Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lecture with Computer Exercises: Modelling and Simulating Social Systems with MATLAB

Project Report

Equal Headway Instability

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1. Abstract

Equal headway is a preferred mode of operation of public transportation systems. Passengers can expect when vehicles depart from their location and when they arrive at their desired destination. However, equal headway is not stable. Random factors in the system trigger equal headway instability and the instability may grow, reducing overall efficiency of the system. While previous work focuses on mechanisms carried out by the service provider to increase the stability, this work proposes a mechanism which relies on passengers following instructions issued on site to skip trams. In the simulation model, the proposed mechanism can reduce the mean delay of an urban tram system by a maximum of 90%, without increasing the average number of people waiting at the stations.

2. Individual contributions

The contribution to this work by each member is equal. The MATLAB code was jointly written. For the writing of this report, Edmond was responsible for describing the model and Maicol was responsible for generating and describing the results.

3. Introduction and Motivations

Efficient public transport is crucial to a city. An effective and punctual public transport system minimizes enormous economic costs brought by delays, and helps reduce traffic jam as citizens are more likely to switch to public transport with confidence. However, maintaining such a system is not trivial. Random factors may destabilize the system, making it operate below the optimal level. This project looks into one particular issue, equal headway instability.

Equal headway refers to the ideal condition that vehicles (e.g. tram, bus, train) arrive at regular intervals. Maintaining equal headway is not an easy task, however. Even there is no other traffic between stations, tram or bus services may not achieve equal headway because of the random arrival of passengers. The following simple example illustrates this.

At any time instant, the number of passengers at one station (e.g. station A) may be more than another. Consequently, a tram (tram A) at station A takes longer time to load the passengers than the tram behind (tram B) loading passengers at the station before (station B). Tram A is then delayed, and the distance between tram A and tram B is reduced. When tram B arrives at station A, there are fewer passengers to load than average (because tram A has just left not long ago) and tram B finishes loading earlier than average (because there are fewer passengers to load than average). An instability is then triggered. If the next station tram A arrives has also a larger number of passengers than average, the instability grows. This is described as platooning, which can be characterized by the reduction in distance between tram A and tram B. Note that the tram behind tram B (e.g. tram C), because tram B has finished loading and left earlier than average, has more passengers to load than average at its next station. This will create another similar tram A - tram B platoon in tram C - tram D, for example. It is as well worth noting that the capacity of tram B may not be fully utilized, whereas tram A is full. This indicates inefficiency of the transport of passengers created by this instability.

Various strategies have been proposed in literature to increase the stability of the system (Gershenson & Pineda, 2009). However, the proposed strategies mostly are responsibilities of the service provider while strategies relying on the responsibility of passengers are limited. This project aims to introduce effective and applicable rules on passenger behaviour that increase the stability of the system, so that it self-stabilizes and allows for less uniformity and more randomness in the arrival of passengers. The project focuses on a typical generalized tram service system.

Fundamental Questions

This project aims to answer the question of whether the stability of the system can be increased if passengers follow the instructions of wilfully skipping a tram. The instruction is issued by the incoming tram if:

1) the incoming tram is delayed; and
2) there is another tram closely behind; and
3) the previous tram at this station was not skipped

This report and the comment sections in the code will refer the case of passengers following the instructions as “passenger behaviour” or “people behaviour”.

A tram is said to be ‘closely behind’ if it will take half the headway time for the tram to arrive. That is, if the scheduled headway is 5 minutes, a tram is said to be closely behind if it can arrive within 2.5 minutes.

4. Description of the Model

The model of the simulation is based on what is presented in Gershenson and Pineda (2009), with modifications.

A cyclic track is assumed and the number of trams is equal to the number of stations.

The relative scale of different parameters (e.g. size of a time instant, capacity of a tram) is of importance in the simulation. For a realistic scaling, reasonable values are taken from real-life situations. The following describes the model and the choice of several important parameters and scales.

