How does rail perform against autonomous buses? Two case studies in Switzerland

Marc Sinner

Ulrich Weidmann

Institute for Transport Planning and Systems, ETH Zurich

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Marc Sinner
Institute for Transport Planning and Systems
ETH Zurich
Stefano-Franscini-Platz 5
8093 Zürich
marc.sinner@ivt.baug.ethz.ch

Ulrich Weidmann
VPPR
ETH Zurich
Rämistrasse 101
8092 Zürich
weidmann@sl.ethz.ch

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Abstract

The emergence of autonomous buses has potentially large consequences within the system of public transportation. At the moment, buses have low fixed costs and high marginal costs. For each additional bus put in operation to increase the available capacity, an additional driver has to be paid a salary. On the other hand, rail has high fixed costs and lower marginal costs. With autonomous buses, the comparative advantage of rail in terms of economies of scale is coming under pressure.

In this paper, the conclusions of a doctoral thesis aiming at the holistic assessment of the competitive situation of trains and buses in regional transport shall be presented. It establishes a framework including a cost-allocation model for operating cost of trains and buses, the maintenance cost of infrastructure as well as the possibility to take into account non-monetary benefits such as shorter travel or access times.

After presentation of the main results of the aforementioned assessment framework, the latter shall be applied to two case studies of regional railway lines in Switzerland: Schwanden – Linthal and St. Gallen – Weinfelden.

Keywords

autonomous bus, automated train, costs, travel times, access times, Schwanden, Linthal, St. Gallen, Weinfelden, Gossau, Sulgen

1 Introduction

Autonomous driving technology is one of the major subjects of current research in transportation. As soon as cars can be driverless, the same also applies to buses. The required technology is not fundamentally different. The emergence of autonomous buses has potentially large consequences within the system of public transportation. Buses currently have low fixed costs and high marginal costs. For each additional bus put in operation to increase the available capacity, an additional driver has to be paid a salary. On the other hand, rail has high fixed costs and lower marginal costs. With autonomous buses, the comparative advantage of rail in terms of economies of scale is coming under pressure.

The **effects of the autonomous bus on the railway system in regional traffic** are the core topic of the main author's dissertation being submitted later this year. This paper contains case studies of the following two railway corridors which have been carried out as a part of this thesis:

1. **Schwanden – Linthal**
2. **St. Gallen – Weinfelden**

2 Cost parameters

Before the actual case studies, this section summarizes the cost parameters which are going to be used. Their development is explained in detail in the forthcoming dissertation. Parts of them have been published as the following papers: Sinner et al. (2018a,b), Sinner & Weidmann (2018). The comparison of bus and train services from the perspective of the public contracting authority is done at three different levels stacking up as shown by the blocks in Figure 1:

- **Level 1 - Operating costs**, with costs of train infrastructure being accounted as laid down in SBB Infrastruktur (2017);
- **Level 2 - Total cost criteria**, with inclusion of full-costs of infrastructure of both rail and bus;
- **Level 3 - Generalized costs** with inclusion of monetarized benefit criteria, being travel time, access time and transfers.

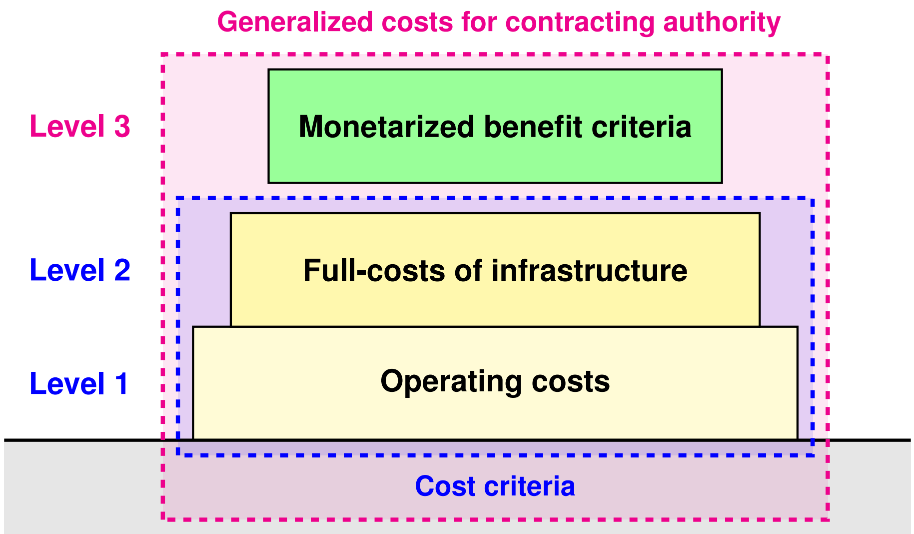


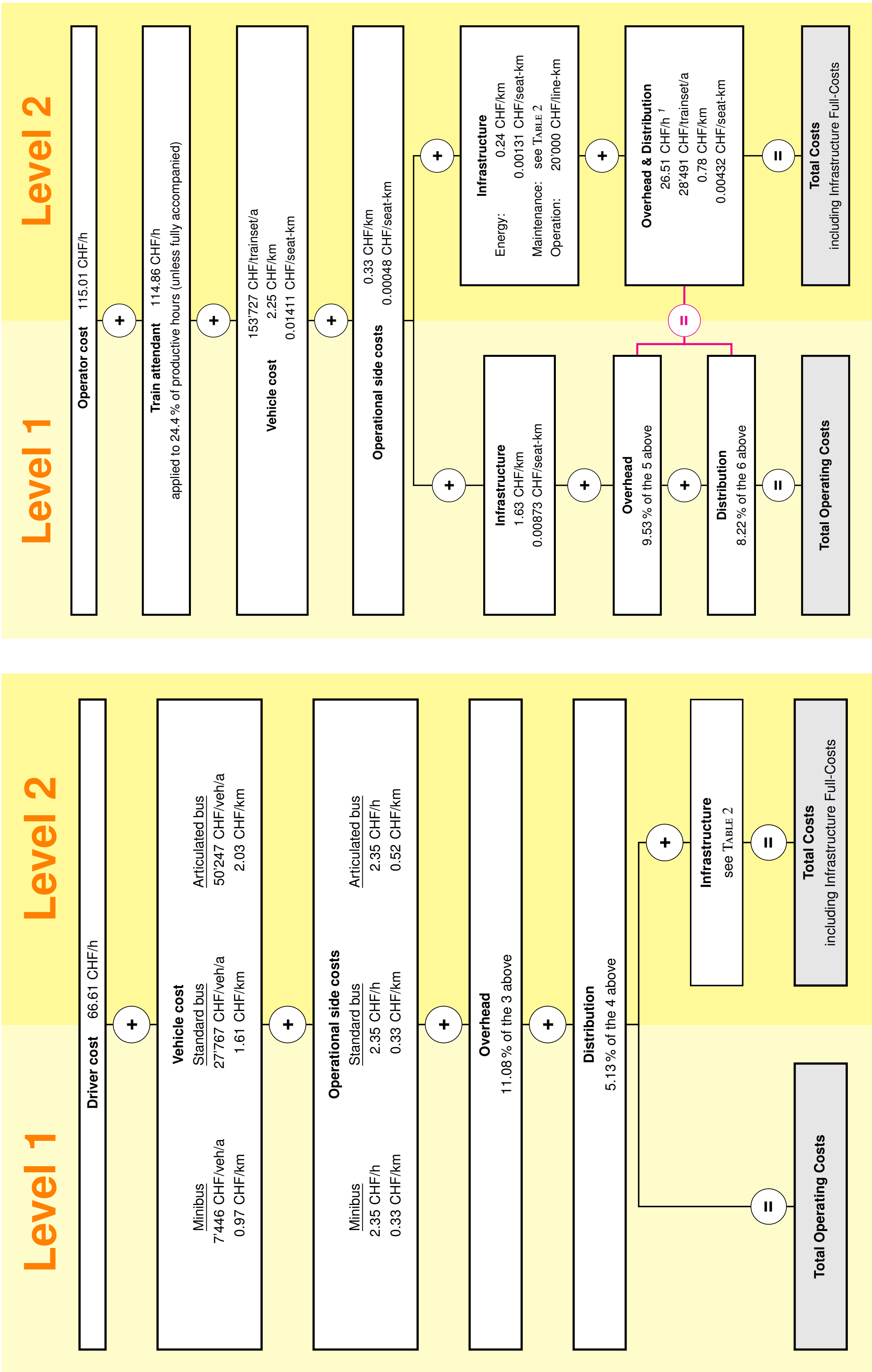
FIGURE 1: Levels of comparison for decision model

