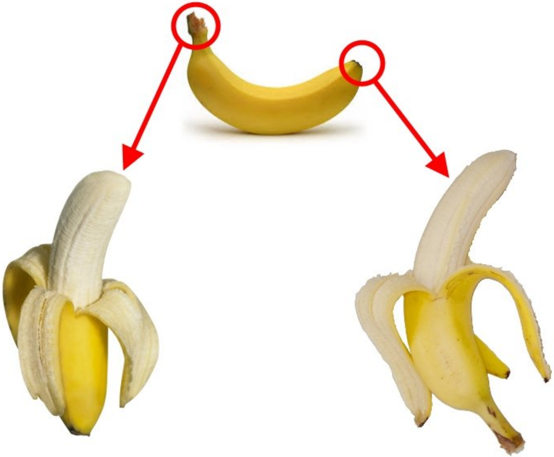
Hybrid Cyclicity: Combining The Benefits Of Cyclic And Non-Cyclic Timetables

The main product of a Train Operating Company is a train timetable.

What is a timetable?

A railway timetable is defined as a set of arrival and departure times of every train from each of its stopping stations.



Two types of timetables exist: Cyclic and Non-Cyclic.

The cyclic timetable originates from the Periodic Event Scheduling Problem (PESP), which was first defined by Serafini and Ukovich (1989).

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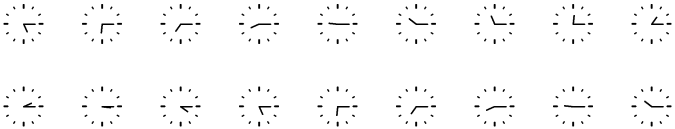
A set of events is scheduled in an equally spaced intervals, *e.g.* STRC - approx. every 365 days.

A special subset of cyclicity is the clockfaced timetables:



Event every xx:15.

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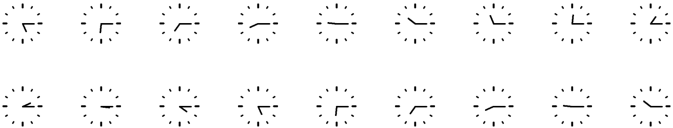
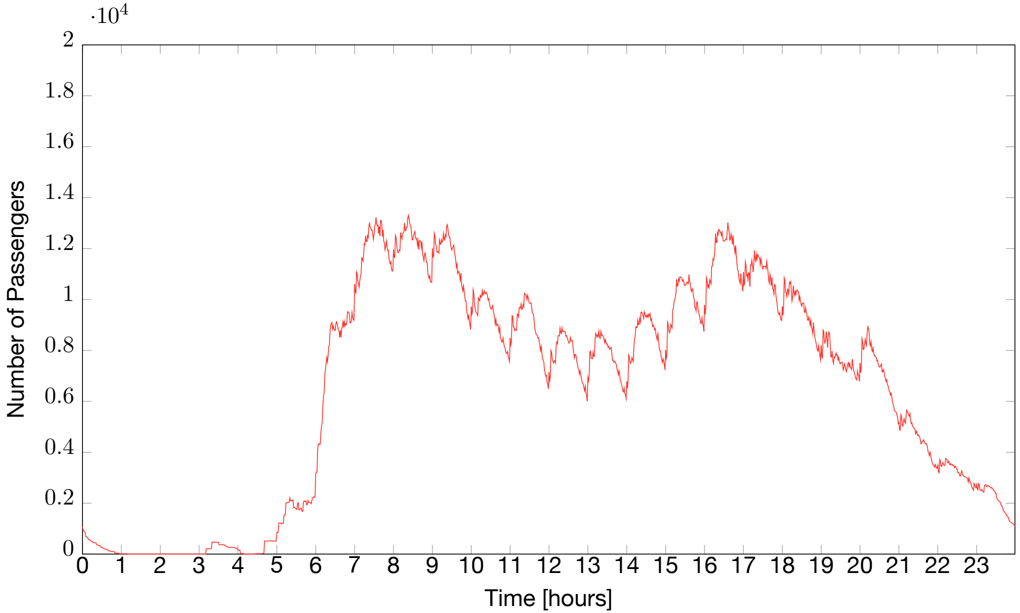


Event every xx:15. Especially popular within:

Issue: The demand is not uniformly distributed.