<u>a. Time</u>

A time instant in the simulation is set to have a length of 30 seconds, and the total duration of the simulation is 3 hours. Therefore, the number of time instants simulated for is 360.

<u>b. Length</u>

The track is discretized into a number of cells. In the simulation, the “length” of a cell equals the length of a tram coach and the length of a station for simplicity. A full cycle of a tram trip has a length of 50 cells.

<u>c. Trams</u>

There are in total 5 trams in the system. At the beginning of the simulation, they are equally distributed across the track (i.e. they are separated by 9 cells from each other), and they are not at any stations (i.e. they are moving). Each tram has a capacity of 60 passengers, which is a realistic number of a typical urban tram coach. Initially they are set to be half-full, so that each tram has 30 passengers on board.

For simplicity, each tram has one coach only. It can be easily changed if necessary, however.

Trams have a speed of 1 cell/time instant. They are assumed to be able to accelerate to this speed in no time, that is, a tram departs a station and moves to the next cell in one time instant. If there is a tram in front, the tram stops until the next cell is empty again. In each time instant a tram can move, remain position and/or load and unload passengers.

d. Stations

Similar to trams, the 5 stations are equally spaced in the system with 9 cells separating every two stations. Stations have an infinite capacity so that there is no limit on the number of passengers waiting at the stations.

e. Passengers boarding and getting off

The addition of passengers into the system follow the Poisson distribution and occurs every time instant. In each time instant, a number of passengers is generated following the Poisson distribution with a pre-set *mean*. Then a random station from the 5 stations is chosen and the generated number of passengers are all assigned to that station in this time instant. This process repeats until the end of the simulation. The mean number of passengers that arrive every time instant is termed “peoplerate” in the code.

If a tram arrives at a station, passengers can get off the tram during a time instant. If there are people waiting at the station, boarding begins after every passenger who wants to get off the tram has got off. Boarding only begins if the conditions for boarding are satisfied. If passenger behaviour is not enabled, passengers at the station can board if the tram is not full. If passenger behaviour is enabled, passengers can board the tram if the tram is not full *and* if the tram did not issue a “not to board” instruction. The conditions of the issuance of the instruction has been described in Section 3.

It is possible for both boarding and getting off the tram to occur in one time instant. A limit on the number of people that can board or get off the tram per tram per time instant is imposed. For example, if the limit is 20, and there are 17 passengers who want to get off the tram, then in this time instant 17 passengers will get off the tram while 3 passengers waiting at the station will board the tram (if there are 3 or more passengers waiting at the station and boarding is allowed by other conditions). The limit is termed the “movement limit” and is represented by variable “pb” in the code.

f. Schedule and delays

The trams in the system follow a schedule. The schedule specifies at which time instant the tram *should leave* the station. If a tram leaves a station at a time later than that specified by the schedule, it is delayed and the extent of the delay is recorded in the system. Whenever a tram leaves a station at a time later than that specified by the schedule, the extent of the delay is recorded and accumulated as a property of that specific tram, and is termed the “accumulated delay”. At the beginning of the simulation, the accumulated delay for all trams is zero.

A realistic schedule has to be set so that trams mostly depart on time for an average passenger load. To achieve this, each tram, after arriving at a station, has to stay for a minimum number of time instants before it can depart, even if there are no passengers who want to get off the tram and there are no passengers at the station who want to board the tram. This minimum number of time instants is set to be 3, which equals 1.5 minutes, and is termed the "minimum waiting time". In setting the schedule, a tram is said to be on time if the number of time instants the tram takes from one departure at a station to the next departure at the next station equals the number of time instants a tram should take to travel from one station to the next station plus the minimum waiting time. For example, recall that every two stations are separated by 9 cells. Thus, it takes a tram 10 time instants to travel from one station to the next (speed = 1 cell/instant). Assuming the minimum waiting time of 3 time instants can accommodate the passenger load (passengers can complete boarding and getting off in 3 time instants), the tram should leave this station 10 + 3 = 13 instants after the departure of the previous station.

