Herd Routes: A Feedback Control-Based Preventative System for Improving Female Pedestrian Safety on City Streets

Madeleine Woodburn[a], Wynita M. Griggs[b], Jakub Mareček[c] and Robert N. Shorten[a]

[a]Dyson School of Design Engineering, Imperial College London, South Kensington, UK; [b]Department of Civil Engineering, Department of Electrical and Computer Systems Engineering, Monash University, Clayton, Victoria, Australia; [c]Czech Technical University in Prague, Czech Republic

ARTICLE HISTORY
Compiled May 10, 2024

ABSTRACT
Over two thirds of women of all ages in the UK have experienced some form of sexual harassment in a public space. Recent tragic incidents involving female pedestrians have highlighted some of the personal safety issues that women still face in cities today. There exist many popular location-based safety applications as a result of this; however, these applications tend to take a reactive approach where action is taken only after an incident has occurred. This paper proposes a preventative approach to the problem by creating safer public environments through societal incentivisation. The proposed system, called 'Herd Routes', improves the safety of female pedestrians by generating busier pedestrian routes as a result of route incentivisation. A novel application of distributed ledgers and ergodic feedback control is proposed to provide security and trust, a record of system users' locations and IDs, and a platform for token exchange. A proof-of-concept was developed using the simulation package SUMO (Simulation of Urban Mobility), and a smartphone application was built in Android Studio so that pedestrian Hardware-in-the-Loop testing could be carried out to validate the technical feasibility and desirability of the system. With positive results from the initial testing of the proof-of-concept, further development could significantly contribute towards creating safer pedestrian routes through cities, and tackle the societal change that is required to improve female pedestrian safety in the long term.

KEYWORDS
Pedestrian safety; dynamic pricing; ergodic control theory; stochastic behaviour; distributed ledger technology; hardware-in-the-loop

1. Introduction

Females of all ages face gender inequities in every day life, and the associated feelings of compromised safety and fearfulness that can arise. In cities, for instance, the day-to-day manifestation of these inequities typically centre around harassment in public spaces. Of course, in these situations, women do as much as they can to prioritise their personal safety. Notably, women approach walking through cities with extreme caution, especially at night.

In London, for example, there are ongoing initiatives such as the UN Women's global

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CONTACT W. M. Griggs. Email: wynita.griggs@monash.edu

initiative of ‘Safe Cities and Safe Public Spaces for Women and Girls’, which commits to identifying gender-responsive, locally relevant and owned interventions (UN Women, 2022). Despite this, a report by the All-Party Parliamentary Group (APPG) for UN Women UK, which investigated sexual harassment in public spaces, found that 71% of women in the UK have experienced some form of sexual harassment in a public space (APPG for UN Women UK, 2021). These statistics are alarming.

In an effort to counter the situation of potential danger when walking through a city alone, especially at night, we propose, in this paper, a feedback control-based system that incentivises people to cluster together on common walking routes. We call the system, ‘Herd Routes’, and describe its design and demonstrate its utility. In particular, we demonstrate that the ergodic control framework described in Fioravanti et al. (2019) is a suitable choice to build the Herd Routes system upon. The framework allows for the incorporation of human decision-making in response to the currently proposed incentivisation amount which is output from a controller. Moreover, the act of employing the framework in the modelling of our system exposes further interesting theoretical problems yet to be solved by the control community. We discuss these problems in Remark 1 and Section 6.

The remainder of the paper is composed as follows. Initially, stakeholder interviews and consequence scanning workshops were employed to outline the design requirements for the system, and these are described in Section 3. Simulation of the system, its design using ideas from distributed ledgers and feedback control, and a prototype application are discussed in Section 3.2. The results of the prototype testing to validate the technical feasibility, and user-centred hardware-in-the-loop testing to validate the desirability, are discussed in Sections 4 and 5. Finally, conclusions and directions for future work are presented in Section 6.

2. Related Work and Contributions

The system proposed in this paper brings together two technology bricks – distributed ledger technology and feedback control – in an effort to alleviate pedestrian safety concerns; in particular, female safety. In this section, we give a very brief overview of some of the related prior work on these topics.

Female Safety: The issue of female safety is of great interest worldwide and many innovative systems are being developed with this goal in mind. However, in spite of this, somewhat surprisingly, there are few peer-reviewed papers specifically on the topic. One of the few works in this direction is presented in Akram et al. (2019). Here, the authors outline the design of a smart safety device for women that relies on providing security via a fingerprint-based method of connectivity (Chen et al., 2016). This solution can be categorised as a reactive device, whereby action is taken only after an incident has occurred. Similarly, Akram et al. (2019) describes a Raspberry Pi-based ‘Smart Ring’ for female safety (Sogi et al., 2018) that is embodied as a wearable and requires minimal human interaction to instantaneously connect to the concerned authorities when a ‘trigger’ movement is detected. The proposed technique uses GPS tracking of the Smart Ring to establish the user’s coordinates, which can then be sent to user-specified close contacts. Applications such as Safe & The City (2022), Path Community (2022) and Safetipin (2022) set themselves apart from the market by how they share data about unsafe experiences. In creating a database of crowd-sourced safety reports and alerting authorities such as police and local councils if any incident occurs, they aim to reduce incidents and user fear. CityMapper[1], a popular route navigation application specifically designed for use in cities, recently released a 'main road' safety feature which acknowledges that 'sometimes, the fastest way to get there isn't the best way to get there' (Citymapper, 2022). This was implemented after female users had complained that the routes suggested by the application's algorithm had led them through badly lit, quiet streets with multiple turns – and even through parks late at night. This feature has been successful as females seeking a greater feeling of safety prefer to walk down busier, well-lit main roads than the alternative fastest route. All of these solutions have in common that they are reactive in that they respond after an incident has occurred. As we shall see, we wish to develop preventative systems that alleviate as much as possible the likelihood of an incident occurring in the first place.

Distributed Ledger Technology (DLT): A key enabling technology for this work is a distributed ledger. A distributed ledger is a database maintained in a peer-to-peer network. Recently, a number of papers based on distributed ledgers technologies, for example, Blockchain (Ranathunga et al., 2020), proposed a framework for IoT ecosystems that embed a greater sense of trust within the architecture of the IoT system, and we shall build on this approach. The literature is vast on this topic and we only mention briefly some illustrative works. For example, Ranathunga et al. (2020) utilises a distributed ledger layer that manages reputation, interaction, ID management and access control. The consideration of trust is expanded to a user-centric model for access control, as proposed by Hashemi et al. (2017). The use of DLTs for establishing peer-to-peer trust has been tested in many applications, including for medical data (Azaria et al., 2016), user-centric control of personal data (Hashemi et al., 2017), transfer of personal data between broker and receiver (Kiyomoto et al., 2017), distributed networks of vehicles in a Smart City (Rehman et al., 2020), and prescription drugs records (Jamil et al., 2019).

