Abstract—Environmental sustainability is multi-dimensional in nature, and has been addressed through its various facets over the years. It is only through such concerted and consistent effort that environmental sustainability can be achieved. We consider one such facet - that of transportation. Specifically, we consider bicycles and the role they play in minimizing related carbon footprint. Through use of IoT (Internet of Things) and social media, we illustrate how a ‘network’ of bicyclists can further reduce transportation carbon footprint and address environmental sustainability. We study the contractual mechanisms that could maximize carbon emission reduction through shared bicycle usage. Our results show that increased carbon emission cost increases shared bicycle usage, while harsh biking environment negatively impacts the shared bicycle program and thereby related carbon footprint. We also show that it’s more efficient to offer shared-bicycle users reduced rental fee or offer free service for long distance travels.

Keywords: Bicycle Sharing, Social Media, Quantified Self, Environmental Sustainability, IoT

I. INTRODUCTION

Bicycles and their general ecosystem have not witnessed any major disruptions until recently with the integration of sensors (e.g., GPS). Before such electronics became commonplace on bicycles, the bicycle rider received minimal feedback and related useful information (e.g., current location) to be able to adjust the speed, etc. to, for example, get to the destination on time. With the ready availability of sensors (e.g., Bridgelall 2015) as well as means to connect bicycles to the Internet, the bicycle rider is now able to receive real-time feedback as well as be knowledgeable on the current status/information on where the bicycle is, if everything (e.g., tire air pressure) is OK with the bicycle and the rider, among others.

With the widespread availability of social media, connected bicycles can now interact in real-time with other bicycles and bicyclists. Similar to connected automobile, the concept of connected bicycle is seen to be beneficial to both the bicycle rider and the overall system in terms of both environmental sustainability, provision of instantaneous status (e.g., mechanical systems) of the bicycle and its rider, etc. The synergistic interplay between social media and connected bicycles through advances in Internet of Things (IoT) has the potential to generate more usefulness with minimal cost in terms of convenience, environmental impact, among others. Such IoT devices also have the potential to deliver instantaneous feedback on the bicycle’s state (e.g., brake pad wear) in real-time.

While connected bicycles can independently communicate with external entities (e.g., other connected bicycles) to generate synergies, widespread availability and use of such bicycles are a few years away in the future. In the meanwhile, shared-bicycles that exhibit some of the features of connected bicycles such as the ability to be seamlessly shared among riders, knowledge of the status of some its maintenance components (e.g., working pedals), among others, are already in wide-spread use across several cities around the world.

We therefore consider bicycle sharing, specifically from a social media perspective, and illustrate how a set of shared bicycles together generate synergies in the presence of social media. To put the issue in perspective, we first provide a brief discussion on IoT and quantified self as they relate to shared bicycles. We then discuss bicycle sharing. From an environmental sustainability perspective, bicycle sharing programs provide visibility of the underlying dynamics to help facilitate the reduction of negative incidents such as accidents and higher carbon footprint - all through the use of social media and their variants. We also derive
the conditions when bicycle sharing is preferred.

Given the paucity of published research papers on the synergies between bicycle-sharing and social media as they relate to environmental sustainability, our main purpose in this paper is to raise awareness and to urge researchers to study the dynamics present in this important intersection area. A secondary purpose is to gather related discussions together in one place.

The remainder of this paper is organized as follows:
We provide a brief discussion on IoT and quantified self in Section II. With this basic background knowledge, we then discuss bicycle-sharing in Section II. We then put these together in Section III on social media and shared bicycles. In Section IV, we consider shared-bicycle systems and some of its dynamics from an environmental sustainability perspective. We discuss our results and conclude the paper in Section V.

II. IoT, Quantified Self, & Bicycle Sharing

The Internet of Things (IoT) comprises ‘things’ that are connected through a network, which ultimately forms the Internet. These ‘things’ themselves are entities with the ability to communicate with other entities. At this point in time, a majority of these entities are passive RFID (Radio-Frequency IDentification) tags that have the ability to communicate with RFID readers (Zhou 2009), which then can readily be connected with the Internet (Manyika et al. 2015).