It is worth noting that, for a low passenger load, maintaining a minimum waiting time optimal for an average load decreases the efficiency of the system. Yet, maintaining a minimum waiting time optimal for an average load when there is a high passenger load inevitably creates delays. The search for an optimal minimum waiting time is not the focus of this project.

5. Implementation

The implementation of the model in MATLAB is straightforward. A “current” matrix is defined which contains the current status of the system, e.g. positions of the trams, number of passengers on-board each tram and waiting at the stations, delays of the trams, etc. During each time instant iteration, a series of commands are computed to define a “transition” matrix. The “transition” matrix is of the same structure as the “current” matrix, but the information it contains represents the status of the system at the next time instant. At the end of each time instant iteration, the information in the “transition” matrix is simply copied to the “current” matrix.

In the code, the “current” matrix is a while the “transition” matrix is b.

<u>Research Methods</u>

The MATLAB code will generate two parameters for comparison between the two scenarios, namely, with and without passenger behaviour.

The values for comparison include:
1) the average number of people waiting at the stations at the end of the simulation; and
2) the mean delay of trams at the end of the simulation

A number of simulations are carried out with different mean values for the Poisson distribution that the arrival of passengers follow. It is expected to give insights to how the passenger behaviour strategy reacts to an increasing passenger load, compared to that without passenger behaviour strategy.

6. Simulation Results and Discussion

The simulations were computed with the following parameters:

```
tracklength = 50;                    % length of the track

initpostram = [10 20 30 40 50];      % initial position of trams
inittrampass = [30 30 30 30 30];     % initial number of tram passengers
posstat = [5 15 25 35 45];           % position of the stations

minwaitingtime=3;                    % if a tram is not delayed, the
                                     minimum number of waiting time
                                     instants of the tram at a station

pb=20;                               % movement limit
cap=60;                              % tram capacity

duration_simulation = 180;           % duration of the simulation in
                                     minutes
ntimeinstant=duration_simulation*2;

behaviour=true;                      % whether a tram can skip the
                                     station if the tram is delayed and
                                     another tram is close behind

peoplerate=1:40;                     % Mean number of people arriving
                                     at a random station for each
                                     instant of time
```

A total of 60 simulations were evaluated and the results averaged on themselves. The values obtained are the average trams delay, the average people waiting at the stations, and the total number of tram skipped by the people. It is important to note that the values refer to the last instant of time of each simulation, and that are all related to the same boundary conditions imposed and so only functions of the changing mean people arrival rate.

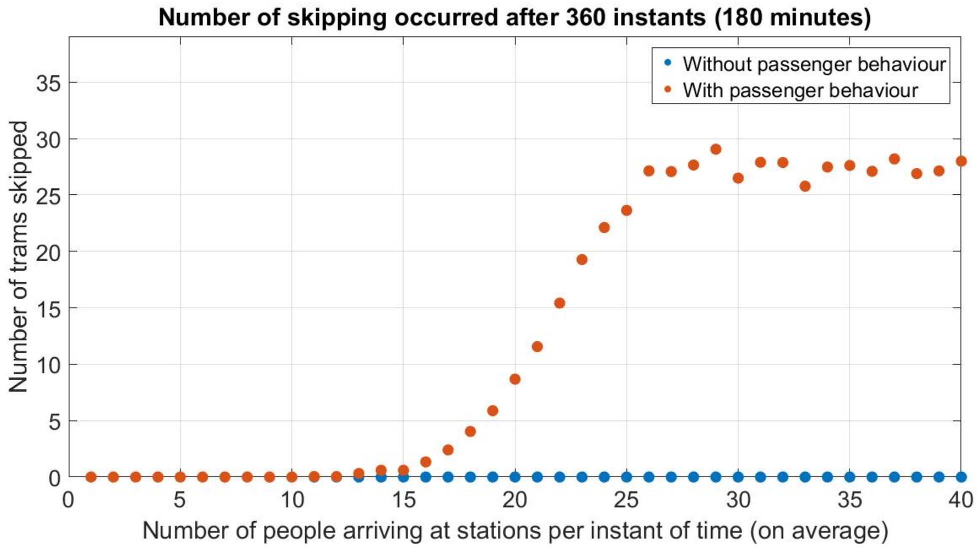

Figure 1 Number of skipping occurred at the end of simulation (after 180 minutes)