Ergodic Control: The use of feedback control in social science-like applications is a relatively new topic. A key consideration in many such applications is the ergodic nature of the control, as explained in Section 2.D of the IEEE Control Systems Society's 'Control for Societal-Scale Challenges: Road Map for 2030' (Annaswamy et al., 2023). See also Ferraro et al. (2018); Fioravanti et al. (2019); Griggs et al. (2018); Kungurtsev et al. (2023); Mareček et al. (2023) and the references therein.

Contributions

The contributions of our work are three-fold:

- we introduce a use case that is novel to the control community and of high societal importance;
- we apply our recent theoretical results of Fioravanti et al. (2019), Kungurtsev et al. (2023) and Mareček et al. (2023) on ergodic control to this application; and
- we bring together DLT and feedback control, which could be of independent interest.

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[1] `https://citymapper.com`

3. Stakeholder Analysis

The issue of female safety is complex and, in order to inform our design, a number of stakeholder interviews were conducted; further details can be found in Woodburn et al. (2022).[2] In addition, a Consequence Scanning workshop (Doteveryone, 2022) was conducted on Figma (2022), which is a collaborative online tool. The workshop was split into three sections: identifying intended and unintended consequences of proposed solutions; prioritisation of these consequences; and finally, examining how to address the consequences with design requirements. Furthermore, in addition to the interviews and workshop, an examination of statistics in the literature concerning real and perceived female pedestrian safety was conducted to identify common themes in regard to safety when walking alone or at night. Key findings of these surveys were as follows.

1. Adults in the UK feel less safe walking alone in 'all settings' after dark, compared to during the day. 'All settings' can include a quiet street close to one's home, a busy public space (e.g., a high street), or a park or other open space (Office for National Statistics, 2022).

2. Women in the UK feel less safe compared to men in 'all (of the above) settings' after dark (Office for National Statistics, 2022).

3. The findings were corroborated in other countries too; for instance, in Australia, a report published by the Australian Bureau of Statistics (2015) noted that, in 2010 and 2006, only 48% of adults felt safe or very safe walking alone in their local area at night, with men being more likely to feel safe or very safe walking alone at night than women (i.e., 68% compared to 29%).

4. The findings are also merited by the actual statistics on gender-based violence. A survey by FRA (European Union Agency for Fundamental Rights, 2014, Section 5: Stalking) utilised a random sample of women aged 18 to 74 years, with a minimum of 1,500 women in each EU Member State, except Luxembourg. Across the EU, it was found that 8% have been followed around or experienced somebody loitering outside their home or workplace. It was also found that out of the most serious incidents of gender-based violence by a non-partner, 20% took place out in the street, a car park or other public area.

For the victims of stalking, common psychological consequences included (European Union Agency for Fundamental Rights, 2014, p. 90) anxiety (30% of victims), feeling vulnerable (24%), difficulties in sleeping (19%), depression (11%) and panic attacks (9%). The FRA results are in line with the UK national results. FRA reported that 19% of women in the UK have experienced stalking since the age of 15; and the Office for National Statistics (2017) reports that 20.9% of women in the United Kingdom have experienced stalking since the age of 16, compared to 9.9% of men.

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[2] Human participation in this study consisted of several participants reporting their opinions on the utility of the system, and several comments are recorded without attribution; see, for example, Section 4.2. All participants agreed in writing that material could be used in publication of the results. Advice was sought by the PI, Robert N. Shorten, from the Ethics Officer at the Dyson School of Design Engineering, and it was agreed that publication was at the discretion of the PI, and that no permissions were required to report on the participants' comments.

5. A common view is exemplified in a quote by 18-year-old university student Roisin Young Murphy, cited in Ward (2019), who noted that females walking home on a weekend can mean ‘walking past four or five venues where intoxicated men tend to crowd on the footpath’, but that the route can be just as scary on a ‘dead quiet’ weeknight.

This final point indicates that local knowledge of the characteristics of individual streets should be considered when regulating pedestrian activity on incentivised routes. In other words, the success of the system may not be a matter of merely seeking to increase the number of people on a street; but rather, we should seek to regulate activity such that desired densities of ‘trusted pedestrians’ (i.e., pedestrians who are system users and have achieved some level of trustability) are maintained on the different streets along the route, to ensure that enough trusted system users are present to deter opportunistic miscreants from harassing *any* pedestrians (i.e., system users or not) on the route. Furthermore, the desired density may be time-varying and could be predetermined or updated in real time.

3.1. Iteration of Concepts

We proposed a number of concepts for improving female safety to our stakeholders.

1. The first concept explored, called ‘Paired Routes’, allowed two system users’ routes to be matched together and then superimposed to maximise the amount of time that they would be walking together. Each interaction between system users would be stored on a distributed ledger.

2. The second concept was a token exchange concept that allowed a user to request a ‘buddy’ to escort them along their route. The token exchange would incentivise the ‘buddies’ to escort users to their destination, similar to an Uber ride-hailing model. After discussions with stakeholders, these concepts were discarded as the risk of system misuse would be too high, and would need to rely on thorough and heavily secured verification of new users.

3. The third concept, entitled ‘Herd Routes’, was chosen as the selected concept. As opposed to the two discarded concepts, this system proposal has no need for interaction with another system user. It also utilises distributed ledgers as a way of incentivising societal behaviour change (Ferraro et al., 2018), which is an integral part of the long-term vision for creating an environment where women are not subject to sexual harassment in public spaces. The concept relies on the insight that busier streets generally have a greater perceived safety for women (albeit keeping in mind that other factors can affect perceived and real safety too, as mentioned earlier in this section). This logic was similarly applied in CityMapper’s ‘Main Road’ feature: when deciding between an empty street and a busier one, women are more likely to choose the latter to walk along. **Herd Routes generates pedestrian flow along specified routes by incentivising system users with payment in the form of tokens.** As well as increasing safety by increasing or regulating pedestrian traffic along routes, the system should also keep a record of which system users were on the routes over time, similar to other navigation-based safety applications. This would not necessarily increase perceived safety in the instant, but would provide evidence if an incident were to occur.

The user inputs their final destination into the application, and the algorithm routes them along the incentivised route, which would be busier due to the generated pedestrian flow. This is a system that all citizens can use, even those who do not feel unsafe, and therefore contributes towards creating safer public spaces for female pedestrians. The user-facing embodiment of this system will be a route navigation application. As seen in Figure 1, the system can be thought of as comprising three distinct layers: (i) the user; (ii) the application; and (iii) the ledger. All three layers interact with each other to create a holistic view of the system.