Costs at both comparison levels 1 and 2 are calculated along the procedures given in FIGURES 2(a) and 2(b) for conventional buses and trains respectively. The necessary details for the inclusion of infrastructure full-costs of conventional systems at comparison level 2 are given in TABLE 2. Benefit criteria are monetarized by using the WTP-values in TABLE 1.

TABLE 1: Relevant WTP-values

		All purposes	Commuting	Business	Leisure	Shopping
VTTS PT	[CHF/h]	15.92	17.75	39.43	13.25	13.60
Access time	[CHF/h]	26.63	25.87	71.69	25.15	11.69
Transfers	[CHF]	2.70	2.22	4.11	2.75	2.24

Cost parameters of autonomous buses and automated trains at levels 1 and 2 are given in FIGURES 3(a) and 3(b). The variable $n_{\mathrm{max,veh}}$ designates the maximum number of vehicles in service on the line under consideration throughout one week day. This maximum is generally occurring during the peak hours. The necessary details for the inclusion of infrastructure full-costs of automated / autonomous systems at comparison level 2 are given in TABLE 3.



(a) Conventional bus costs

(b) Conventional train costs

Figure 2: Costs of conventional systems at levels 1 and 2

TABLE 2: Infrastructure maintenance cost of conventional systems

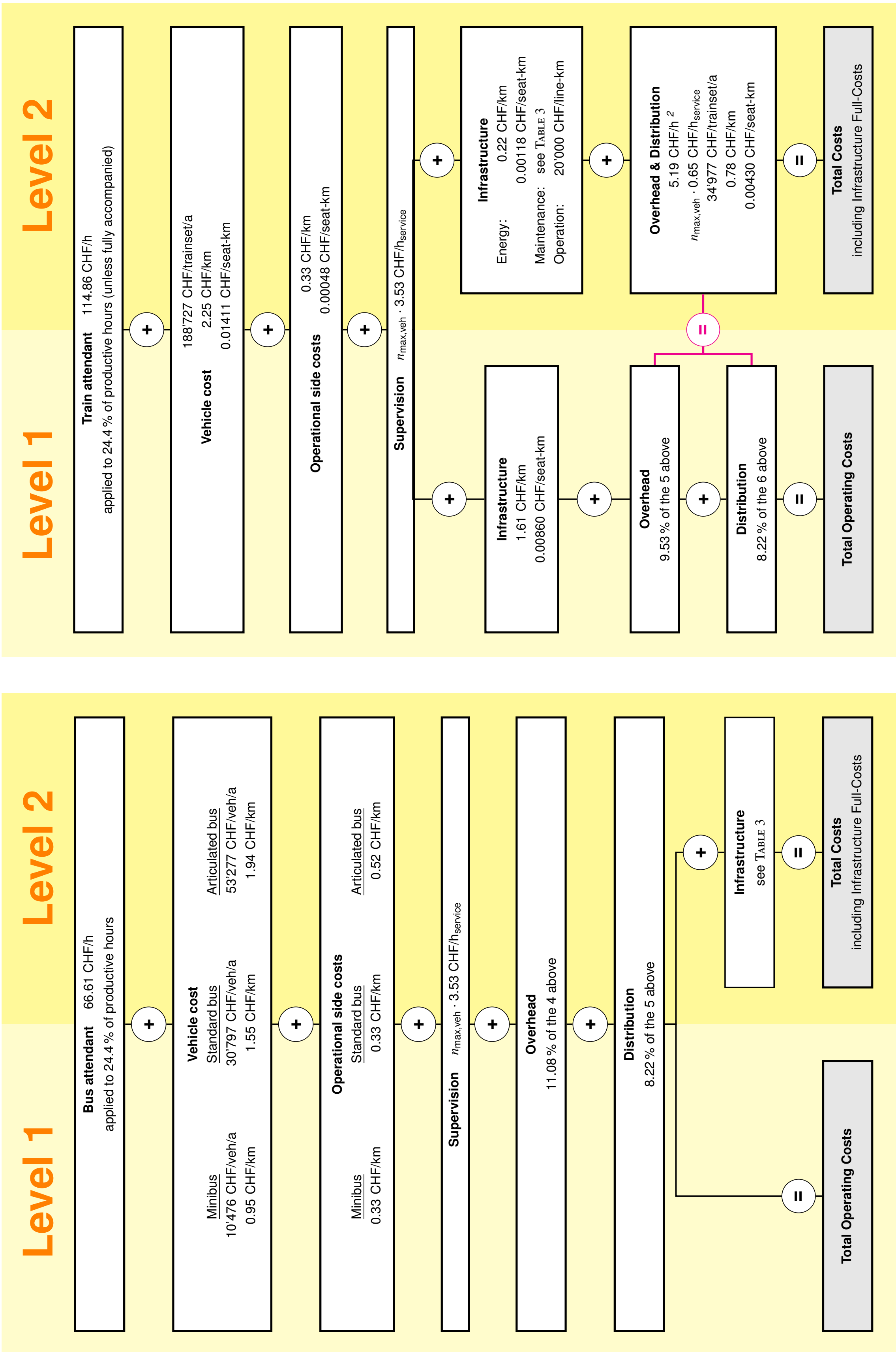
Infrastructure component		**Maintenance cost**
BUS INFRASTRUCTURE		
Bus infrastructure along non-dedicated roads		2'150 CHF/km/a
Ordinary road	single-lane	35'700 CHF/km/a
	double-lane	38'200 CHF/km/a
Tunnel	$l < 600\,\mathrm{m}$	86'600 CHF/tunnel-km/a
	$600\,\mathrm{m} < l < 2000\,\mathrm{m}$	167'000 CHF/tunnel-km/a
	$l > 2000\,\mathrm{m}$	251'000 CHF/tunnel-km/a
Bridges	single-lane	495'700 CHF/bridge-km/a
	double-lane	728'200 CHF/bridge-km/a

NOTE: Cost figures of bus infrastructure are mutually exclusive!

TRAIN INFRASTRUCTURE		
Track (rails, sleepers, etc.)		4'500 CHF/km/a + 0.00166 CHF/seat-km
Substructure		2'600 CHF/km/a
Train protection equipment		15'400 CHF/km/a
Overhead line		3'400 CHF/km/a
Telecommunications		5'100 CHF/km/a
Total		**31'000 CHF/km/a + 0.00166 CHF/seat-km**
Switches		12'900 CHF/switch/a
Tunnel	single-track	66'000 CHF/tunnel-km/a
	double-track	93'000 CHF/tunnel-km/a
Bridge	single-track	460'000 CHF/bridge-km/a
	double-track	690'000 CHF/bridge-km/a
Stations		9'400 CHF/platform/a

NOTE: Cost figures of train infrastructure are additive, with the exception of the substructure which is mutually exclusive with tunnels and bridges!