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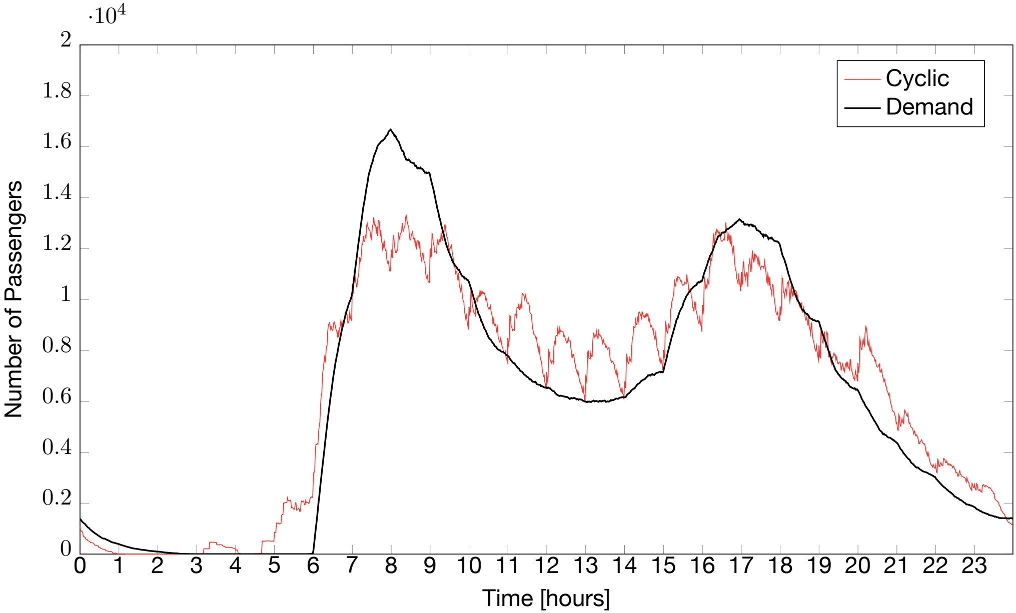

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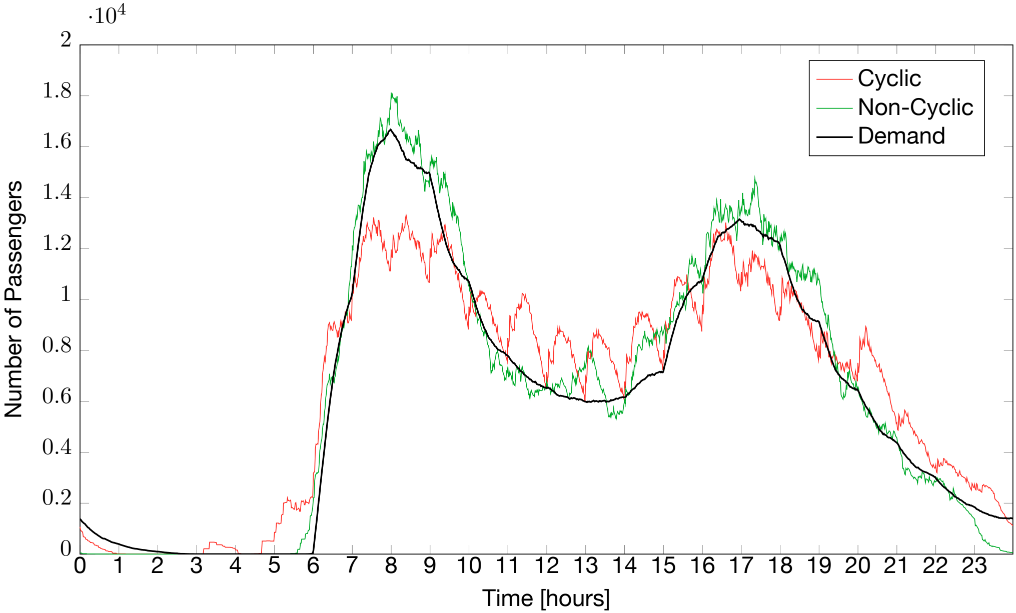

Passengers find the regularity of a timetable easier to be memorized (Wardman et al. (2004), Johnson et al. (2006)).

Therefore one is not superior to the other.