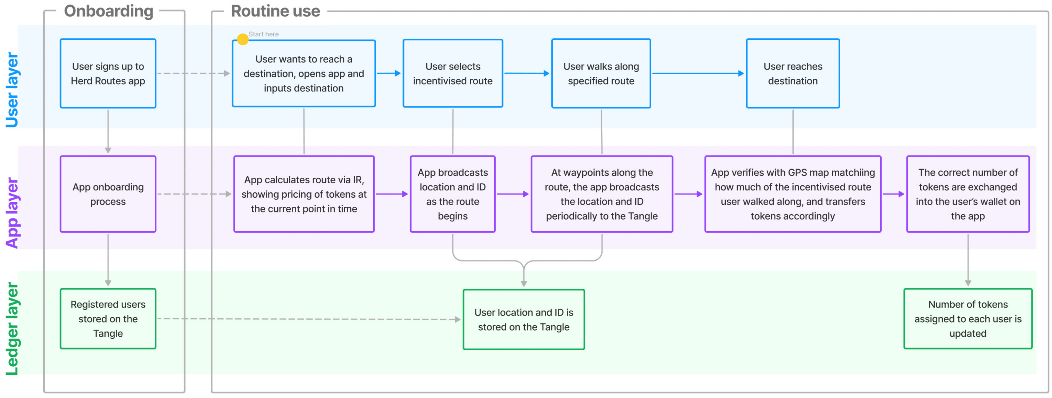

Figure 1. Herd Routes system overview.

The security, trust and core functionality of the Herd Routes system is facilitated by DLTs. As shown in Section 2, the existing use cases and functionalities of DLTs in Smart Cities have proven to be very successful. There are, however, many different types of platforms, the most notable of which is Blockchain (Blockchain.com, 2022). Although widely used, this platform has drawbacks that mean it is not viable for use in the IoT industry. Blockchain has an associated transaction fee for any value of transaction, meaning micropayments become illogical if the transaction fee is greater than the value of payment. Due to the fact that Blockchain participants can be categorised into those who transact and those who approve transactions, an opportunity presents for inadvertent discrimination or misuse of the system. For the Herd Routes system, using a ledger platform that is inherently discriminatory works against many ethical design considerations (Popov, 2018). The IOTA Tangle[3] was developed specifically for use within the IoT industry due to its high scalability, zero fees and near-instant transfers, and therefore was selected as the ledger that best supported the Herd Routes system (IOTA Foundation, 2018).

The Herd Routes system employs a dynamic pricing controller to price the tokens according to how many system users there currently are, and how many there needs to be, for a street to be perceived as 'safe'. As a result of this, the system contains a feedback loop, where the number of system users, the token price, and the number of non-system users all influence one another.

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[3] `https://www.iota.org/get-started/what-is-iota`

3.2. System Design

Prototype Overview: Herd Routes is a large-scale urban system that could not be fully prototyped at this early stage of its conception due to its complexity. Therefore, to validate the concept and explore the feasibility of the system, a model was built to replicate its core functionalities. The build of the prototype was broken down into two phases: Phase (1) consisted of the development of a simulation of Herd Routes using the SUMO (Simulation of Urban MObility) software package and Python; and Phase (2) comprised of a Hardware-(or Person-)in-the-Loop test that utilised the simulation environment from Phase (1). In particular, once the simulation of the system was constructed, an Android smartphone application, for a real person to use, was designed and built for integration with the simulation. The smartphone application communicated with the simulation via an external server. The system architecture for the prototype, illustrated in Figure 2, shows how the Python script interacted with the SUMO software, posted message data to the Tangle, and received incoming data from the Android device.

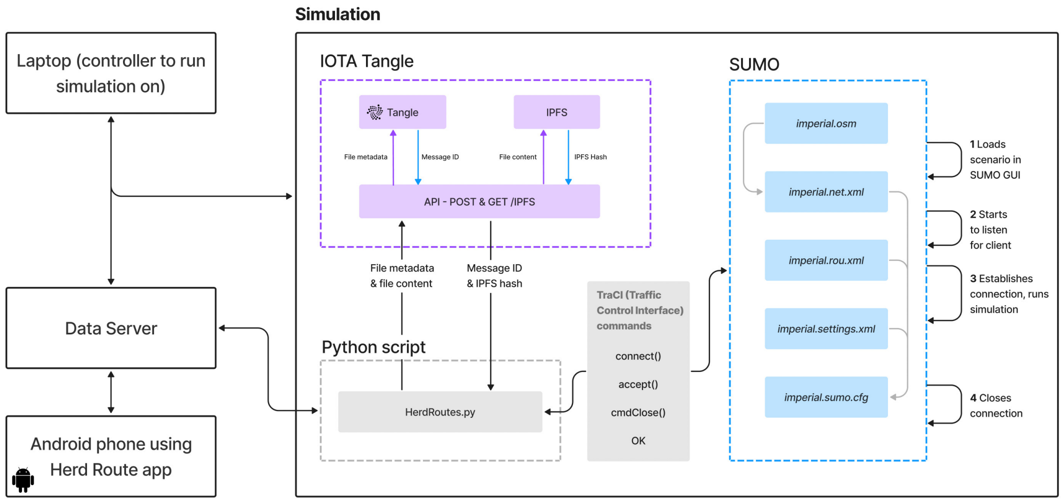

Figure 2. System architecture for the prototype, used in the Hardware-in-the-Loop testing.

Phase (1) – SUMO Simulation: SUMO is an open-source, multi-modal traffic simulation package that has been designed to model large-scale urban networks (Eclipse SUMO, 2022). It is widely used in industry and research due to its flexibility and wide range of resources and documentation available. The Herd Routes SUMO simulation was developed in the Visual Studio Code IDE using Python 3.9.7. The Python script communicated with the SUMO software using the Traffic Control Interface (TraCI) APIs. TraCI uses a TCP-based client/server architecture to provide access to SUMO. Once a connection had been established, the client could edit and manipulate the simulation, request information about any agent or environment, and ultimately close the connection down.

The SUMO software also includes a graphical user interface, called the SUMO-GUI. It provided useful visualisation of the simulated environment, displaying the movement of agents on the map. For the purpose of the Hardware-in-the-Loop testing, a map of the Imperial College South Kensington campus was downloaded from OpenStreetMap[4] (see Figure 3) and imported into SUMO (see Figure 4). Moreover, the route coloured purple in Figure 4 illustrates the route that was chosen to be incentivised. The agent visualisation was useful while the simulation was being developed and iterated upon, as it provided a sanity-check for modelling the rationale of the agents, ensuring that the functionality of the simulation was as intended.

Figure 3. Downloaded area from OpenStreetMap.

The main algorithm (Algorithm 1) used for the simulation was comprised of three core functionalities, which were implemented as a further three discrete algorithms, as follows:

(1) the dynamic pricing control (incorporating a simple model of rational human behaviour) (Algorithm 2);
(2) monitoring of the real-time usage of incentivised routes by system users who had made the decision to utilise them (Algorithm 3);
(3) and the IOTA Tangle communications and protocols (Algorithm 4).

Rational simulated pedestrians were generated such that each agent was assigned its own departure time and provided with a nominal, random route to walk. When joining the network upon their departure time, agents also had a 60% chance of being Herd Routes system users. (This percentage can be altered to reflect any real-world probability of a pedestrian being a Herd Routes system user.) Every 30 simulation time steps, the token price was updated; and any Herd Routes system user, who had not yet decided at some time prior whether to utilise an incentivised route or not, proceeded to make a random decision on whether to use an incentivised route based on the newly updated token price. Once on an incentivised route, at each waypoint along it, the agent would post their location and system user ID to the IOTA Tangle,

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[4] `https://www.openstreetmap.org/#map=15/51.4974/-0.1776`

Figure 4. Area imported into SUMO, where the incentivised route is coloured purple.

thus paving the way for the pedestrian to be paid for using an incentivised route. Further details can be found in the pseudocode for Algorithms 1 to 4.