[1] These unit cost parameters assume trains being accompanied by a train attendant at the default ratio of 24.4 % of productive hours. If trains are fully accompanied, the time-dependent cost component of the overhead and distribution cost blocks changes.



(b) Automated train costs

(a) Autonomous bus costs

Figure 3: Costs of autonomous / automated systems at levels 1 and 2

TABLE 3: Infrastructure maintenance cost of autonomous / automated systems

Infrastructure component		Maintenance cost
AUTONOMOUS BUS INFRASTRUCTURE		
Bus infrastructure along non-dedicated roads		2’350 CHF/km/a
Ordinary road	single-lane	45’800 CHF/km/a
	double-lane	48’900 CHF/km/a
Tunnel	$l < 600\,\mathrm{m}$	90’200 CHF/tunnel-km/a
	$600\,\mathrm{m} < l < 2000\,\mathrm{m}$	174’000 CHF/tunnel-km/a
	$l > 2000\,\mathrm{m}$	261’000 CHF/tunnel-km/a
Bridges	single-lane	505’800 CHF/bridge-km/a
	double-lane	738’900 CHF/bridge-km/a
NOTE: Cost figures of bus infrastructure are mutually exclusive!		
AUTOMATED TRAIN INFRASTRUCTURE		
Track (rails, sleepers, etc.)		4’500 CHF/km/a + 0.00166 CHF/seat-km
Substructure		2’600 CHF/km/a
Train protection equipment		23’100 CHF/km/a
Overhead line		3’400 CHF/km/a
Telecommunications		7’700 CHF/km/a
Total		**41’300 CHF/km/a + 0.00166 CHF/seat-km**
Switches		12’900 CHF/switch/a
Tunnel	single-track	66’000 CHF/tunnel-km/a
	double-track	93’000 CHF/tunnel-km/a
Bridge	single-track	460’000 CHF/bridge-km/a
	double-track	690’000 CHF/bridge-km/a
Stations		9’400 CHF/platform/a

NOTE: Cost figures of train infrastructure are additive, with the exception of the substructure which is mutually exclusive with tunnels and bridges!

[2] These unit cost parameters assume trains being accompanied by a train attendant at the default ratio of 24.4 % of productive hours. If trains are fully accompanied, the time-dependent cost component of the overhead and distribution cost blocks changes.

3 Case Study Schwanden- Linthal

The corridor Schwanden – Linthal is the southern, roughly 11 km long part of the single track branch line Ziegelbrücke – Linthal in the Canton of Glarus. The railway line and the parallel road both closely follow the river Linth. The area with alpine topography is only sparsely populated. The section between Schwanden and Linthal is entirely located on the territory of the municipality Glarus Süd (with 430.2 km^2 the largest municipality of Switzerland, Bundesamt für Statistik (BfS), 2018a) having a population of roughly 10'000 inhabitants in 2017 (Bundesamt für Statistik (BfS), 2018b), spread over almost 20 villages in the Linth valley and the neighboring Sernftal joining the former at Schwanden. The road from Linthal over the Klausenpass into the Canton of Uri is only open summer. In winter, the Linth valley is a dead end.

Current public transport service consists of the hourly S25 service Zurich – Linthal (accelerated between Zurich and Ziegelbrücke, serving all stations beyond to Linthal) and the also hourly S6 service Rapperswil – Schwanden. In peak-hours, there is a bus service Schwanden – Linthal connecting to the S6 at Schwanden, thus providing half-hourly connections to Linthal in alternation with the S25.

3.1 Passenger Demand

Passenger demand is calculated by using cross-section loads from the national passenger transport model of Switzerland (Nationales Personenverkehrsmodell, NPVM) and station passenger frequencies by SBB Personenverkehr Nachfrageentwicklung (2017). The **highest load of 769 passengers per day per direction** (assumed the same for 365 days / year) occurs in the cross-section immediately south of Schwanden. Around 70 % of these passengers are through-travelers in Schwanden. Travelers to and from stations serving multiple villages (Nidfurn-Haslen, Luchsingen-Hätzingen, Diesbach-Betschwanden) are split on the respective towns proportionally to the number of inhabitants and jobs according to the data sets GWS and STATENT by the Federal Staistical Office. [3] For the temporal distribution of passengers within one day, we will assume the one given by Weidmann (2013).

3.2 Scenario Definition

FIGURE 5 provides a map of the entire corridor. It shows the current railway line with its stations. The alternative bus service corresponds to the peak-hours courses offered as connections to the

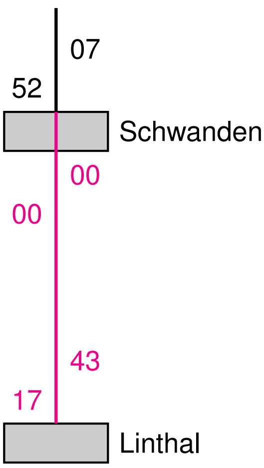
[3] Nidfurn-Haslen: 34 % - 66 %; Luchsingen-Hätzingen: 67 % - 33 %; Diesbach-Betschwanden: 53 % - 47 %

S6 to/from Schwanden (see above). Besides a handful stops which have been added, no further changes to its route have been implemented.

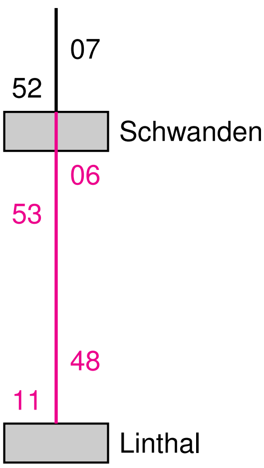
Three train schedule and frequency scenarios as shown by the netgraphs in FIGURE 4 are considered. Schedule **T1** at 60 minutes frequency (FIGURE 4(a)) corresponds to the current schedule of the S25. The train has a very long stop of 8, respectively 7 minutes in Schwanden to wait for the oncoming train. At the moment, there is no further passing track between Schwanden and Linthal. This situation is particularly unattractive for passengers. The "Ausbauschritt 2035", at the moment at the stage of planning, foresees a passing track in Leuggelbach (Bundesamt für Verkehr (BAV), 2018). This additional infrastructure allows schedule T2 with shorter stop in Schwanden. Schedule **T2** is a necessary condition for the introduction of a 30 minutes frequency (with a short turnaround in Linthal, FIGURE 4(c)), but can also be applied to 60 minutes frequency (FIGURE 4(b)). Schedule T1 is only possible with 60 minutes frequency. Please note that the number of productive hours (as an input to the cost model) is the same for all three scenarios. With 30 minutes frequency, the layover time in Linthal is converted into trip time. Staff cost is not affected in any way by this change.

Three train types with different capacities are considered:

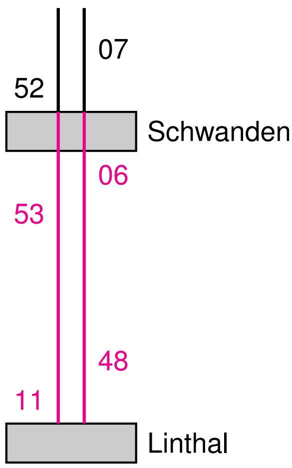
- GTW 2/6 with 100 seats, suitable for 60 min and 30 min frequencies,
- 4-coach Flirt with 200 seats, also suitable for both frequencies,
- DPZ with roughly 350 seats, currently used on the S25, only suitable for scenarios with 60 minutes frequency.