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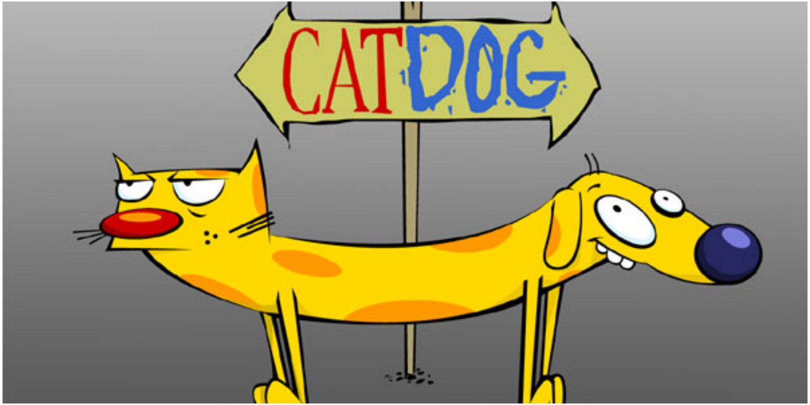

Why not both?

What we want to combine and how:

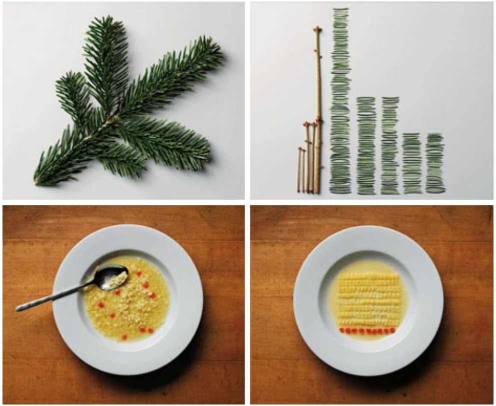

Figure: Ursus Wehrli

Regularity: Taken care of by the design

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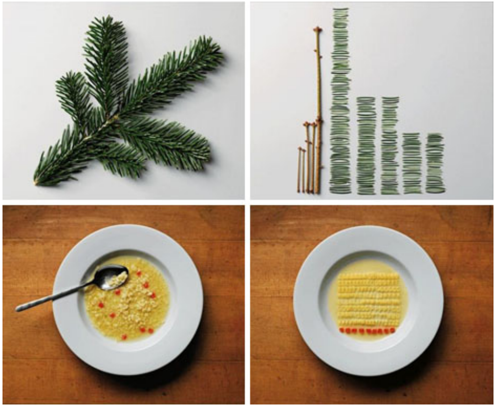
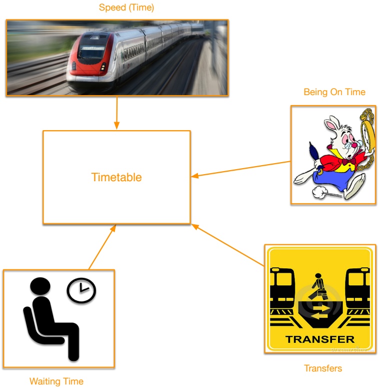


Figure: Ursus Wehrli

Regularity: Taken care of by the design



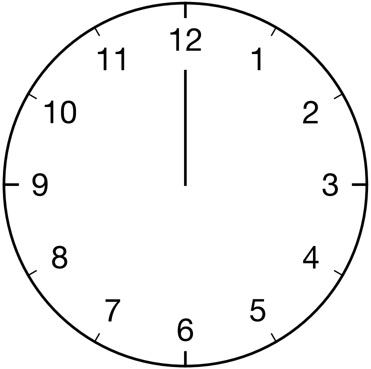
Flexibility: Passenger satisfaction, maximized by solving the Passenger Centric Train Timetabling Problem

$$\mathcal{S}_i^{tp} = -VOT \cdot \left(\sum_{\ell \in L^p} r_i^{p\ell} + \beta_W \cdot w_i^{tp} + \beta_T \cdot (|L^p| - 1) + \beta_E \cdot \delta_{ip}^t + \beta_L \cdot \gamma_{ip}^t \right), \qquad \forall i \in I, \forall t \in T_i, \forall p \in P_i,$$

$r_i^{p\ell}$	–	running time/ in-vehicle time
w_i^{tp}	–	waiting time
$\lvert L^p \rvert - 1$	–	number of transfers
δ_{ip}^t	–	early schedule passenger delay
γ_{ip}^t	–	late schedule passenger delay
$-VOT$	–	value of time
$\beta_W, \beta_T, \beta_E, \beta_L$	–	estimates from literature

What are the combinations?