Dynamic Price Control: Dynamic pricing control was applied to regulate the amount of people on the incentivised route. In our simulations, for simplicity, we regulated the number of people on the incentivised route according to a desired total of 100; however, in reality, one would more likely regulate according to a desired pedestrian density. The dynamic price control was implemented using a lag controller specified by

$$\pi(k) = \beta\pi(k-1) + \kappa[e(k) - \alpha e(k-1)] \tag{1}$$

and represented in Figure 5 by C. Discussion on the preferred use of a lag controller over a PI controller in feedback loops featuring similar characteristics to ours can be found in Fioravanti et al. (2019). In particular, after some experimentation, we set $\alpha = -4.01$, $\beta = 0.99$ and $\kappa = 0.5$. By letting $\kappa = 0.5$, for instance, as opposed to choosing κ to be a smaller, positive value, we were able to reduce the steady state error of the lag controller to near zero. On the other hand, increasing κ too much, so that it is almost equal to 1, results in more noise in the response, with the time taken for the steady state error to stabilise increasing.

Elaborating further on Figure 5:

- C denotes the lag controller which takes an error, e, as input and produces an output, π, where π represents the payment to be offered to each Herd Routes system user to entice them to take an incentivised route;

Algorithm 1 Main Simulation Algorithm

Data: Number N of agents; total number T of simulation steps; fixed interval I for token-pricing updates.
Result: Specified number N of pedestrian agents with nominal routes are inserted into the simulation at pre-specified departure times to validate the dynamic pricing, incentivisation of walking routes, and IOTA checkpoint elements of the Herd Routes system.

```
// Preliminaries.
Generate $N$ agents with individual departure times and random routes

// Run the simulation.
Start the SUMO simulation and connect it to the Python script via TraCI
while time step $i \leq T$:
  if $i$ is divisible by $I$:
    update the token pricing using Algorithm 2
    for each agent on the network who is a Herd Routes system user:
      let the agent decide whether to take an incentivised route based on the
      token price
      if agent decides 'yes':
        append agent ID to list of agents taking an incentivised route
        navigate agent onto selected incentivised route
      end
    end
  end
  for Herd Routes system users currently on incentivised route and who
  decided 'yes' in current or prior time step:
    communicate with the IOTA Tangle via Algorithm 3
  end
  $i$ += 1
end

Close the connection between the Python script and SUMO
Close the simulation
```

Algorithm 2 Dynamic Pricing Control Algorithm

Data: target amount (either total number or density) `fixedDemand` of agents on incentivised route; Agent Population Information: amount of agents `agentsOn` on incentivised route; amount of agents `agentsOnPrior` on incentivised route in prior time step; Moving Average Filter Output: $\hat{y}$; Controller Information: controller input e, $e_{\mathrm{H}istory}$, $\pi_{\mathrm{H}istory}$, α, β, κ.
Result: Updated token price, π.

```
$\hat{y} = (\texttt{agentsOn} + \texttt{agentsOnPrior})/2$
$e = \texttt{fixedDemand}$ - $\hat{y}$
$\pi = \beta \times \pi_{\mathrm{H}istory} + \kappa[e - \alpha \times e_{\mathrm{H}istory}]$, cf. (1)
$e_{\mathrm{H}istory} = e$
$\pi_{\mathrm{H}istory} = \pi$
```

Algorithm 3 Incentivised Routes Usage Algorithm

```
Data: Herd Routes system user's location; list of waypoints along incentivised route
Result: Monitor the real-time usage of incentivised routes by Herd Routes system users who have made the decision to utilise them.

Get location
if location is in waypoints (i.e., if agent is at a waypoint):
    do IOTA location and ID posting, and token exchange (Algorithm 4)
end
if agent completes use of incentivised route:
    navigate to original nominal destination
end
```

Algorithm 4 Tangle Location and ID Posting Algorithm

```
Data: Herd Routes system user's ID and location; agreed upon token payment
Result: Connect to the Tangle, check the health of the Devnet, post the agent's ID and location to the Tangle, and facilitate the token payment exchange.

Compile SUMO agent data (i.e., ID and location) into a Tangle message
Check health of Devnet and generate address
Post agent data to Tangle
(Receive payment via Tangle)
```

- F denotes a moving average filter with output $\hat{y}(k) = (\texttt{agentsOn}(k) + \texttt{agentsOn}(k-1))/2$, where $\texttt{agentsOn}(k)$ denotes the total number of agents currently on the incentivised route;
- we will consider P_i, for $i = 1, \ldots, M$, a 'black box' denoting a Herd Routes system user, which contains the agent's decision-making apparatus (which will be discussed below, see Figure 6), and potentially a subsequent delay, between when a decision to use the incentivised route is made, and when the agent actually arrives at the incentivised route;
- P_i, for $i = M+1, \ldots, N$, is a 'black box' denoting a non-Herd Routes system user;
- y_i, for $i = 1, \ldots, N$, is either equal to 0 (if agent i is not currently on an incentivised route) or 1 (otherwise), and is influenced by an agent's nominal route, and also by π if the agent is a Herd Routes system user;
- and `fixedDemand` is the constant, desired number of people on the incentivised route, as stipulated by a city based on some safety criteria.

The decision-making apparatus of the Herd Routes system users functioned as follows. Every 30 simulation time steps, the token price was updated by the controller (see Algorithm 2) and forwarded to any Herd Routes system users who had not yet decided to use an incentivised route. The probability that the user would accept the new token price, and thus re-route to an incentivised route, was subsequently found by locating the token price, π, along the x-axis of Figure 6, and observing the probability associated with that price on the y-axis. Note that the function illustrated in Figure 6 is demonstrative of a very basic model of a rational agent, in that the probability an agent will accept the token price increases as the price itself (i.e., the amount that

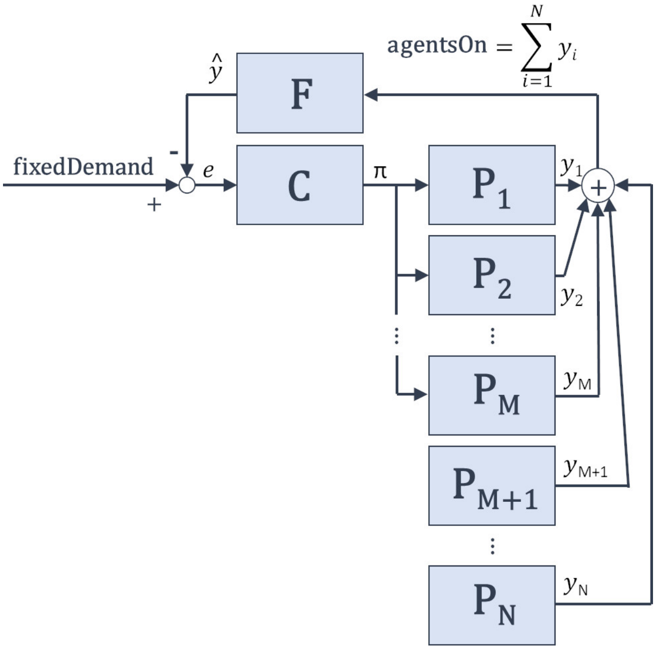

Figure 5. Dynamic pricing feedback loop for setting the value of the tokens.

the agent will be paid) increases. In this paper, for simplicity, all Herd Routes system users' decision-making was described by the same basic model. Next, for each Herd Routes system user, the Python function `random.uniform(0,1)` was invoked. Finally, the output of the uniform random number generator (which was unique for each agent) was compared to the probability obtained from the y-axis of Figure 6 (which was the same value for each agent, for simplicity, in this paper). If the output of the random number generator was less than the probability determined from the y-axis of Figure 6, then the agent decided to use an incentivised route; and vice versa.

