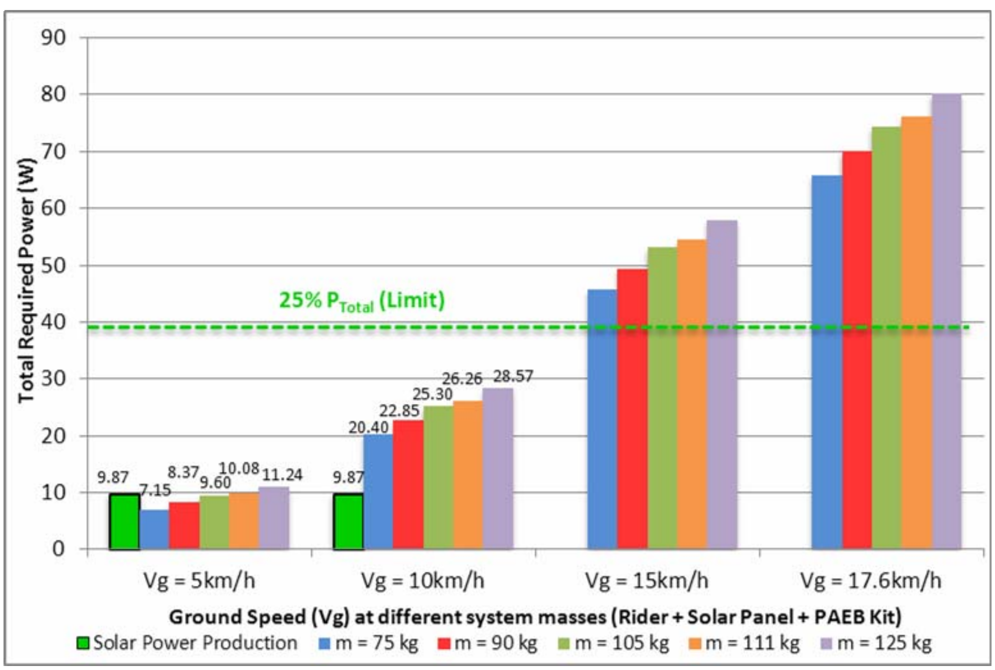

Figure 6. Effect of rider mass (m) at differing ground speeds (V_g).

IX. Extension of Applicability of On-board Solar Power Production

The analysis presented in Section VIII aimed to identify riding conditions conducive to supplementing 25% of P_{Total} through solar power generation. Favourable results were limited to very specific riding conditions, which realistically would not be constant during a typical bicycle ride. Nevertheless, an understanding of the effects of various system losses (P_{Drag}, P_{Slope}, and $P_{Friction}$) was valuable in acknowledging how P_{Total} changes under differing riding conditions using local solar and meteorological data. It is important to note that analysis thus far has focused on real-time solar power generation for the designed PAEB system. Opportunities of daytime battery recharge using the designed PAEB system as well as possibilities for expanding solar panel area are investigated in this section to see if possible improvements in the applicability of on-board solar power generation may be achieved.

A. Solar Power Generation for Battery Charging

In contrast to utilizing on-board solar power generation in real-time during riding, solar energy can also be stored by recharging the battery of the PAEB system when it is not in use. The ability for the solar panel to recharge the battery is based on the current it sends to the controller. The rated power and current for the solar panel is 24 W and 1.24 A, respectively, under testing conditions of 1000 W/m^2 (SunWize Technologies, 2010). The actual power produced by the solar panel is based on the average hourly summer daytime irradiance data shown in Figure 2 and **Error! Reference source not found.**. Equation (6) was used to calculate the actual current being sent to the controller at each hour during the day:

$$I_{Actual} = (P_{Actual} / P_{Rated})\, I_{Rated} \qquad (6)$$

The resulting hourly daytime current distribution follows the same distribution as the average hourly summer daytime irradiance due to P_{Actual} being directly proportional to I_{Actual}. As such, the rate at which the battery can be recharged also follows this distribution, where more power will be restored to the battery during midday hours than at the start or end of the day. The total amount of energy restored to the battery over the course of a typical summer day is 138.20 Watt-hours (Wh). This was calculated by adding all of the power generation over the course of the 14-hour analysis period (i.e., 6 am to 7 pm).