θ Shifted Cyclic Timetable

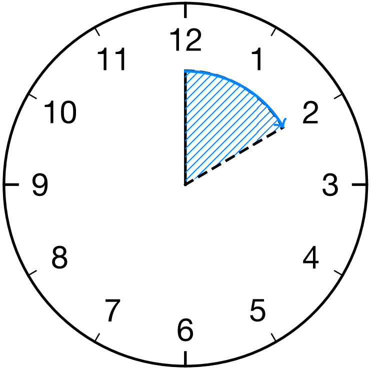


$\Delta_v^\ell \in <-\theta, \theta>$

For a cycle of 60 minutes:

- $\theta = 0$ is equivalent to the cyclic timetable
- $\theta = 30$ is the maximum deviation without overlapping trains
- We test values between 0 and 30 in 3 minute intervals

θ Shifted Cyclic Timetable



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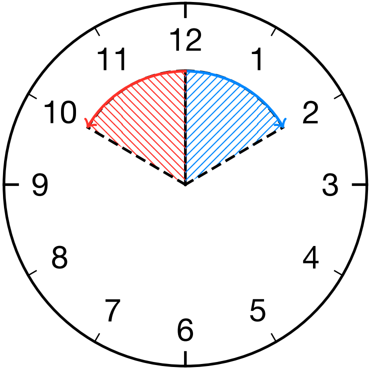
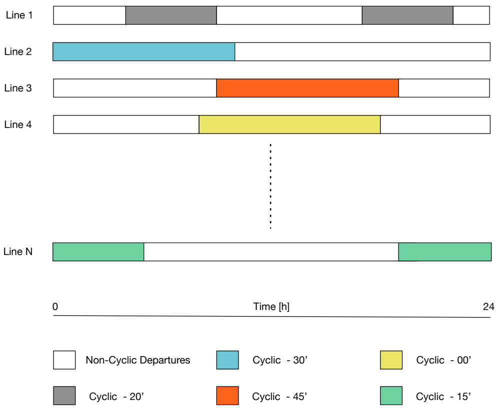


$\Delta_v^\ell \in < -\theta, \theta >$

For a cycle of 60 minutes:

- $\theta = 0$ is equivalent to the cyclic timetable
- $\theta = 30$ is the maximum deviation without overlapping trains
- We test values between 0 and 30 in 3 minute intervals

ξ Partially Cyclic Timetable



$$\eta = max(|V^{\ell}|) \cdot \frac{\xi}{100}$$

η trains per line have a cyclic departure time, the rest is free

For a cycle of 60 minutes:

- $\xi = 0$ is equivalent to the cyclic timetable
- $\xi = 100$ is equivalent to the non-cyclic timetable
- We test values between 0 and 100 in 10% intervals

Hybrid Cyclic Timetable

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	0	0	0	0	1	2	2	1	2	1	1	0	1	1	1	1	0	2	0	1	1	0	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	0	1
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	3	2	2	1	0	0	2	0	1	1	2	1	0	0	0	1	0	0
0	0	0	0	0	0	1	1	2	0	1	1	0	1	1	3	1	2	0	1	1	0	1	0
0	0	0	0	0	0	1	0	1	1	0	1	1	0	1	1	1	1	0	1	1	0	0	0
0	0	0	0	0	0	1	1	3	2	0	0	0	0	0	0	1	1	2	0	0	0	0	0
0	0	0	0	0	0	1	3	0	2	0	0	0	0	0	2	2	1	0	2	0	0	0	0
0	0	0	0	0	0	2	1	3	0	2	0	0	0	2	0	1	1	0	0	0	0	0	0
0	0	0	0	0	0	2	2	2	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	2	1	0	0	0	2	1	2	1	2	1	2	1	0	0	1	0
0	0	0	0	0	1	1	3	1	1	0	2	1	1	1	2	1	3	0	0	0	0	0	0
0	0	0	0	0	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	2	1	0	0	0	0
0	0	0	0	0	0	1	2	0	0	1	1	0	0	0	0	1	0	0	0	1	0	0	0
0	0	0	0	0	0	2	1	1	1	0	1	0	1	2	1	3	1	1	1	1	0	1	0
0	0	0	0	0	0	2	3	1	1	1	0	2	0	0	1	1	1	2	2	0	1	0	0
0	0	0	0	0	0	1	1	2	0	0	1	3	1	0	3	1	1	1	0	0	0	0	0
0	0	0	0	0	1	2	1	1	1	1	1	1	0	1	1	1	1	2	0	1	0	0	0
0	0	0	0	0	0	0	0	1	2	1	1	0	0	0	0	0	1	1	1	0	1	0	0
0	0	0	0	0	0	0	1	3	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	1	1	1	1	0	1	1	0	1	2	2	1	2	2	1	1	0	0	0
0	0	0	0	0	1	3	1	2	2	1	0	0	1	0	2	1	1	0	1	1	1	0	0
0	0	0	0	0	0	1	0	2	2	0	1	0	1	1	1	2	0	0	2	0	0	0	0
0	0	0	0	0	0	0	3	1	1	2	0	2	0	1	1	1	0	2	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	3	0	0	0	0	0
0	0	0	0	0	0	0	2	1	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	0	0	0	1	1	0
0	0	0	0	0	0	2	2	0	0	0	1	0	1	1	1	0	0	1	0	0	0	0	1