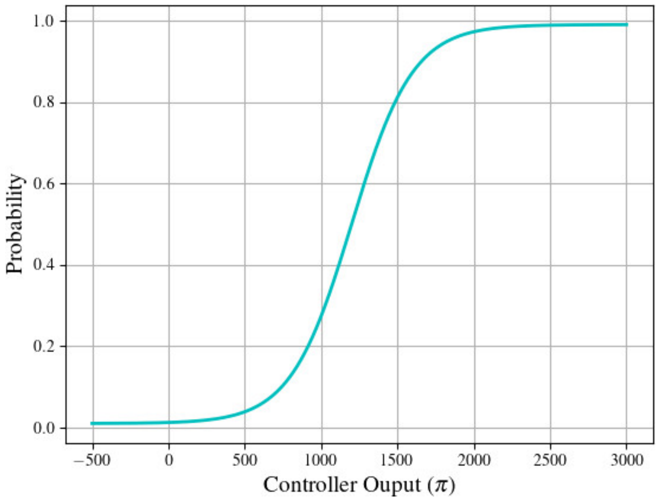

Figure 6. The probability of a pedestrian deciding to use an incentivised route versus the current token price. This simple model reflects typical price acceptance for a rational agent.

The dynamic pricing control algorithm (i.e., Algorithm 2) was tested to evaluate the suitability of the model over time. The model parameters were set such that the total number of agents on the road network at any moment would be maintained at approximately 300 (except for towards the beginning of the simulation when agents were still departing); the controller was updated every 30 simulation time steps; and 10 simulations were run in total, with each simulation consisting of 10,800 time steps, so that the convergence of the control output, and the success in regulating the feedback control loop, could be observed in terms of expected values and standard deviations. The target number of pedestrians desired to be on the incentivised route at any moment in time (i.e., `fixedDemand`, see Algorithm 2) was chosen to be 100.

In regard to our feedback control design, it is pertinent at this point to make the following remarks.

Remark 1. Our proposed dynamic pricing control system is based on the ergodic control framework described in Fioravanti et al. (2019); refer to Theorem 12 in the aforementioned reference, in particular. Roughly speaking, Theorem 12 of Fioravanti et al. (2019) states that, given a stable, linear, time-invariant controller and a stable, linear, time-invariant filter, in feedback with an ensemble of agents exhibiting behaviours such as demonstrated via Figure 6, above, then the feedback loop is guaranteed to converge in distribution to a unique invariant measure. This means, for instance, that the expected values of e and π are guaranteed to converge in the limit, regardless of initial conditions. Thus, as system designers, based on this result, we are hypothetically able to guarantee a level of predictability concerning our Herd Routes application (e.g., in terms of the amount of incentivisation that will likely be required in the long run). However, our process of implementing a dynamic pricing control for Herd Routes also exposes and emphasizes the need to further extend upon the prior theory presented in Theorem 12 of Fioravanti et al. (2019). In particular, our Herd Routes application highlights the necessity for the consideration of time delays; additional agents in the feedback loop that are not Herd Routes system users; and time-varying agent behaviours (e.g., agents joining and/or leaving the network over time; and/or changing their minds as to whether to use an incentivised route, as reflected by changes over time in the shapes of their associated probability functions, which could be related to changes in the local weather, etc.). As we will see in Section 4.1, the time delays (between when an agent decided to use, and then actually arrived at, the incentivised route), and the fact that agents joined and left our network over time, did not appear to destroy the convergence properties of our control system's steady state behaviour. This is good news and, while a full theoretical analysis of these observations is beyond the scope of our current paper, is an observation worth making and thus flagging for elaboration on in a future work. ■

Remark 2. It is also worth observing that the successful application of ergodic control theory to Herd Routes helps to illustrate how results of the kind obtained in Fioravanti et al. (2019), and (notably) any future extensions thereof incorporating time delays, etc., could similarly be applied in other intelligent transport and mobility-related contexts as well. Examples include:

- incentivising drivers to utilise certain car parks or electric vehicle charging stations over others, for the benefit of controlling traffic congestion or electricity grid stability;
- social sensing applications (see, for instance, Ghosh et al. (2022));
- online labour platforms and two-sided markets (see, for instance, Griggs et al.

(2021)). ■

Tangle Location and ID Posting, and Token Exchange: Within the Herd Routes system, the inclusion of a distributed ledger served three primary functions:

1. a means of trust and security to the IoT system;
2. a ledger for system user IDs and locations to be stored;
3. and a platform for token exchange during and/or after completion of an incentivised journey.

The second functionality, specifically, was demonstrated in our Python simulation, as this was the minimum functionality required for the proof-of-concept. Due to changes in IOTA protocols that were deployed in April 2021 (IOTA Foundation, 2022), Chrysalis (known as IOTA 1.5) with Hornet node software was deployed within the simulation. The Client class was used to provide high-level abstraction of the IOTA.rs library. This class was instantiated before starting any interactions with IOTA nodes. The library automatically chose a starting node within the Devnet[5] (similar to the Mainnet, except tokens are free and it incurs less computational power to interface) for the simulation to connect to. After the health of the network was checked, the IOTA update (see Algorithm 4) was called.

If a Herd Routes system user within the simulation had navigated onto an incentivised route, their location and ID (retrieved via the TraCI commands `TraCi.person.getlocation()` and `Traci.person.getID()`, respectively) were sent to Devnet at each waypoint that they passed along the route. In doing so, a record of the location of each system user was stored in case of an incident (e.g., harassment or an incursion on the pedestrian's personal safety while walking).

This information was sent as a message; that is, a type of data structure that is broadcast to the IOTA network and represents a node in the Tangle graph. Every message is referenced by a `message_id` which is based on a hash algorithm of binary content. For the proof of concept, `IndexationPayload` was used. This type of payload enabled the addition of an index to the encapsulating message, as well as the raw message data. For prototyping purposes, this was the most useful as it allowed for an easier search within the Tangle explorer (see Figure 7), which was used to validate the completion of the data post.