In Figure 1, it is possible to see the number of skipped trams as a function of the people arrival rate. It is easy to notice 3 areas:

- The first area refers to people rate going from 0 to 12, where the condition of skipping a tram are never satisfied.
- The second area goes from 13 to 25. In this area, we see a rise in the number of skipped trams. This is the area where the people behaviour plays a fundamental role.
- The third area goes from 26 to 40. Here, it is possible to see that the number of skipped trams reach a saturation value. This value is function of the boundary condition imposed for the simulation (principally number of trams and duration of the simulation).

It is important to notice that the values relative to these three areas are valid only for the boundary condition imposed at the beginning of the simulation. It is clear that, changing one of these conditions (for example, number of trams in the track) the three zones will adapt consequently.

In Figure 2 and Figure 3, it is possible to notice the influence of the people behaviour on the overall system dynamics. Here we would like to point out the two major effects: the effective reduction of the trams delay and the increasing of people waiting at the station. The first one is the desired effect: when a tram is delayed, if people are instructed not to board, then the tram can recover some time, reducing the overall delay. On the other hand, if people are instructed to skip a tram, then the station will be crowded for more time. This is of course the biggest drawback of the strategy of "people behaviour".

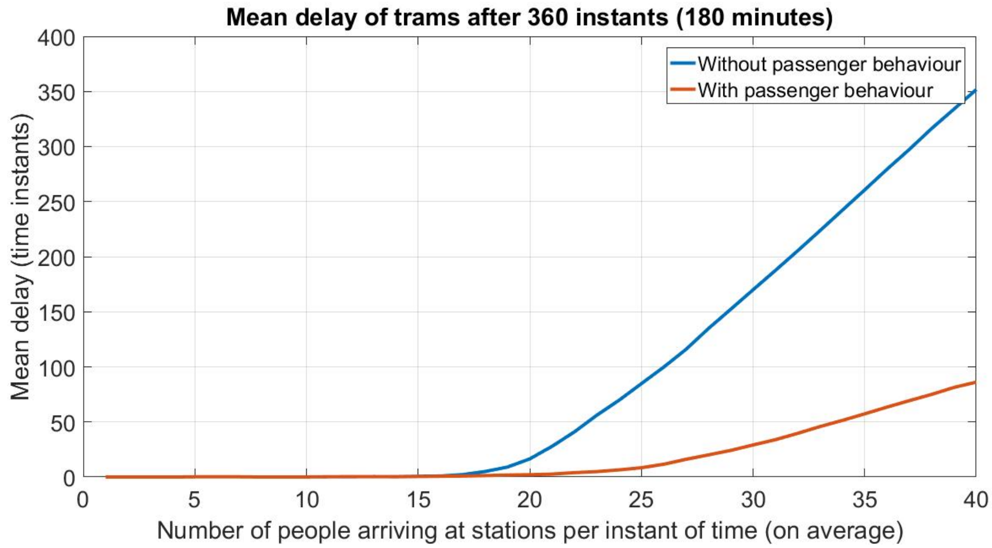

Figure 2 Mean delay of trams at the end of simulation (after 180 minutes)