A cycle can have:

- no train
- a cyclic train
- a cyclic train and one or more non-cyclic ones

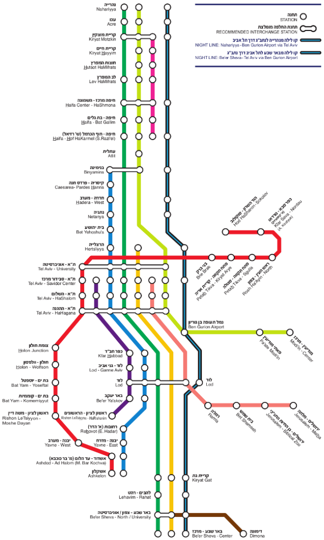
Model

$$\max \ \textit{satisfaction} \tag{1}$$
$$\textit{satisfaction function} \tag{2}$$
$$\textit{at most one path per passenger} \tag{3}$$
$$\textit{link trains with paths} \tag{4}$$
$$\textit{cyclicity} \tag{5}$$
$$\textit{train scheduling} \tag{6}$$
$$\textit{train capacity} \tag{7}$$
$$\textit{schedule delay} \tag{8}$$
$$\textit{waiting time} \tag{9}$$

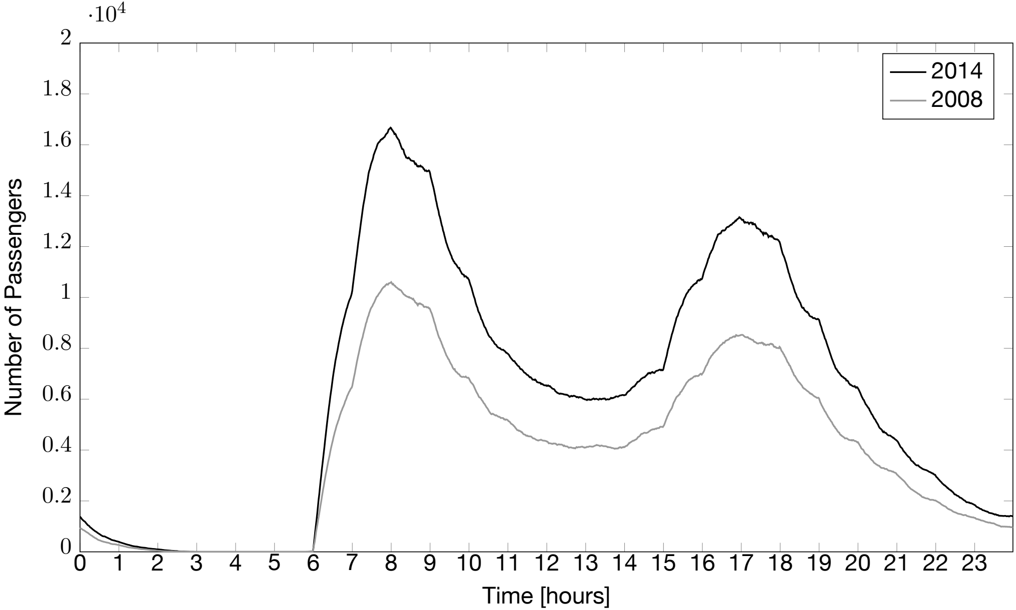
Methodology: Simulated Annealing

Case Study

Israel 2008



- OD Matrix for an average working day (Sunday to Thursday) in Israel during 2008
- 47 Stations
- 2162 ODs
- 34 (unidirectional) lines
- 380 trains
- Min. transfer – 4 mins
- VOT – 21.12 NIS per hour
- 126 036/193 886 Passengers