Phase (2) – Hardware-in-the-Loop (HIL) Testing (Application Build): Simulating the system with Python and SUMO proved useful in evaluating the functioning of the implemented pricing control and IOTA integration; however, simulation alone was not enough to gauge the perspective of a real user on the design. Therefore, a smartphone application (see Figure 8) was built in the native Android IDE (Google Developers, 2022) and coded in the Java and XML languages. Using HIL testing allowed for a human-centred approach to be taken, with behaviour and responses directly inputted into the simulation. It enabled user feedback (not provided by the simulation alone), which was utilised to make iterations to the system design. We note that the HIL method has been successfully employed in other large-scale urban system projects, such as in Griggs et al. (2015) and Sweeney et al. (2022).

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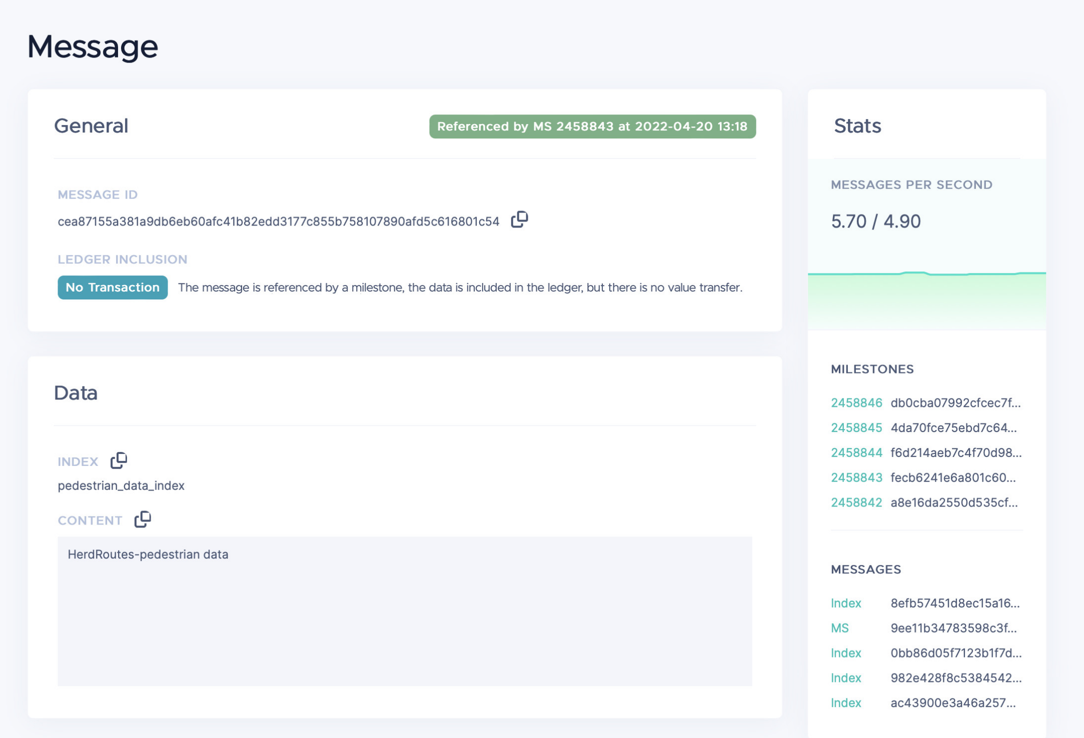
[5] `https://legacy.docs.iota.works/docs/getting-started/1.2/networks/devnet`



Message

General

Referenced by MS 2458843 at 2022-04-20 13:18

MESSAGE ID

cea87155a381a9db6eb60afc41b82edd3177c855b758107890afd5c616801c54

LEDGER INCLUSION

No Transaction The message is referenced by a milestone, the data is included in the ledger, but there is no value transfer.

Data

INDEX

pedestrian_data_index

CONTENT

HerdRoutes-pedestrian data

Stats

MESSAGES PER SECOND

5.70 / 4.90

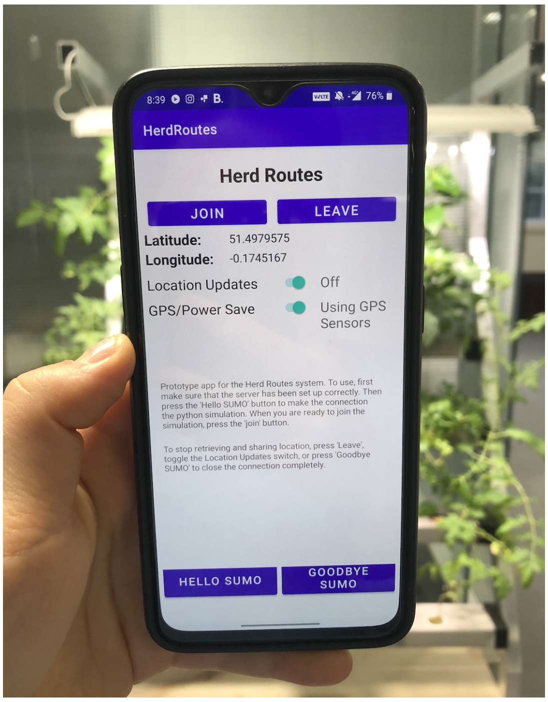
MILESTONES

2458846	db0cba07992cfcec7f...
2458845	4da70fce75ebd7c64...
2458844	f6d214aeb7c4f70d98...
2458843	fecb6241e6a801c60...
2458842	a8e16da2550d535cf...

MESSAGES

Index	8efb57451d8ec15a16...
MS	9ee11b34783598c3f...
Index	0bb86d05f7123b1f7d...
Index	982e428f8c5384542...
Index	ac43900e3a46a257...

Figure 7. The Tangle explorer, with an example message that the simulation sent to the Devnet.



Latitude: 51.4979575
Longitude: -0.1745167
Location Updates Off
GPS/Power Save Using GPS Sensors

Prototype app for the Herd Routes system. To use, first make sure that the server has been set up correctly. Then press the 'Hello SUMO' button to make the connection the python simulation. When you are ready to join the simulation, press the 'join' button.

To stop retrieving and sharing location, press 'Leave', toggle the Location Updates switch, or press 'Goodbye SUMO' to close the connection completely.

Figure 8. Herd Routes prototype smartphone application downloaded on an Android device to be used in the Hardware-in-the-Loop simulation.

Google Play Services was used to retrieve the GPS data from the phone. Version

19.0.1 of `play-services-location` was included in the gradle dependency list in order for the Location Provider library to be functional. This was utilised in the `SendGPS` and `updateGPS` methods to retrieve the user's GPS location. The application connected to the simulation by using a client socket on an external host IP address and designated port number. This allowed the transfer of the GPS coordinates in the worker thread to be processed by the Python simulation. Once processed, the GPS coordinates were converted to Cartesian X and Y coordinates by the TraCI `ConvertGeo` method, which were then used to find the nearest `edgeID` in the map for the real-life agent to be inserted.

4. Results & Evaluation

4.1. SUMO Simulation with Dynamic Price Control

The results of testing the dynamic pricing control, obtained from running the SUMO simulation 10 times, where each simulation consisted of 10,800 time steps, are provided in Figures 9, 10 and 11. As can be seen, the system successfully maintained the mean number of pedestrians on the incentivised route close to the desired value of 100.