The total amount of energy able to be stored in the PAEB modification kit battery is 333 Wh and was calculated by multiplying the rated battery voltage (37 V) by the rated battery amp-hours (9 Ah). As such, a full day of solar charging using the on-board solar panel is expected to recharge approximately 42% of the battery. Figure 7 depicts the required power for different trip distances at the base case riding speed of 17.6 km/h and a sustained power requirement of 76.24 W. If 100% of P_{Total} is supplied by the battery (i.e, no human input), a trip distance of approximately 75 km can be achieved on a battery initially fully charged. Trip distances of 30 km and 130 km can be achieved when limiting trip energy requirements to less than the amount able to be recharged in one day (138.20 Wh) for 100% battery supplied power and 25% battery supplied power, respectively. It is important to note that this analysis does not include additional solar power generated over the duration of the trip while riding.

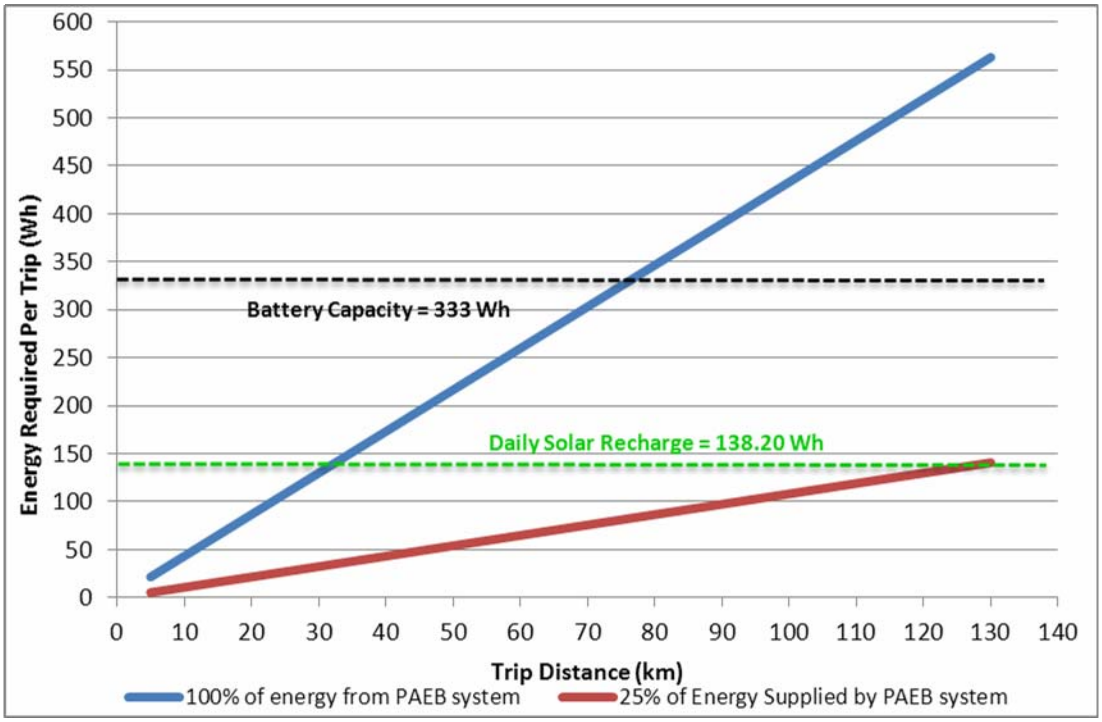

Figure 7. Comparison of required energy under base case riding conditions for varying trip distances supplying 100% and 25% of P_{Total} using battery power.

B. Solar Trailer

The size of the initial solar panel used in the analysis was selected based on the space limitations of the bicycle. Since insufficient solar power generation was achieved for typical city riding conditions, an analysis of applying the base case riding conditions to different sizes of solar collection surfaces irrespective of typical space restrictions of the bicycle was conducted. The characteristics of the existing solar panel (i.e., panel efficiency and mass) were retained for this analysis and scaled appropriately for each solar collector area.

The use of a bicycle trailer towed behind the PAEB was approximated in mass and dimensions to accommodate the expansion of available surface area for solar power generation A study conducted by Landis et al (2004) looked into the application of existing regulations for bicycles to the emergence of new types of land based vehicles not adequately classified by cars or bicycles. Included in the study were average dimensions of actual trailers recorded as a part of multiple data collection events. The average trailer length and width reported in this study were 2.9 m and 0.66 m, respectively, resulting in an area of approximately 1.92 m^2.

The solar collector areas chosen ranged between the area of the existing solar panel (0.18 m^2) and the area defined by the average trailer dimensions, approximated at 2 m^2. The approximate mass of a two-wheel trailer was found to be 5kg (Carry Freedom, ND). The additional frontal area provided by the trailer was assumed to be 0.3 m^2. The frontal area of the trailer was not deemed to provide the same magnitude of aerodynamic losses as the bicycle and rider due to the trailer being in the wake of the bicycle. The expected system improvements can be attributed to significant increases in solar collection area with only minor increases in system mass and aerodynamic drag (Table 3).