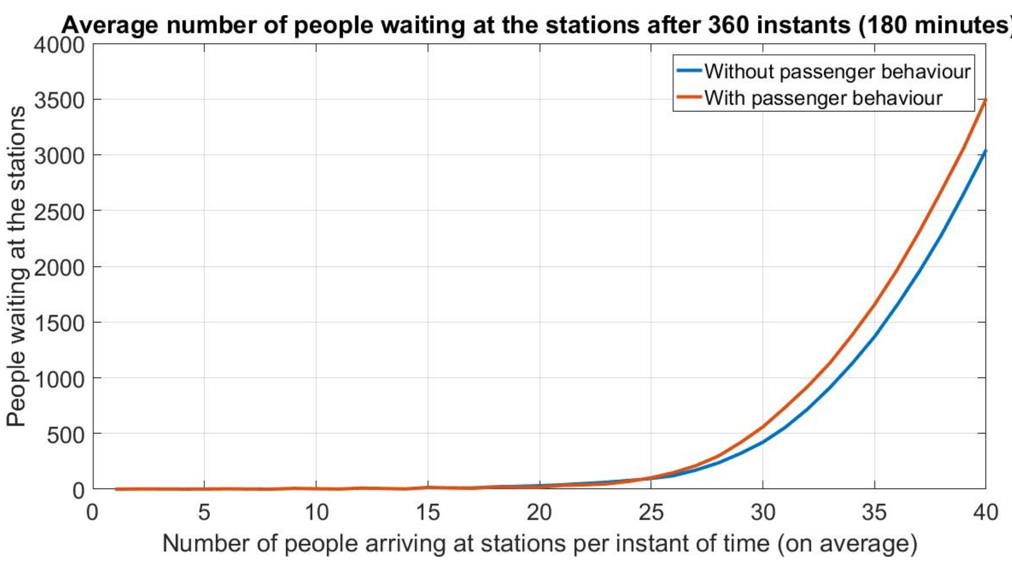

Figure 3 Average number of people waiting at the stations at the end of simulation (after 180 minutes)

The most interesting part corresponds to the second area (peoplerate = 13 to 25), in which the passenger behaviour begins to play a role in the dynamic before reaching a saturation point. See Figure 4 and Figure 5. The first thing we would like to point out is that, although people are skipping a tram and so the station are more crowded, the overall number of people waiting at the station is fewer than or equal to that in the case of no "people behaviour" (in the range considered in Figure 5). This is due to that the improved efficiency of the trams, which have the possibility to cover the track in a uniform way (i.e. no platooning effect due to the delay), achieves a smoother and better transportation of people.

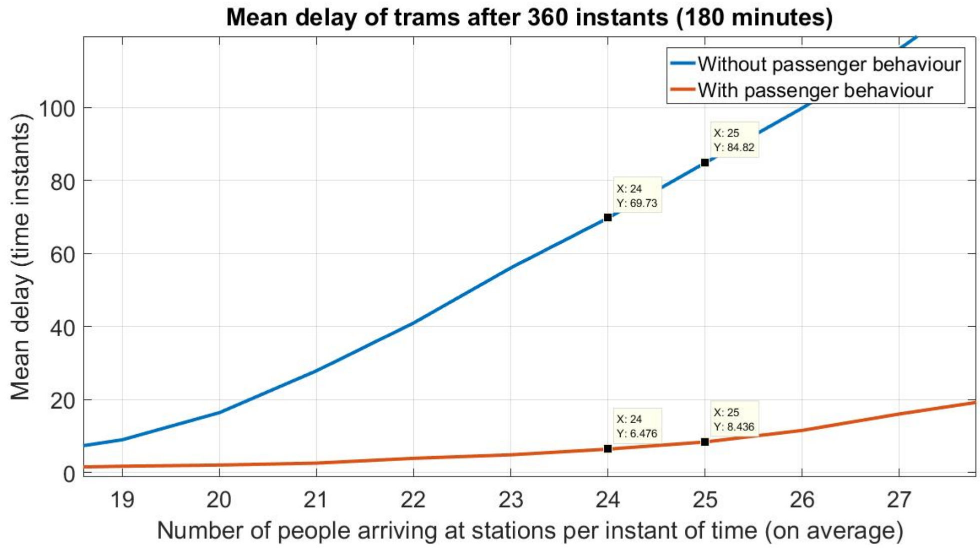

Figure 4 Mean delay of trams at the end of simulation (after 180 minutes) (Zoomed-in)