The relevance of IoT to the shared-bicycle ecosystem is through sensors that are not uncommon in these bicycles. These sensors can then be connected to the Internet through connected bicycle docking stations.

A related concept is quantified self, which is the general idea of measurement of data about oneself. For example, in a shared-bicycle context, a quantified self measurement could include the approximate amount of time spent cycling - this is readily available since almost all bicycle sharing systems keep track of check-out and check-in times. Quantified self is significant in the bicycle sharing ecosystem since its users have a high likelihood for observation of a (even if small) subset of their quantified self numbers.

The increase in overall bicycle use is directly or indirectly due to a general trend on increased preference for residential accommodation that allows for walking, is close to public transportation, social and other activities, work, school, or entertainment. This preference is apparently pronounced (Table I) among the so-called Generation Y or Millennials, namely the generation cohort born in the 1980s and 1990s (Urban Land Institute 2013).

In a recent Roland Berger report, Freese and Schönberg (2014) estimate the shared-bicycle market to reach 3.6-5.3 billion Euros by 2020. Shared-use mobility complements traditional fixed route transit, and includes tools and services that facilitate shared transportation means. Some of these services include bicycle sharing, car sharing, as well as other shared ride services that are generally initiated through the Internet (Filler 2014). Based on convenience as well as constraints, the use of shared transportation has increased significantly over the past several years. While the transportation mode used certainly is not new, what is new are technological advances such as those related to social media which facilitate ease of connection among all stakeholders in this general ecosystem. These stakeholders are interested in the convenience provided by shared transportation as well as the efficiency and effectiveness with which supply and demand are matched in this ecosystem with several transportation choices.

While affordability and convenience are essential for the continued growth of shared transportation, the inconveniences associated with traditional fixed route transportation as well as congested commutes, extremely constrained funding for public transportation, declining car ownership rates, and the sheer lack of sufficient parking facilities in urban areas have certainly helped push its steady growth.

Among the shared transportation modes, bicycle-sharing has been increasing in popularity in urban...
areas for short trips. A majority of bicycle-sharing systems use a network of locations in which a bicycle can be either picked up or dropped off. Recent advances and widespread use of IoT technologies such as RFID (Radio Frequency IDentification) that include smartcards, magnetic fobs, among others, as well as wireless technology provide necessary infrastructure to rent out or return bicycles respectively at a nearest facility with available bicycles or docking space.

The use of information systems and technology in automated self-service kiosks facilitates the smooth operation of most bicycle-sharing systems. Such systems now exist in several cities around the world. For example, bikes.oobrien.com lists 151 cities around the world that have bicycle-sharing systems in use, and www.bikesharingmap.com lists several of these bicycle-sharing systems on a world map (e.g., Capital Bikeshare 2014, Shaheen 2014). A majority of these systems operate with short-duration rentals that span a few minutes to a few hours, while multiple day and weekly rentals are generally less common in most bicycle-sharing systems.

In the past few years, the number of bicycle-sharing systems has expanded rapidly all over the world. It has become quite popular given its simplicity and convenience. However, its further growth depends in large part on the existence and maintenance of well-connected network of bicycle routes that cover all parts of the city or town of interest as well as the management of increasingly crowded multi-modal traffic streams. Given that bicycle-sharing is relatively inexpensive, easy to use, and convenient, the perception of safety despite their use of shared and overcrowded roads is of paramount importance.

III. Social Media & Bicycle-sharing

In a sense, social media has the potential to extend the connectedness of shared bicycles. Data gathered through social media as the connection point among bicycles as well as bicycle riders are generally richer than those generated solely from hardware. For example, IoT nodes situated along the street can automatically update the status of that street for uninterrupted and smooth flow of bicycle traffic. Likewise, a quantified self sensor can trigger an alarm through related social networks when something is amiss with the bicycle, its rider, road conditions, among others. Information on the current status of the bicycle (e.g., flat tire) can also be used to recommend nearby service locations as appropriate and necessary. Through social media, a bicycle-sharing service can broadcast the instantaneous status of a service location that include the number of bicycles that are available for immediate rental, the number of available docking spaces for returning bicycles, the general traffic conditions for bicycles and automobiles near that location, the length of current waiting-list when appropriate, among others. This information can be utilized to automatically suggest the best bicycle-sharing service nearby.