(a) Schedule T1, frequency 60 min



(b) Schedule T2, frequency 60 min



(c) Schedule T2, frequency 30 min

FIGURE 4: Train scenarios Schwanden – Linthal

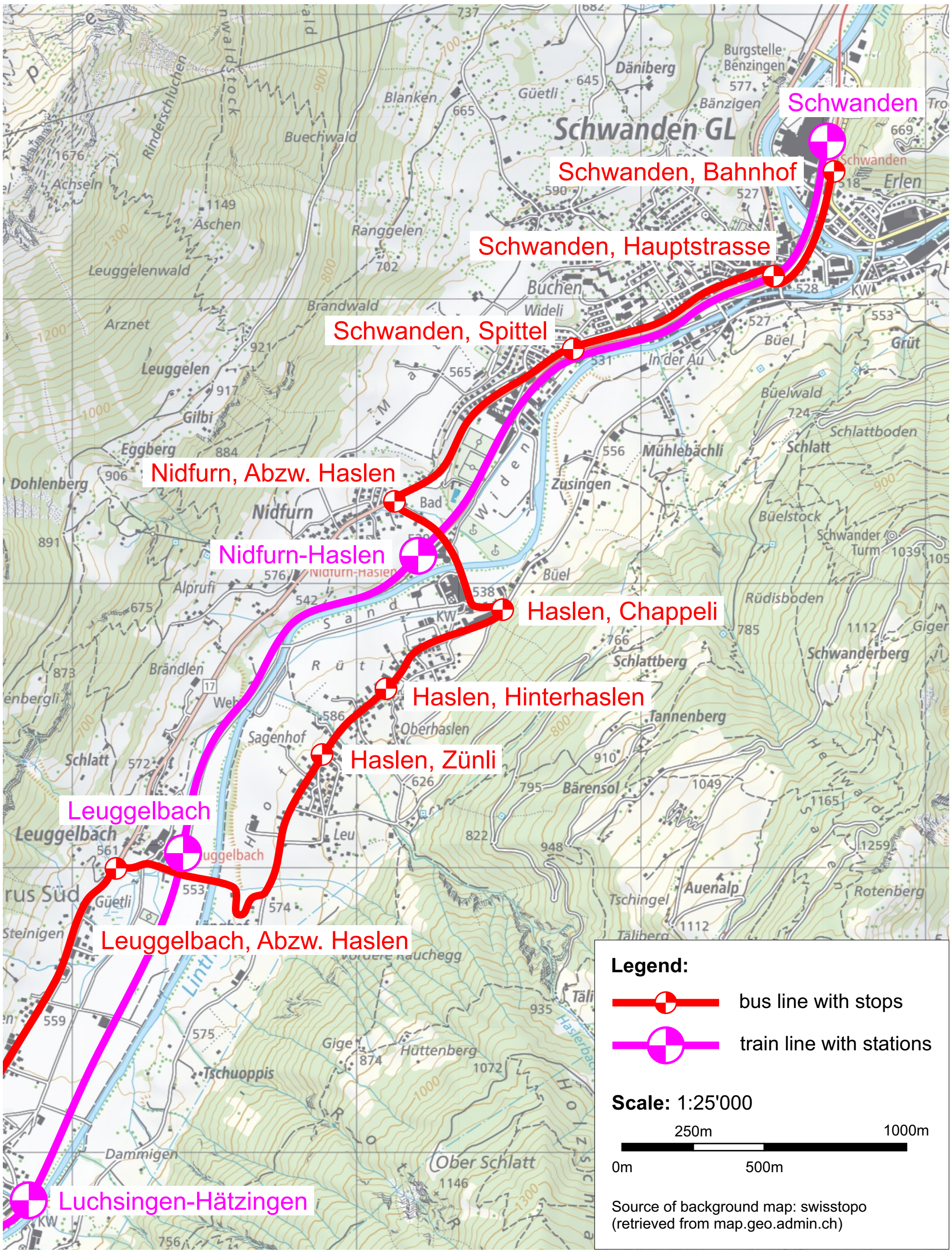


Figure 5: Map of corridor Schwanden – Linthal (continued)

We also consider **three different bus schedule and frequency scenarios**. They are shown by the netgraphs in Figure 6 (over-next page). The scheduled journey time of the bus from Schwanden to Linthal, Post is 28 minutes. It is thus possible to operate the hourly service with one vehicle (with very short turnaround times at both terminal stations). This corresponds to schedule **B1**, which can be operated with a minimal frequency of either 60 minutes (Figure 6(a)) or 30 minutes (Figure 6(b)). However, connection times in Schwanden are rather long with 7, respectively 10 minutes depending on the direction of travel. They can be shortened by using

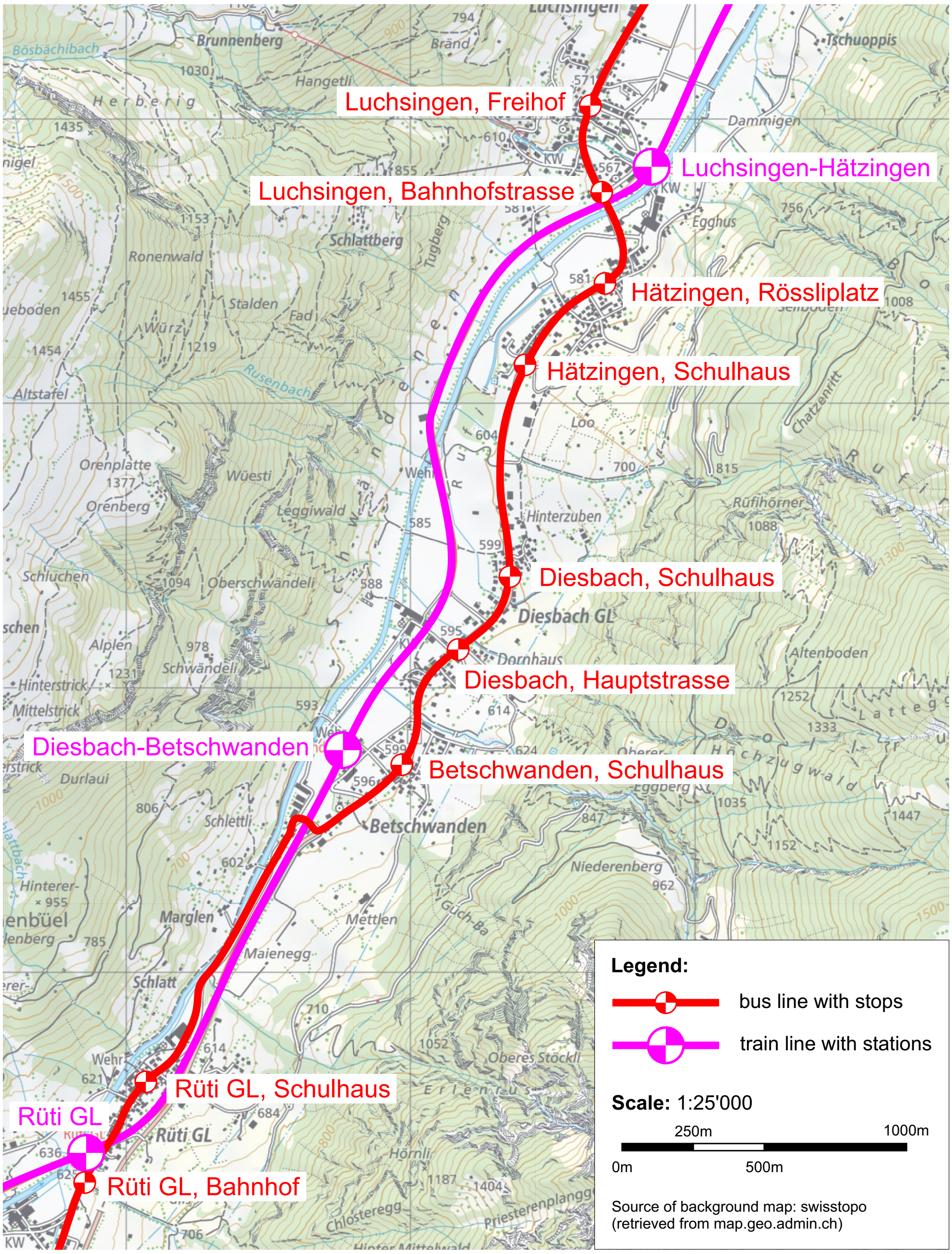


FIGURE 5: Map of corridor Schwanden – Linthal (continued)

schedule **B2** shown by FIGURE 6(c). The very short turnaround in Schwanden is not possible anymore, hence an additional vehicle is required. That's why we assume that this schedule option is only meaningful with a minimal frequency of 30 minutes (layover of 22 min in Schwanden; with hourly service it would be 52 min).