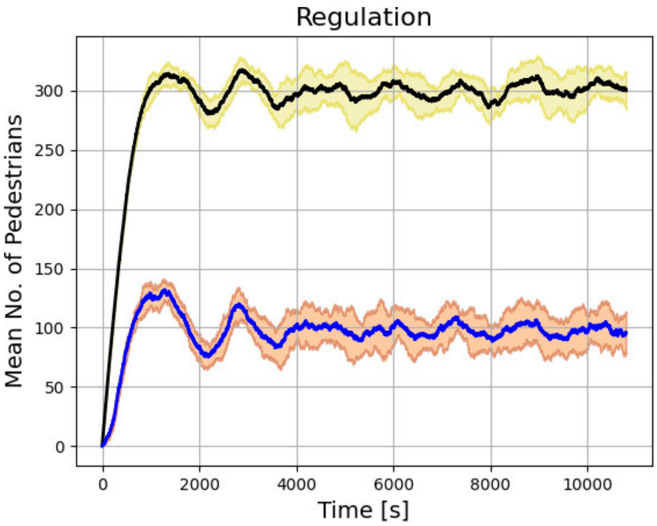


Figure 9. Regulation of the number of pedestrians on the incentivised route to the desired value of 100. In particular, the blue line indicates the mean number of pedestrians on the incentivised route (from ten simulations) versus time. The red shaded region indicates the area within one standard deviation from this mean. Meanwhile, the black line has been included to illustrate the mean number of pedestrians on the network, in total, (from ten simulations) versus time. The yellow shaded region indicates the area within one standard deviation from this mean.

The high peaks observed at the commencement of the simulation runs in the blue lines of Figures 10 and 11 are present due to the initial conditions chosen in regard to the pedestrians. Specifically, at the commencement of each simulation, no pedestrians were on the network; and thereafter, approximately one pedestrian was added to the simulation (i.e., departed from an origin and commenced a walking trip) every 2 time steps. Each pedestrian was given a uniquely generated, random, nominal route to walk. The evolution of the total numbers of pedestrians on the network can be observed by the black line in Figure 9. An equilibrium of roughly 300 pedestrians in total on the

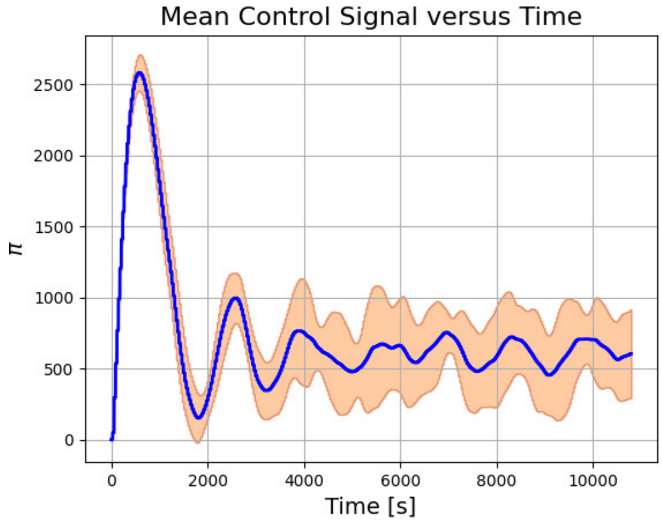


Figure 10. The evolution over time of the controller output, π. The blue line indicates the mean control output (from ten simulations). The red shaded region indicates the area within one standard deviation from the mean.

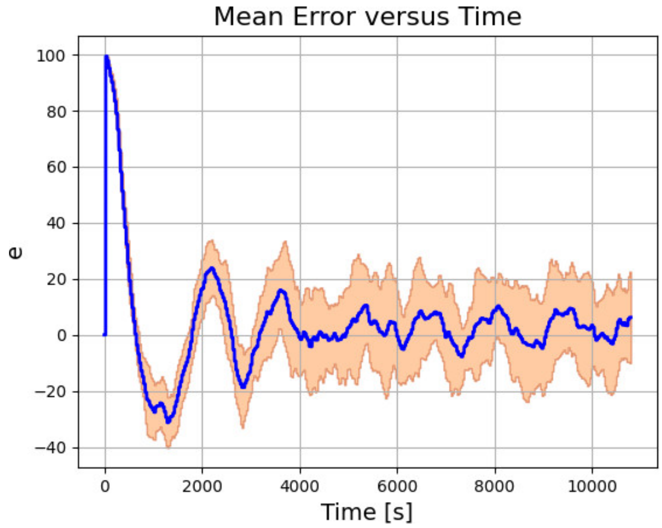


Figure 11. The evolution of the mean error, e, over time. The blue line indicates the mean (from ten simulations). The red shaded region indicates the area within one standard deviation from the mean.

network was achieved by approximately the 1000th time step; that is, once the number of pedestrians departing from their origins roughly began equalling the number of pedestrians arriving at their destinations and leaving the network. In summary, the controller had to 'work harder' at the beginning of each simulation, by offering a higher payment to try to entice more pedestrians onto the incentivised route, given that not many pedestrians were on the network, in general, at the beginning of a simulation.

4.2. Hardware-in-the-Loop

The prototype user interface was loaded correctly and the simulation was successfully connected to, and joined, in all real human participant cases (see Figure 12). Having completed the test, on average, participants were more likely to be aware of other pedestrians while walking along a route (as rated on a scale of 1-10). When asked about participating in a large-scale system, feedback included: ‘it feels safe and makes you feel part of a community’; ‘it’s a non-invasive way of showing areas which are busier’; it ‘made me want to use it as I felt I was helping others’; and ‘I felt nervous knowing that other people knew where I was’. On the subject of data privacy, participants were on average less happy knowing their location was being used; however, there was a large disparity in opinion. Despite this, 63% of the participants said that the use of location data was justified within the context of a female safety application.

Figure 12. A participant using the prototype smartphone application to participate in the hardware-in-the-loop testing.

When discussing the system more generally, the consensus was that a street with 5-10 other pedestrians on it would feel busy and therefore would have a greater perceived safety. The opinion was unanimous that it was acceptable that other system users would benefit from the safety application in the form of tokens. City-specific rewards and social utility tokens were voted as the most desirable option for token forms.

5. Discussion

5.1. Business Case

Incentivisation of specified routes underpins the success of the Herd Routes system. Although this system was designed for maximum social impact, and therefore at its core would be operating as a not-for-profit business, someone would need to provide the value of a token. When exploring who would pay for this system, the following questions were considered:

1. What form of token would be exchanged?
2. Who are the critical stakeholders who would need to sign off on this system in order for it to be rolled out?
3. Who has a vested interest in this system working?
4. How does the token exchange work initially, and then over a longer period?

By analysing similar female safety applications, it can be seen that various financing strategies have been used. Some generate revenue from advertisements, while others sell on data-generated insights from their application to third parties (typically government institutions, local councils and urban planning companies). All instances agree on the fact that the user in question should not have to pay. The options for the system financing are discussed in Table 1; however, from the qualitative feedback received, options with tokens based on social utility were preferred.