Given the directionality of streets, the source and the destination for a trip, a shared (and possibly connected) bicycle rider can be informed of the most appropriate directions to take in order to satisfy some objective (e.g., shortest distance route, scenic route, routes with dedicated bicycle lanes). With necessary information from other sources and the social media, the potential demand in a few days at a given bicycle rental service location can be estimated and appropriate actions can be taken before-hand (e.g., arrange for more bicycles to be transported to this location the night before) when a spike in demand is expected.

In terms of environmental sustainability, a related social media application or the shared bicycle can suggest the most efficient next action (e.g., return/rent bicycle to/from nearest service location, visit with a social media friend who is at a nearby service location). Shared bicycles can also use the social media to obtain timely help. For example, receive advice from other bicyclists on issues related to one’s connected bicycle in real-time through social media.

While the benefits that arise from synergy between social media and shared bicycles is clear, several questions beg to be studied. For example, to minimize the carbon footprint associated with travel from a predetermined source to a pre-determined destination, under what conditions is it preferable to use a shared bicycle? What characteristics of the issue at hand (e.g., traffic congestion) should more weight be placed on information retrieved through social media as a source? Do social media accounts that are directly or indirectly useful for connected bicycles get some sort of credit? A related question is, since information generated through social media and connected bicycles form a continuum with a sequence of decisions as well as helpful nodes that lead to an action item, how should credit assignment be handled? How should associated privacy concerns and legal issues be addressed (Eckhoff and Sommer 2014, Kohler and Colbert-Taylor 2015)? And, so on. We briefly consider
one of these in the next section.

IV. Analysis

In a shared bicycle program, such as Vélib' in Paris, bicycles are parked across various locations in and around the city. The dispersion of these bicycle locations determines the service coverage. Clearly, a set of important parameters determines the success of any such bicycle-sharing program with a large number of active customers. First of all, it’s the rental cost \( c \) that can be determined as a function of travel distance \( d \) utilized by the bicyclists. A shared-bicycle renter enjoys an individual welfare \( w \) from using the bicycle, for example through supplanting walking, increasing travel speed, tourism coverage, among others.

We use the following notations:

- \( d \): travel distance
- \( c \): rental cost per km of shared bicycle use
- \( s \): carbon cost per km of driving
- \( w \): individual welfare per km from riding bicycle
- \( a \): carbon cost savings per km traveled by bicycle
- \( \theta \): the share of carbon cost savings that is given back to the customer
- \( e \): physical attenuation of bicycle rider per km
- \( n \): number of shared-bicycle customers
- \( i \): \( i \)th shared-bicycle customer
- \( k \): bicycle rider’s physical attenuation speed
- \( V \): reservation profit per customer
- \( U \): reservation utility of a bicycle renter

For a shared-bicycle customer \( i \), individual welfare can be written as that from riding bicycles in km and his share of of carbon cost savings less the rental cost.

We define the physical attenuation function as \( e = (d_i)^k \), where \( k \) is the parameter that determines the attenuation speed. A prospective bicycle renter would choose to use the shared-bicycle option if he receives positive welfare, such that

\[
W_i \geq 0
\]

And the theoretical maximum possible benefit for using the bicycle can be found by taking the first and second order derivatives of \( W \) (\( \partial W/\partial d_i \) and \( \partial^2 W/\partial d^2_i \)), and occurs when:

\[
d_i^* = \sqrt[2-k]{\frac{w + \theta a - c}{k}}
\]

The customer chooses to travel by bicycle instead of other transportation means or even walking if \( (w + \theta a - c)d_i - (d_i)^k \geq 0 \). Consequently,

\[
d_i \leq \sqrt[k]{w + \theta a - c}
\]

When the shared-bicycle program designs its pricing structure, the above constraint is equivalent to:

\[
c \leq w + \theta a - (d_i)^{k-1}
\]

A bicyclist’s individual welfare without considering savings related to carbon cost is:

\[
W_0 = wd_i - cd_i - e(d_i)
\]

and the optimal usage is:

\[
d_0^* = \sqrt[2-k]{\frac{w - c}{k}}
\]

We find that carbon cost saving incentive affects optimal distance traveled during shared-bicycle usage by

\[
d_i^* - d_0^* = \sqrt[2-k]{\frac{w + \theta a - c}{k}} - \sqrt[2-k]{\frac{w - c}{k}}
\]

Theorem 1: Increased carbon cost savings increases the usage of bicycle-sharing services.