The vehicle used for all bus calculations is a **standard bus with 45 seats**. A larger vehicle is not possible, as some parts of the bus route use narrow roads with sharp turns.

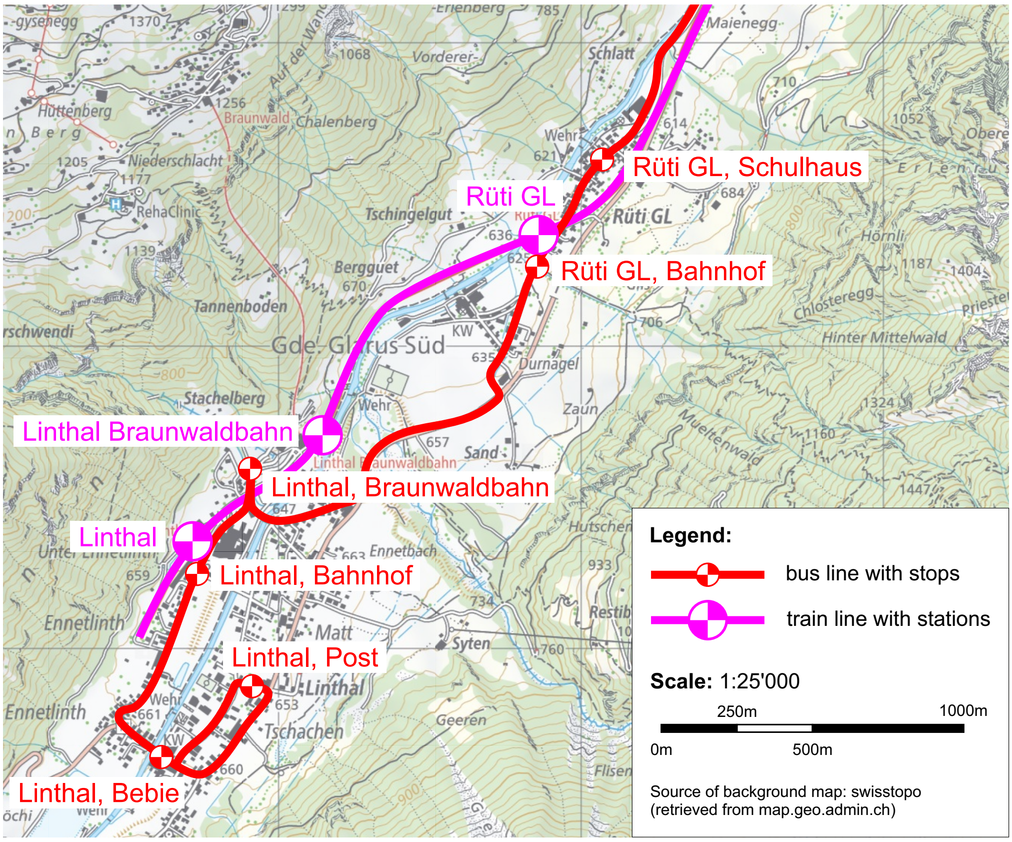
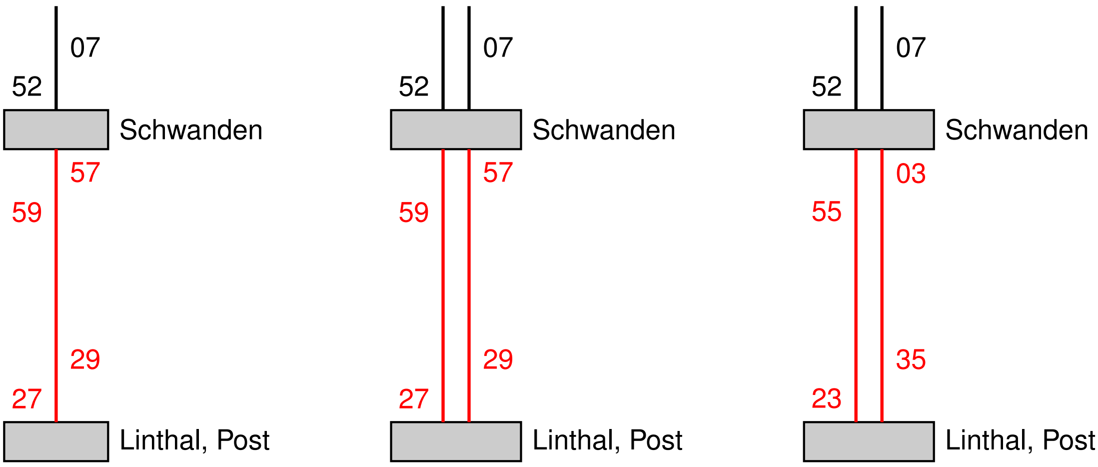


FIGURE 5: Map of corridor Schwanden – Linthal



(a) Schedule B1, min. frequency 60 min

(b) Schedule B1, min. frequency 30 min

(c) Schedule B2, min. frequency 30 min

FIGURE 6: Bus scenarios Schwanden – Linthal

3.3 Comparison of Operating and Total Costs (Levels 1 & 2)

Operating and total costs at levels 1 and 2 respectively (as of FIGURE 1) have been calculated for all of the above train and bus scenarios, both in conventional operation as well as automated / autonomous operation. Computation of train infrastructure cost for level 2 is more complex than the one of bus infrastructure. The former depends both on the chosen schedule (T1 or T2) as well as on the frequency and the type of vehicle. On the one hand, the passing track in Leuggelbach adds more switches, tracks and platforms to the infrastructure. On the other hand, infrastructure maintenance cost has a variable component depending on the number of seat-km. The number or length of the relevant infrastructure items has been retrieved from Schweers + Wall (2004) and aerial imagery by Bundesamt für Landestopographie (swisstopo) (2018). TABLE 4 on the following two pages draws the comparison of train and bus costs at both levels 1 and 2. The following conclusions can be drawn:

- The cost difference between train and bus grows at the expense of the train when increasing the minimal frequency *ceteris paribus*.
- On this specific line, passenger demand is in a range where the use of smaller train vehicles leads to lower costs, both valid in conventional and automated operation.
- Train schedules T1 and T2 (at 60 min frequency) have the same cost at level 1, but differ at level 2 due to the additional passing track in Leuggelbach.
- Bus schedule B2 has significantly higher costs than schedule B1 (both at 30 min minimal frequency) due to the extra vehicle. With automation, the absolute difference between the two schedules is reduced by roughly two-thirds.