Table 3. Summary of additional mass for increasing solar collection surface area.

Solar Collection Area (m^2)	Additional System Mass (kg)[1]	Total System Mass (kg)
0.18	0	111.0
0.5	7.8	118.8
1.0	12.5	123.5
1.5	17.2	128.2
2.0	21.8	132.8

Notes: 1 - Trailer Mass + Solar Panel Mass

The solar power generation and P_{Total} corresponding to the different solar collection area sizes is shown in Figure 8. All cases of increased solar collection area supplemented P_{Total} by greater than 25%. With a solar collection area of 2 m^2, the quantity of solar power produced surpassed P_{Total}, thus providing 100% of P_{Total} using solar energy. While the mass of additional solar panels only slightly increases $P_{Friction}$, it is evident that additional solar panels create significant benefits to solar power generation. Disadvantages to this design include the increase in size of the system that could limit maneuverability and system appeal to existing PAEB riders.

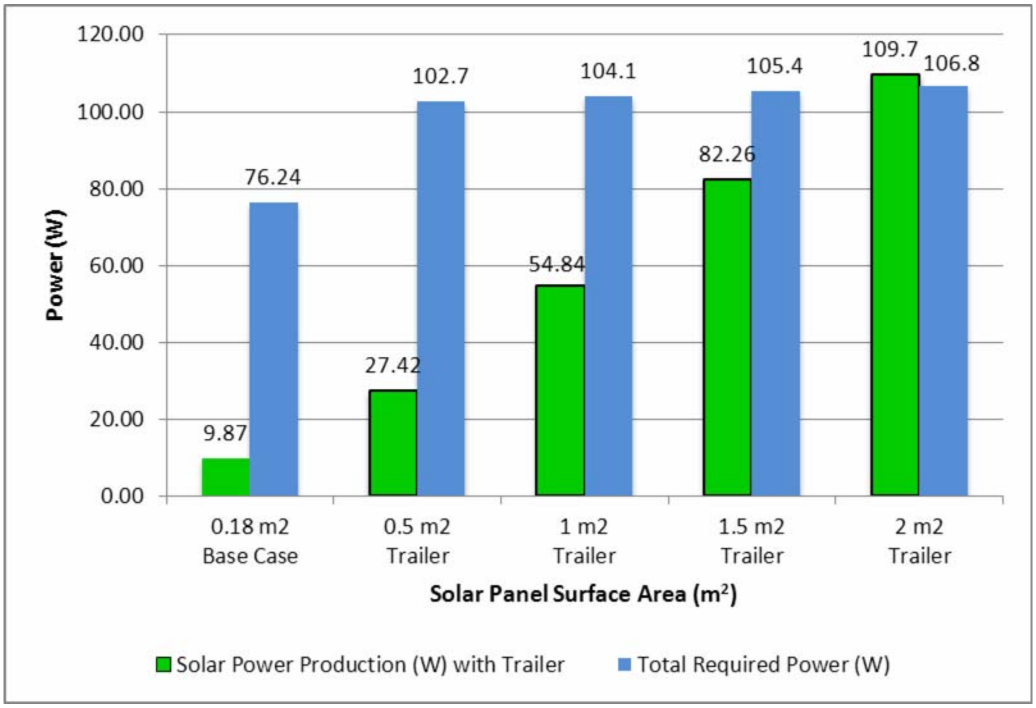

Figure 8. Effects of increasing solar panel collection area using a bicycle trailer under base case riding conditions.

X. Conclusions

On-board solar power generation using the Elora Research Station solar irradiance data supplied only 13% of the required power for typical city riding conditions excluding the effects of wind and uneven riding terrain. Riding conditions that provided greater than 25% of the required power through on-board solar power generation were primarily limited to ground speeds (V_g) much slower than typical city riding speeds. The use of on-board solar power generation is a viable option for recharging the system battery. One full day of solar charging replenishes 138.20 Wh (approximately 42% of battery capacity), which is sufficient to supply 100% of P_{Total} for trip distances up to 30 km. The use of a two-wheeled bicycle trailer adds significant solar power generation capabilities; however, the increase in overall system size limits the practicality of a compact bicycle system for city use. Future considerations for research include incorporating solar irradiance data that accounts for different solar panel orientations (i.e., β greater than 0) and applying this analysis in other geographical locations of known solar irradiance. While on-board solar power generation appears to be a viable alternative for offsetting environmental pollution of rising PAEB use, this technology requires further development to optimize the direct use of solar power during riding. However, using on-board solar power generation for recharging system batteries while not in transit is feasible for reducing dependency on the conventional power grid.

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