Proof: According to (10), the average usage of shared bicycle program increases by \( \sqrt[2-k]{\frac{w + \theta a - c}{k}} - \sqrt[2-k]{\frac{w - c}{k}} \), which strictly increases with carbon cost savings.

Theorem 2: Harsh bicycle riding environmental conditions negatively impact bicycle-sharing program use.

Proof: According to (10), the average usage of shared bicycles decreases when \( k \), the degree of biking harshness or the bicycle rider’s physical attenuation, increases.
A. Optimal Bicycle Sharing Mechanism

In an optimal bicycle sharing setup, a firm carefully designs its bicycle sharing program with respect to appropriate rental cost $c$ and the percentage of carbon emission savings ($\theta$) to share with the customers. The maximization problem is:

$$\text{Maximize}\{P\}$$ (11)

Subject to:

$$(w + \theta a) d_i - c d_i - e(d_i) \geq U$$ (12)

where $U$ represents the reservation utility of a shared-bicycle customer. It forms the participation constraint. The Lagrangian for the bicycle-sharing service provider ($L_P$) is given by:

$$(c + (1 - \theta) a - b) d_i + \lambda [(w + \theta a) d_i - c d_i - e(d_i) - U]$$ (13)

The first order condition over the carbon emission cost savings sharing program $\theta$ is:

$$\frac{\partial L_P}{\partial \theta} = - a d_i + a d_i \lambda = 0$$ (14)

$$\Rightarrow \lambda = 1$$ (15)

Theorem 3: An optimal bicycle-sharing mechanism that maximizes the bicycle-sharing firm’s profit is characterized by $a = b - w + kd_i^{k-1}$.

Proof: The first order condition over the shared-bicycle customer’s usage $d_i$ ($\frac{\partial L_P}{\partial d_i}$) is:

$$(c + (1 - \theta) a - b) + \lambda [(w + \theta a - c)] - kd_i^{k-1} - U]$$ (16)

$$\Rightarrow a = b - w + kd_i^{k-1}$$ (17)

B. Government Direct Incentive Mechanism

The previous results show the optimal mechanism that would increase shared-bicycle rental company’s profit $P$. In an ideal society, we would like to maximize the total carbon emission cost reduction savings $Z$. The government directly designs the contract to distribute the carbon emission savings from bicycle usage to both shared-bicycle renting firms and shared-bicycle customers. The maximization problem is now:

$$\text{Maximize}\{Z\}$$ (18)

Subject to:

$$(w + \theta a) d_i - c d_i - e(d_i) \geq U$$ (19)

$$[c + (1 - \theta) a - b] d_i \geq V$$ (20)

$$\text{where} \ V \text{represents the reservation profit per customer for the shared-bicycle renting firm. These two equations represent the participation constraints for both shared-bicycle customers and the shared-bicycle renting firm. By conditioning on constraints (19) and (20) that both players receive at least their minimum acceptable incentives, we form the Lagrangian for total carbon emission reduction as:}$$

$$L_Z = ad_i + \mu [(c + (1 - \theta) a - b) d_i - V] + \lambda [(w + \theta a) d_i - c d_i - e(d_i) - U]$$ (21)

The first order condition over the carbon emission savings sharing program $\theta$ is:

$$\frac{\partial L_Z}{\partial \theta} = -\mu d_i + a d_i \lambda = 0$$ (22)

$$\Rightarrow \mu = \lambda$$ (23)

Theorem 4: In an optimal regulated mechanism, the carbon emission cost savings is shared with the firm as maximum $\{0, \frac{c + a - b}{a}\}$.

Proof: According to the shared-bicycle renting firm’s participation constraint, $P \geq 0$, so $\frac{c + a - b}{a} \geq 0$. The individual rationality constraint of a shared-bicycle customer indicates that he will maximize the bicycle usage if he receives the highest possible incentive. Because the first order condition of the bicyclist’s utility, $\partial W / \partial d_i = w - c - kd_i^{k-1} + \theta a$, is strictly increasing with $\theta$, it is rational to maximize $\theta$ in order to optimize total carbon emission.