·10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Number of Passengers
2014
2008
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time [hours]

	IR 13/14 as Strictly Cyclic	IR 13/14	cyclic	non-cyclic	perfect service
satisfaction [NIS]	-704 904	-537 503	-476 774	-424 529	-2 089 049
drivers [-]	470	388	388	388	48 960
rolling stock [-]	940	776	776	776	48 960
covered [%]	100	100	100	100	100
time [sec]	12	6	24 997	25 613	1

Table: *Computational results of the existing timetables for the 2008 demand*

	IR 13/14 as Strictly Cyclic	IR 13/14	cyclic	non-cyclic	perfect service
satisfaction [NIS]	-3 792 733	-3 379 596	-2 392 909	-1 365 779	-3 171 721
drivers [-]	470	388	388	388	48 960
rolling stock [-]	940	776	776	776	48 960
covered [%]	99.17	99.32	99.32	99.23	100
time [sec]	11	8	86 627	88 342	2

Table: *Computational results of the existing timetables for the 2014 demand*

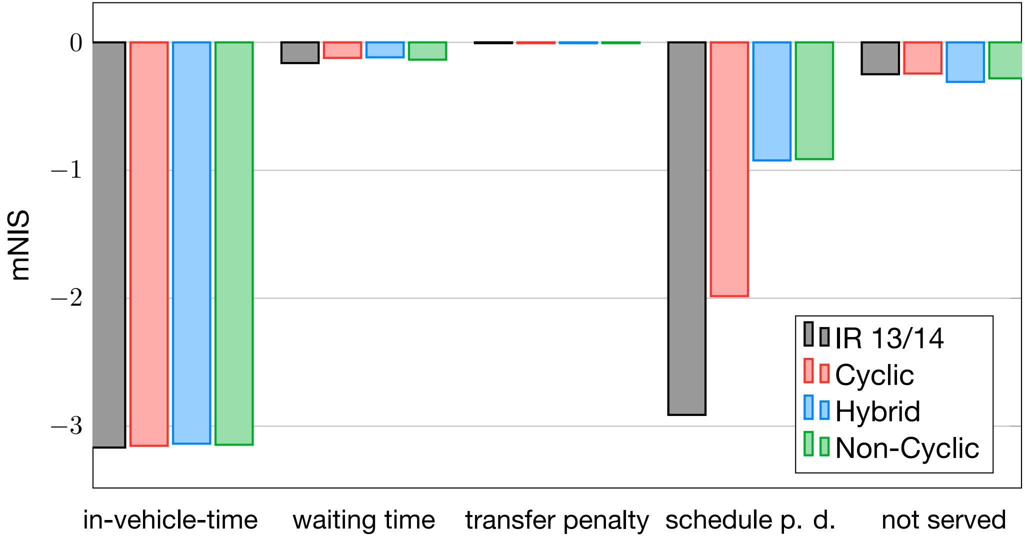
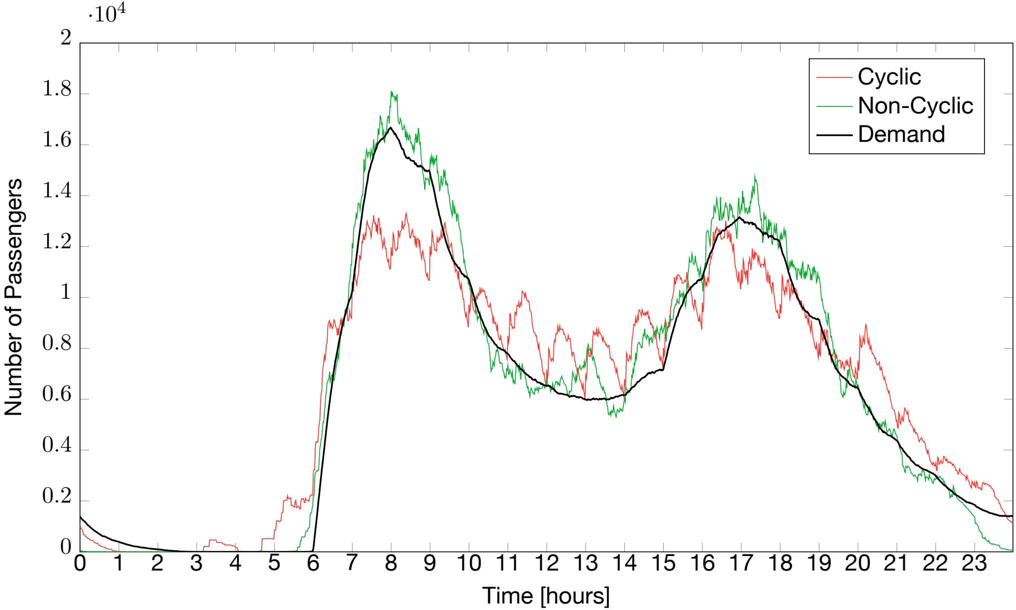
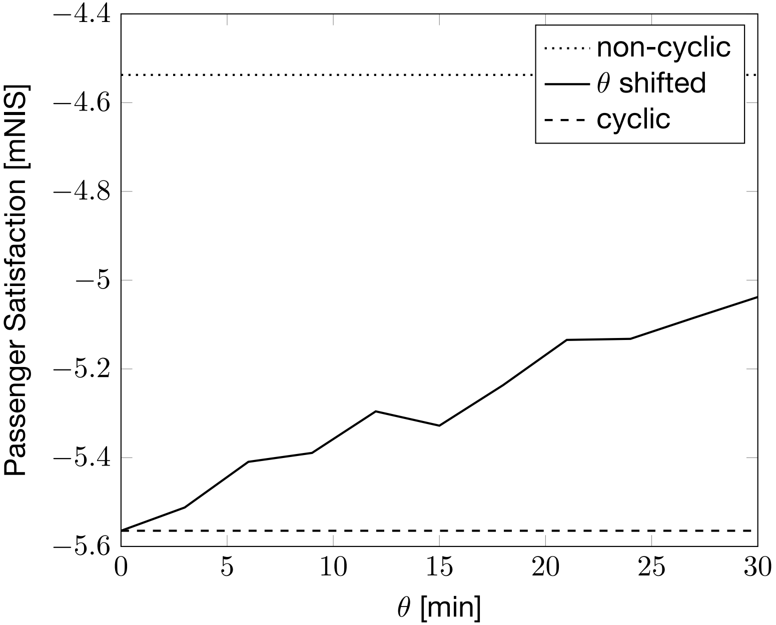