Comparing the cost difference between automated train and autonomous bus on the one hand to the one between their conventional equivalents on the other hand (at either level 1 or 2) yields very interesting findings. In some scenarios, this difference increases, while in others it decreases. In fact, the absolute cost savings of both train and bus thanks to automation depend on a multitude of factors (frequency, rostering efficiency, etc.). Most importantly, both cost reductions are a function of demand.

Conclusion **When considering the monetary costs at either level 1 or 2, the train is generally less cost-efficient than the bus.** This relation holds independently of whether conventional or automated / autonomous operation is considered (in whatever combination). Only in one very specific case in TABLE 4 (automated T2 30 min GTW 2/6 vs conventional B2 30 min), where all positive factors add up in favor of the train, the latter has costs comparable to

Table 4: Schwanden – Linthal: Cost comparison at levels 1 & 2

	Train				Bus		Operating costs at level 1 [CHF/a]			Total costs at level 2 [CHF/a]		
	Freq.	Sche.	Vehicle		Freq.	Sche.	Train	Bus	Δ *	Train	Bus	Δ *
Conventional	60 min	T1	DPZ	Conventional	60 min	B1	3'534'000	1'811'000	-1'723'000	3'761'000	1'841'000	-1'920'000
	60 min	T2	DPZ		60 min	B1	3'534'000	1'811'000	-1'723'000	3'800'000	1'841'000	-1'959'000
	60 min	T1	Flirt		60 min	B1	2'919'000	1'811'000	-1'108'000	3'273'000	1'841'000	-1'432'000
	60 min	T2	Flirt		60 min	B1	2'919'000	1'811'000	-1'108'000	3'312'000	1'841'000	-1'471'000
	60 min	T1	GTW 2/6		60 min	B1	2'734'000	1'811'000	-923'000	3'165'000	1'841'000	-1'324'000
	60 min	T2	GTW 2/6		60 min	B1	2'734'000	1'811'000	-923'000	3'204'000	1'841'000	-1'363'000
	30 min	T2	Flirt		30 min	B1	4'480'000	2'442'000	-2'038'000	4'497'000	2'472'000	-2'025'000
	30 min	T2	Flirt		30 min	B2	4'480'000	3'033'000	-1'447'000	4'497'000	3'063'000	-1'434'000
	30 min	T2	GTW 2/6		30 min	B1	3'660'000	2'442'000	-1'218'000	3'847'000	2'472'000	-1'375'000
	30 min	T2	GTW 2/6		30 min	B2	3'660'000	3'033'000	-627'000	3'847'000	3'063'000	-784'000
Conventional	60 min	T1	DPZ	Autonomous	60 min	B1	3'534'000	1'233'000	-2'301'000	3'761'000	1'266'000	-2'495'000
	60 min	T2	DPZ		60 min	B1	3'534'000	1'233'000	-2'301'000	3'800'000	1'266'000	-2'534'000
	60 min	T1	Flirt		60 min	B1	2'919'000	1'233'000	-1'686'000	3'273'000	1'266'000	-2'007'000
	60 min	T2	Flirt		60 min	B1	2'919'000	1'233'000	-1'686'000	3'312'000	1'266'000	-2'046'000
	60 min	T1	GTW 2/6		60 min	B1	2'734'000	1'233'000	-1'501'000	3'165'000	1'266'000	-1'899'000
	60 min	T2	GTW 2/6		60 min	B1	2'734'000	1'233'000	-1'501'000	3'204'000	1'266'000	-1'938'000
	30 min	T2	Flirt		30 min	B1	4'480'000	1'596'000	-2'884'000	4'497'000	1'629'000	-2'868'000
	30 min	T2	Flirt		30 min	B2	4'480'000	1'798'000	-2'682'000	4'497'000	1'831'000	-2'666'000
	30 min	T2	GTW 2/6		30 min	B1	3'660'000	1'596'000	-2'064'000	3'847'000	1'629'000	-2'218'000
	30 min	T2	GTW 2/6		30 min	B2	3'660'000	1'798'000	-1'862'000	3'847'000	1'831'000	-2'016'000

* Δ = bus cost – train cost; color legend: positive / green = train more cost-efficient, negative / red = bus more cost-efficient.

the bus. Subsequently, we will investigate whether – and if so to what extent – the inclusion of the non-monetary aspects at comparison level 3 changes these results.

Table 4: Schwanden – Linthal: Cost comparison at levels 1 & 2

	Train				**Bus**		**Operating costs at level 1** [CHF/a]			**Total costs at level 2** [CHF/a]		
	Freq.	Sche.	Vehicle		Freq.	Sche.	Train	Bus	Δ *	Train	Bus	Δ *
Automated	60 min	T1	DPZ	Conventional	60 min	B1	2'649'000	1'811'000	-838'000	2'987'000	1'841'000	-1'146'000
	60 min	T2	DPZ		60 min	B1	2'649'000	1'811'000	-838'000	3'028'000	1'841'000	-1'187'000
	60 min	T1	Flirt		60 min	B1	2'037'000	1'811'000	-226'000	2'503'000	1'841'000	-662'000
	60 min	T2	Flirt		60 min	B1	2'037'000	1'811'000	-226'000	2'544'000	1'841'000	-703'000
	60 min	T1	GTW 2/6		60 min	B1	1'924'000	1'811'000	-113'000	2'467'000	1'841'000	-626'000
	60 min	T2	GTW 2/6		60 min	B1	1'924'000	1'811'000	-113'000	2'508'000	1'841'000	-667'000
	30 min	T2	Flirt		30 min	B1	3'590'000	2'442'000	-1'148'000	3'721'000	2'472'000	-1'249'000
	30 min	T2	Flirt		30 min	B2	3'590'000	3'033'000	-557'000	3'721'000	3'063'000	-658'000
	30 min	T2	GTW 2/6		30 min	B1	2'774'000	2'442'000	-332'000	3'075'000	2'472'000	-603'000
	30 min	T2	GTW 2/6		30 min	B2	2'774'000	3'033'000	259'000	3'075'000	3'063'000	-12'000
Automated	60 min	T1	DPZ	Autonomous	60 min	B1	2'649'000	1'233'000	-1'416'000	2'987'000	1'266'000	-1'721'000
	60 min	T2	DPZ		60 min	B1	2'649'000	1'233'000	-1'416'000	3'028'000	1'266'000	-1'762'000
	60 min	T1	Flirt		60 min	B1	2'037'000	1'233'000	-804'000	2'503'000	1'266'000	-1'237'000
	60 min	T2	Flirt		60 min	B1	2'037'000	1'233'000	-804'000	2'544'000	1'266'000	-1'278'000
	60 min	T1	GTW 2/6		60 min	B1	1'924'000	1'233'000	-691'000	2'467'000	1'266'000	-1'201'000
	60 min	T2	GTW 2/6		60 min	B1	1'924'000	1'233'000	-691'000	2'508'000	1'266'000	-1'242'000
	30 min	T2	Flirt		30 min	B1	3'590'000	1'596'000	-1'994'000	3'721'000	1'629'000	-2'092'000
	30 min	T2	Flirt		30 min	B2	3'590'000	1'798'000	-1'792'000	3'721'000	1'831'000	-1'890'000
	30 min	T2	GTW 2/6		30 min	B1	2'774'000	1'596'000	-1'178'000	3'075'000	1'629'000	-1'446'000
	30 min	T2	GTW 2/6		30 min	B2	2'774'000	1'798'000	-976'000	3'075'000	1'831'000	-1'244'000

* Δ = bus cost – train cost; color legend: positive / green = train more cost-efficient, negative / red = bus more cost-efficient.