Theorem 5: Under the following circumstances, $d_i \geq \frac{w + \theta a - c}{k}$ and $\frac{c + a - b}{a} \geq 0$, it is rational to reduce the rental cost, offer shared-bicycle rental for free, or provide monetary pay-back to shared-bicycle customers.

Proof: $d_i \geq \frac{w + \theta a - c}{k}$ represents the threshold distance for a bicycle traveler’s willingness to utilize a shared-bicycle rental. $\frac{c + a - b}{a} \geq 0$ is the shared-bicycle renting firm’s participation constraint for the shared-bicycle program. By reducing rental cost $c$, the shared-bicycle rental company can increase the threshold distance. As long as the shared-bicycle rental company is able to maintain its overall profit at a level that is higher than its reservation profit, it has the flexibility to be able to reduce the rental cost to increase the monetary incentive for shared-bicycle usage. Because of the existence of carbon emission cost profit, the shared-bicycle rental firm can even offer shared-bicycle rentals for free if the rental customer uses the bicycle for long distance travel.
V. Results & Concluding Remarks

Bicycle-sharing systems have been in existence for about five decades now, beginning with Luud Schimmelpennink’s well-known 1965 White Bicycle Plan in Amsterdam in which several hundred bicycles that were painted in white were distributed throughout the city for free use. Ever since, shared-bicycle programs have become quite popular, and have spread to cities across the world. In a majority of cases, such bicycle-sharing programs are initiated and maintained by concerned citizens or the city. While the free use part still remains in most of these shared-bicycle systems, it is generally restricted to the first half-an-hour or so. The shared-bicycle customer is then charged an amount beyond the ‘free’ use period or distance based primarily on the rental duration or distance traveled.

With the advent of social media, the introduction of sensors in shared bicycles, and the serious need to address environmental sustainability and the synergies among these, towns and cities around the world have certainly witnessed an increased interest in shared-bicycle initiatives. The alarming increase in greenhouse gas emissions that are partly due to (public and private) transportation has contributed to this trend. Unfortunately, transportation options that are simultaneously feasible, cost-effective, convenient, and environmentally friendly are rather limited. While walking boasts the smallest carbon footprint of all modes of transportation by a wide margin, it may not always be feasible due to heavy luggage, inclement weather conditions, distance, etc. The next best option might indeed be the use of bicycles. Although bicycles are not zero-pollution means of transportation, as the production of bicycles and their parts do introduce pollution, they are still among the transportation modes with the lowest amount of carbon footprint. Shared-bicycle option reduces that carbon footprint even further.

The existence of sensors in these shared-bicycles and the widespread availability of social media help increase the demand for and ease of use of these bicycles. While shared-bicycles may not necessarily solve all issues related to greenhouse gas emissions related to transportation, their role cannot be refuted. There is, therefore, an urgent need to understand its underlying dynamics.

We discussed and investigated the concept of shared bicycle system, enabled by modern IoT technologies and social media. We considered the problem of how to maximize the carbon emission reduction through bicycle use from a mechanism design perspective. Our results indicate that (1) Increased carbon emission cost savings increases the incentive for usage of bicycle-sharing facilities; (2) Harsh environment negatively impacts shared-bicycle renting firm’s performance; (3) An optimal bicycle sharing mechanism that maximizes the shared-bicycle renting firm’s profit is characterized by \( a = b - w + kd^{k-1} \); (4) In an optimal regulated mechanism, the carbon emission cost savings is shared with the firm as \( \text{maximum}\{0, \frac{a-b}{a}\} \); (5) Under the service provider’s participation constraint and bicycle renter’s individual rationality constraints, it is reasonable and possible to reduce the rental cost, even offer free rentals, or provide monetary pay-backs to shared-bicycle users for long distance travels.

We sincerely hope that the discussion and analysis presented in this paper on the synergies among IoT, social media, and shared-bicycles motivates researchers in this general area to develop models and analyses that help with deep-rooted understanding and the generation of related actionable intelligence.

References