Table 1. Options for Herd Routes system financing.

Institution / Organisation	**Rationale**	**Advantages**	**Disadvantages**
Local shop fronts	Herd Routes generate traffic flow along the routes. High-street shops will benefit from this service and so should pay.	Consistent revenue stream, benefiting the local economy in multiple ways.	Opens up the possibility of a conflict of interests between the route selectors and the system users. Becomes too predictable, could lead to system misuse.
Cryptocurrencies / Ledgers	Use the system to bootstrap ledgers such as IOTA, increasing their popularity and getting them closer to the required number of network users; e.g., NFT Shoe, Sweatcoin (2022).	Short-term lucrative business model.	Excludes potential users that would not have use for cryptocurrencies / don't have interest or see value in it.
Local councils / London boroughs	Local government councils have invested interest in creating as safe an environment as possible; e.g., Path Community (2022).	Lends system credibility, and speeds up implementation times.	Varies borough to borough. Would be difficult to coordinate across multiple local councils initially.
Big corporations / Institutions such as Women's Night Safety Charter (Greater London Authority, 2022)	Use CSR policies to fund a social impact project. Demand from employees and customers.	Access to a large source of financing.	Aligns the system with goals that may deviate from the original mission.
Mayor of London	Local government councils have an interest to create as safe an environment as possible. Tokens could be in the form of city-wide valued commodities such as free TFL journeys.	Lends system credibility, and speeds up implementation times. Opens up potential for highly valued societal tokens.	Potential cap on the value of the tokens. System may be vulnerable to whether priority or funding changes within the public sector.
Home Office / Police	Shared common objective of reducing crime in public spaces.	Strong alignment of objectives that will not change in the future.	Privacy concerns, and vulnerable to changes in public sector funding.

5.2. Security

There is general concern about the movement towards smart cities and the lack of data security. A specific concern is the 'lack of opportunity for giving meaningful consent to processing of personal data' as outlined in Edwards (2016). The proposed Herd Routes system is voluntary, and upon system onboarding, the user grants permission for their location and system identification number to be sent in an encrypted format to the Tangle. By the very nature of the ledger, all transactions from and to it are traceable. This means that any data leak or hacking of the encrypted identifiable information generated by the Herd Routes system would allow the ledger to be traced for all past and future messages or transactions linked to the entity tied to that transaction. This would quickly identify the entity that had misused the system, and would be reported and dealt with accordingly.

Throughout the wider IoT industry and research community, there is debate on the value of data privacy versus the potential for social utility. During the Consequence Scanning workshop that was conducted, it was concluded that all four interviewees already used location-based tracking services, such as Find my Friends, or Snap Maps. From user interview responses, it was clear that there was an acknowledged trade-off between maintaining privacy, especially with other indirect stakeholders such as parents, friends, or the authorities, and making sure that the primary functionality of the safety system worked as well as it could, maximising protection of their welfare.

Preventing System Misuse: The Herd Routes system is designed so that all citizens can use it, but vulnerable pedestrians benefit the most from the creation of safer public spaces. As mentioned previously, this is reliant on location sharing and storing of all system users in an encrypted format. However, to a malevolent system user, Herd Routes could be seen as a search for female pedestrians' locations. Design features could be integrated to encourage proper use, such as the sharing of locations of all users, including any malevolent system user and employing a 'referral system' for new users joining the system. When new users to the system are referred, a chain of user referrals is created. If one user within the chain misused the system, then all of the users linked to that person would also be removed from the application. Adopting a feature like this would mean that the risk of system misuse would decrease, as it is not in the interest of benevolent system users to refer new people who may misuse the system.

Ride-hailing apps, such as Uber[6], all face similar issues regarding system misuse and threat to user safety. In these cases, the success of the application relies on the 'assurance to deliver what is expected and to maintain the trust promised in the mission of the organisation' as stated in Chaudhry et al. (2018). By adding safety features to the application, such as sharing a trip with trusted contacts, real time ID check for drivers, and verifying a trip by using a unique PIN, the risk of system misuse is mitigated.

6. Conclusion & Future Work

In this paper, a novel solution to the pressing issue of improving the safety of female pedestrians in public spaces was proposed. By developing an incentivisation algorithm, which utilised a dynamic pricing controller and integrated with the IOTA Tangle, a proof-of-concept was developed and tested. Hardware-in-the-loop testing allowed real human behaviours to be incorporated into the simulation, and gained preliminary user validation for the concept. The results indicated that this system has the potential to have real impact, not only by improving female pedestrian safety in the short term by generating ideal pedestrian activity on streets to walk down, but also for having longer-term impact on changing the way that all citizens regard the societal behavioural change required to minimise gender-based violence in public spaces.

Directions for future work on the system as a whole include the following. (i) Incorporating a more intelligent method of selecting which routes are incentivised. A

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[6] `https://www.uber.com/gb/en/`

smarter algorithm could be developed by using environmental APIs, the I3 database or using proximity of current system users as an input to the incentivised route generation. (ii) Prototyping the token exchange and developing a stakeholder network to validate the financing of the system. A ‘token conversion’ algorithm would need to be designed. This would calculate how many tokens priced at what value should be transferred to each user based on time spent on the route. (iii) Developing the prototype smartphone application so that it has map navigation functionality and visibility over other system users.

In particular regard to the ergodic control framework used to model the Herd Routes system, multiple directions exist for future exploration and theoretical result development that would be of interest to the control community. Specifically, as mentioned in Remark 1, formal theory concerning the effects of time delays, time variations in agents’ locations and/or behaviours, and the impacts of non-systems users, should be investigated. Preliminary observations in Section 4.1 demonstrated that the time delays (between when an agent decided to use, and then actually arrived at, the incentivised route), and the fact that agents joined and left the network over time, did not appear to destroy the convergence properties of Herd Routes’ steady state behaviour. Other arising theoretical questions concern how long it takes for the convergence of the expected value of the control output to occur, and what the shape of the distribution associated with this expected value looks like. Finally, one can consider whether the feedback system is guaranteed to converge in distribution to a unique invariant measure if it contains multiple different ensembles of agents. This last idea has potential application in the modelling of online labour platforms and two-sided markets, and has been approached in Griggs et al. (2021).

The sum of all of this future work can be encapsulated in a thorough validation of the proposed system in a real-world city. In this paper, for instance, we have used a simple model to imitate a rational human’s behaviour in our simulations (i.e., Figure 6 suggests that, the more a person is offered in payment, the more likely it is that they will go out of their way, with respect to their nominal route, and agree instead to walk along the incentivised route). However, real human behaviour is complex and so this model will likely need to be improved. Real human decision-making should be investigated so that the current model can be enhanced. Furthermore, surveys can be conducted, and historical data from the real-world city be examined in depth, to determine the ideal/desired ‘trusted system user’ pedestrian densities required for individual city streets along incentivised routes.

Acknowledgements

The authors would like to express their thanks and appreciation towards Abigail Langbridge, who provided support and guidance throughout the duration of the project.

The authors have no potential competing interests to report.

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