3.4 Benefit Criteria

3.4.1 Travel times

Schedules of the train and bus scenarios are given in Figures 4 and 6. The train has an end-to-end trip time of 17 min, while the bus takes 28 min. We also take into account stay times in stations, either for transfers or time spent to wait for the oncoming train. Schedules T1 and T2, respectively B1 and B2 differ amongst each other by the stay time in Schwanden. Moreover, T2 has a stay time of one minute in Leuggelbach. Schedules are assumed identical over the entire day and for all days, regardless of working days or weekends.

3.4.2 Access & Egress distances

Access and egress distances weighted by the actual number of habitants and jobs with their actual location of residence or workplace are given in Table 5. Depending on the town, distances to the nearest bus stop are 33 % to 80 % shorter than distances to the nearest railway station. Reductions are the most significant in Haslen, Hätzingen and Diesbach, which all share their station with a neighboring town.

3.4.3 Transfers

The only transfer involved is the one from train to bus and vice versa in Schwanden affecting all passengers transiting the station of Schwanden.

Table 5: Schwanden – Linthal: Access and Egress distances

	# inhab.	**# jobs**	**Distance to railway [m]**			**Distance to bus [m]**		
			inhab.	jobs	average	inhab.	jobs	average
Nidfurn	272	45	566	370	**538**	309	320	**311**
Haslen	515	105	830	654	**800**	193	227	**199**
Leuggelbach	158	29	550	465	**537**	350	348	**350**
Luchsingen	565	213	464	385	**442**	319	231	**295**
Hätzingen	301	87	727	635	**706**	190	136	**178**
Diesbach	209	64	916	908	**914**	169	174	**170**
Betschwanden	200	41	388	277	**369**	281	383	**298**
Rüti	349	39	428	316	**417**	287	253	**284**
Linthal Braunw.	—	—	—	—	—	—	—	—
Linthal	893	323	670	675	**671**	321	285	**311**

Table 6: Schwanden – Linthal: Summary of monetarized benefit criteria

		WTP-value		T1	T2	B1	B2
Time	**travel**	15.92 CHF/h	[pax-min/d]	18’062	18’062	28’446	28’446
	stay	15.92 CHF/h	[pax-min/d]	8’346	2’439	9’458	3’895
	access	26.63 CHF/h	[pax-min/d]	9’655	9’655	4’543	4’543
Transfer		2.70 CHF	[pax/d]	—	—	1’113	1’113
Time	**travel**		[CHF/a]	1’749’000	1’749’000	2’755’000	2’755’000
	stay		[CHF/a]	808’000	236’000	916’000	377’000
	access		[CHF/a]	1’564’000	1’564’000	736’000	736’000
Transfer			[CHF/a]	—	—	1’097’000	1’097’000
Total			**[CHF/a]**	**4’122’000**	**3’550’000**	**5’503’000**	**4’965’000**

3.4.4 Summary

Table 6 provides a summary of the above benefit criteria, including their monetarization. WTP-values as of Table 1 are used. Access distances are converted to times by using a walking speed of 6 km/h. The values in the bottom part of Table 6 are generalized cost components, thus the lower the better the service for passengers. The passage from schedule T1 to T2, respectively B1 to B2 with reduced stay times in Schwanden provides significant benefits for passengers in terms of generalized costs. Secondly, the longer access distances of the train are overcompensated by its shorter travel times. Last but not least, the transfer in Schwanden, inherent to all bus scenarios, significantly contributes to the total generalized costs.

3.5 Comparison of Generalized Costs (Level 3)

Table 7 contains the comparison of train and bus services’ generalized costs at level 3 as of Figure 1. The overall picture is much more nuanced than at comparison levels 1 and 2 where the bus was always (except in one specific scenario) the more cost-efficient option. Within the same combination of conventional or automated / autonomous operation, generalized costs spread over a range of roughly 1’200’000 CHF. When both modes train and bus are operated the same way, this range spreads more or less equally over positive (i.e. in favor of the train) and negative (i.e. in favor of the bus) values. When the train is automated, while the bus is not, this range of 1.2 million CHF is entirely located on the positive side. The opposite is true when the bus is autonomous while the train is not. When comparing the different schedules within the same mode, we notice the following. At level 1, the passage from train schedule T1 to T2 is cost-neutral (cf. Table 4), and at level 2 it causes additional infrastructure maintenance. In return, its effect at level 3 is overall positive, as passengers’ travel times can be shortened

Table 7: Schwanden – Linthal: Generalized cost difference at level 3, all cost values in [CHF/a], positive = in favor of train, negative = in favor of bus

Bus operation	Train Frequency	Train Schedule	Train Vehicle	Bus Frequency	Bus Schedule	Train operation: Conventional	Train operation: Automated
Conventional	60 min	T1	DPZ	60 min	B1	-538'000	236'000
Conventional	60 min	T2	DPZ	60 min	B1	-5'000	767'000
Conventional	60 min	T1	Flirt	60 min	B1	-50'000	720'000
Conventional	60 min	T2	Flirt	60 min	B1	483'000	1'251'000
Conventional	60 min	T1	GTW 2/6	60 min	B1	58'000	756'000
Conventional	60 min	T2	GTW 2/6	60 min	B1	591'000	1'287'000
Conventional	30 min	T2	Flirt	30 min	B1	-71'000	705'000
Conventional	30 min	T2	Flirt	30 min	B2	-19'000	757'000
Conventional	30 min	T2	GTW 2/6	30 min	B1	579'000	1'351'000
Conventional	30 min	T2	GTW 2/6	30 min	B2	631'000	1'403'000
Autonomous	60 min	T1	DPZ	60 min	B1	-1'113'000	-339'000
Autonomous	60 min	T2	DPZ	60 min	B1	-580'000	192'000
Autonomous	60 min	T1	Flirt	60 min	B1	-625'000	145'000
Autonomous	60 min	T2	Flirt	60 min	B1	-92'000	676'000
Autonomous	60 min	T1	GTW 2/6	60 min	B1	-517'000	181'000
Autonomous	60 min	T2	GTW 2/6	60 min	B1	16'000	712'000
Autonomous	30 min	T2	Flirt	30 min	B1	-914'000	-138'000
Autonomous	30 min	T2	Flirt	30 min	B2	-1'251'000	-475'000
Autonomous	30 min	T2	GTW 2/6	30 min	B1	-264'000	508'000
Autonomous	30 min	T2	GTW 2/6	30 min	B2	-601'000	171'000

Data source: cost differences at level 2: Table 4; monetarized benefit criteria: Table 6.

significantly. For the bus, the situation is different. At levels 1 and 2, schedule B2 (at the same minimal frequency) causes much higher costs due to the additional vehicle. With automation, this cost surplus is reduced. At level 3, we have to differentiate between conventional and autonomous operation. In the former, the additional operating cost cannot be compensated by the customer benefits. B1 yields a better balance (from the bus perspective) than B2. In autonomous operation, the operating cost surplus is outweighed by customer benefits. B2 thus yields a better balance (from the bus perspective) than B1. The previous statement regarding comparison of cost differences (at level 2) between automated train and autonomous bus to those between their conventional equivalents stays equally valid at level 3. Within the same combination of frequency, schedules and vehicle, the *difference of cost deltas* at level 3 is the same as at level 2, since the delta of monetarized benefit benefit criteria, which is added on top of level 2, does only depend on the chosen combination of schedules.