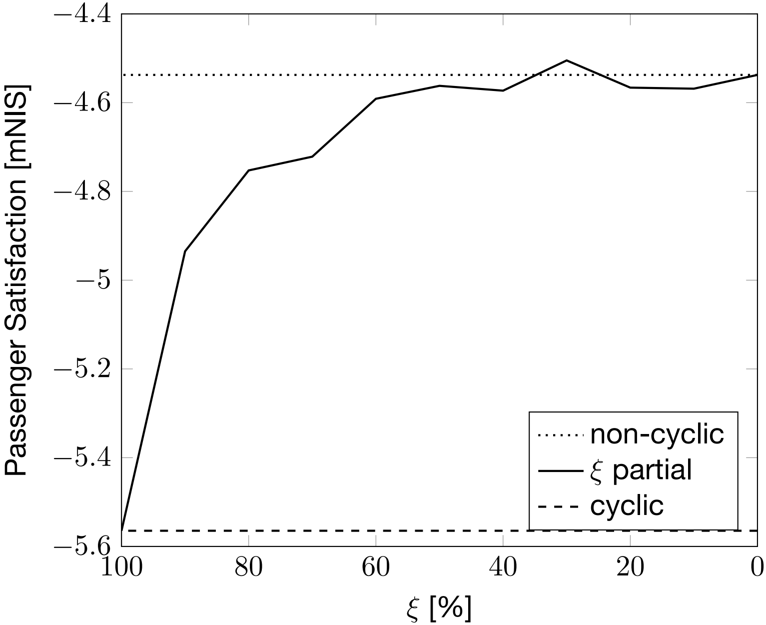
Figure: *Breakdown of the passenger satisfaction for various timetables under the 2014 demand*