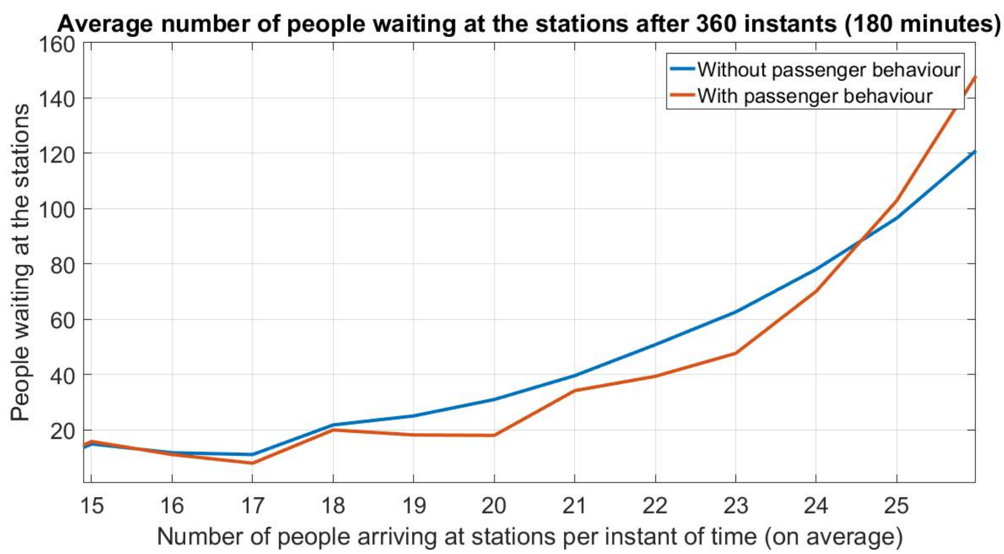

Figure 5 Average number of people waiting at the stations at the end of simulation (after 180 minutes) (Zoomed-in)

If we now look at the trams delay (Figure 4), we can see that the people behaviour brings a reduction of the overall delay of the 90% and 89% respectively for peoplerate of 24 and 25, without increasing the average number of people waiting at the station.

7. Summary and Outlook

The above results open an interesting prospect for the improvement of the efficiency of the public transportation system. In this simulation, in a stable situation, a tram arrives at a station each 6.5 minutes (13 time instants, including minimum waiting time). We instructed people to skip the boarding of a tram if the arriving tram at the station was delayed and if there was another one coming within the half of the time (i.e. 2 minute and 30 seconds). The simulation proved that choosing to lose that time brings a benefit to all the other passengers. This corresponds to the old dilemma whether to maximize our own profit penalizing others (i.e. don't lose more time) or to cooperate in order to achieve a higher benefit for everyone, renouncing at maximizing the personal gain.

It may be argued that the results depend on the specific parameters chosen for the simulation (e.g. number of trams, minimum waiting time at the stations, etc.). This project, however, does not focus on the numerical values of the results, but rather the existence and qualitative behaviour of the phenomenon when the strategy of passenger behaviour is implemented. We have observed the same results in the qualitative sense for the range of parameters we varied.

This work has implemented a simulation model based on the previous study by Gershenson and Pineda (2009), and added and investigated the effects of the behaviour of passengers on equal headway instability. Results from this simple model highlighted the advantages brought by passenger behaviour. Nevertheless, there are suggestions for further development of this model. Further work can include road traffic as road traffic acts as one more random factor which may destabilize the system. Whether the implementation of passenger behaviour can make the system more resistant to road traffic incidents is worth investigation. Further work can as well explore unequally distributed stations, or that some stations are in busier districts so they have higher passenger arrival rates. Less uniformity of the system imposes a more difficult test to a mechanism.

8. References

Gershenson, C., & Pineda, L. A. (2009). Why Does Public Transport Not Arrive on Time? The Pervasiveness of Equal Headway Instability. PLoS ONE, 4(10), e7292. http://doi.org/10.1371/journal.pone.0007292