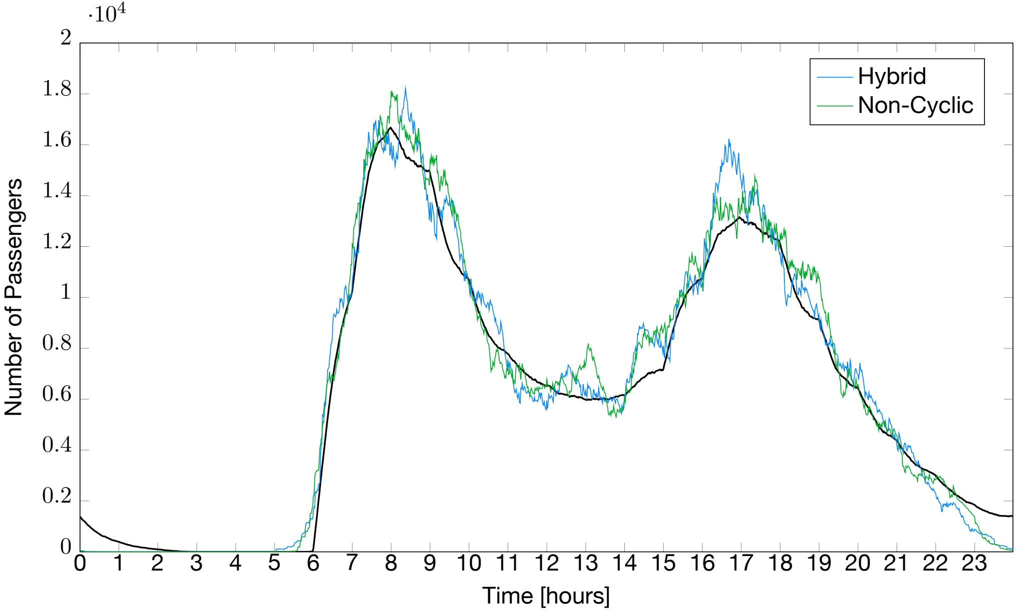
·10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Number of Passengers
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time [hours]
Cyclic
Non-Cyclic
Demand



−4.4
−4.6
−4.8
−5
−5.2
−5.4
−5.6
Passenger Satisfaction [mNIS]
0
5
10
15
20
25
30
θ [min]
non-cyclic
θ shifted
cyclic



−4.4
−4.6
−4.8
−5
−5.2
−5.4
−5.6
Passenger Satisfaction [mNIS]
100
80
60
40
20
0
ξ [%]
non-cyclic
ξ partial
cyclic



·10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Number of Passengers
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time [hours]
Hybrid
Non-Cyclic

Conclusion

Case Study

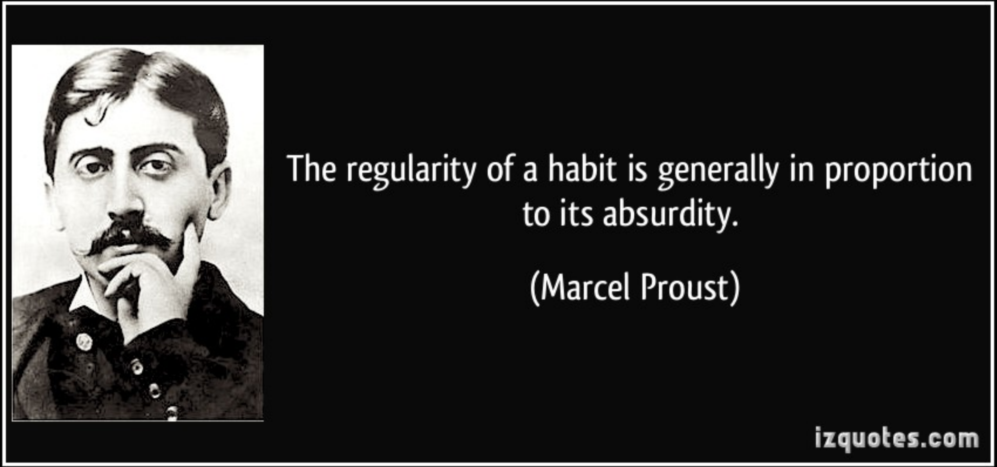
- Difference in Pax. Sat. between cyclic and non-cyclic timetable: 18.5%
- θ Shifted Timetable can reduce the difference to a half
- ξ Partially Cyclic can diminish the difference already at $\xi = 60$ with a train ratio 3:1
- Hybrid Cyclic finds the same ratio, provides good level of service

General

- As the demand is time dependent, purely cyclic timetable is not a good option
- Hybrid cyclic timetable can diminish the impact of the cyclicity constraints

Future Work

- Elastic Demand
- Need of an opt-out
- Maximize Profit
- Adapt Pricing Scheme



Thank you for your attention.

References

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Serafini, P. and Ukovich, W. (1989). A mathematical model for periodic scheduling problems, *SIAM J. Discret. Math.* **2**(4): 550–581.

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