Conclusion Unlike cost comparison at levels 1 and 2, the difference of generalized costs at level 3 yields a much more diverse overall picture regarding competitiveness of train and bus. When both modes are operated the same way (either both conventional or both automated / autonomous), there are some scenarios where the train has the lower generalized costs and some others where the bus does. In contrast, when only one mode is automated and the other one stays conventional, the automated mode is superior. **The line Schwanden – Linthal is at the edge between the domains of train and bus in terms of generalized costs. A robust statement on the superiority of the one or the other is not possible, as the result depends too much on the specific schedule and frequency being chosen.**

3.6 Conclusion

For the corridor Schwanden – Linthal the main findings are:

- At **comparison levels 1 and 2, the bus is** in all examined scenarios (except one) **the most cost-efficient option**. Automation of either mode does not reverse this ranking. However, it has a notable effect on the cost difference between both modes. Automation helps saving costs for both modes.
- The **absolute amount of the cost saving achievable through automation strongly depends on the specific scenario parameters** such as schedule, frequency and vehicle type. In some scenarios, the bus saves more through automation, while in others the train saves more. A generally true statement also applicable to other lines is not possible.
- When comparing the **generalized costs at level 3, the results are most nuanced** than at levels 1 and 2. Which mode is the more cost-efficient one depends on automation. If both train and bus are either conventional or automated / autonomous, their generalized costs are very similar (with a slight advantage for the one or the other depending on the scenario parameters). In contrast, if only one mode is automated while the other is not, then the automated mode is the more cost-efficient one. Especially the shorter travel times and the missing transfer in Schwanden are comfort elements which provide significant advantages

to the train. Its longer access times are overcompensated by the shorter travel times. This finding applies equally to conventional and automated / autonomous operation.

4 Case Study St. Gallen – Weinfelden

The line St. Gallen – Weinfelden is a secondary railway in Eastern Switzerland. It connects the two main arterials of the region: on the one hand Zurich – Winterthur – St. Gallen and on the other hand, further north, Zurich – Winterthur – Weinfelden – Romanshorn. Trains running from St. Gallen to Weinfelden use the double-track main line St. Gallen – Zurich until Gossau (ca. 10 km), where the secondary line divides out northwards. At Sulgen (ca. 7 km east of Weinfelden), the latter joins the double-track main line Romanshorn – Zurich. The section in-between the two main arterials – from Gossau to Sulgen – is the focus of this case study. It is 23 km long and is single track on the entire way. There are passing tracks at the intermediate stations of Arnegg, Hauptwil, Bischofszell Stadt, Bischofszell Nord and Kradolf. The line characterized by two high bridges over the rivers Sitter and Sornbach as well as steep slopes of up to 17 ‰ in the vicinity of Bischofszell (Schweers + Wall, 2004).

The towns in the corridor (Gossau and Sulgen excluded) have a population of roughly 14’000 inhabitants. Among these towns, Bischofszell is the largest municipality with around 6’000 inhabitants (Bundesamt für Statistik (BfS), 2018b). The corridor Gossau – Sulgen is located in two different cantons: the southern section from Gossau to Hauptwil is part of the Canton of St. Gallen, while the continuation northwards is located on the territory of the Canton of Thurgau.

The railway line is currently served by the S5 service St. Gallen – Weinfelden. On the northern section from Weinfelden to Bischofszell Stadt, trains are running every an half an hour (Monday to Sunday). On the southern section, the minimal frequency is only 60 minutes. During peak-hours Monday to Friday, frequency on the southern section is increased to 30 minutes, too. The reason for this somehow particular schedule is the interaction of the two cantons: while the Canton of Thurgau is funding a full-fledged 30 minutes schedule for the section located on its territory, the Canton of St. Gallen limited its subsidies to an hourly service with 10 additional pairs of courses during peak-hours Monday to Friday (Schweizer Eisenbahn-Revue, 2019).

4.1 Passenger Demand

The **highest load of 2’780 passengers per day per direction** occurs the cross-section immediately north of Gossau. Hence, the current schedule does not reflect the actual demand distribution

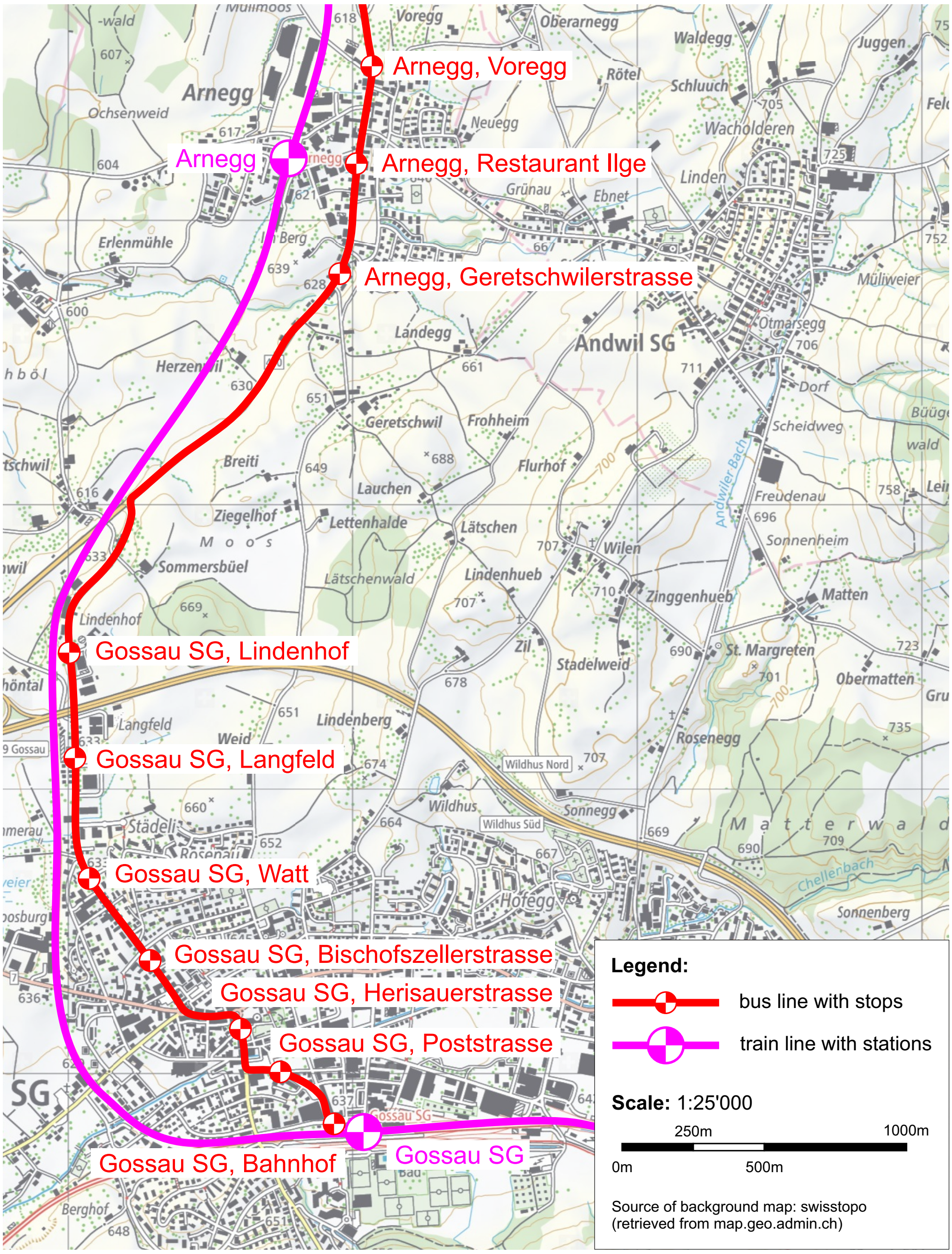


Figure 7: Map of corridor Gossau – Sulgen (continued)

across the corridor. Furthermore, we assumed that 80 % of the passengers arriving/departing at/from Gossau and Sulgen are through-travelers. For the temporal distribution of passengers within one day, we will again assume the same one by Weidmann (2013).

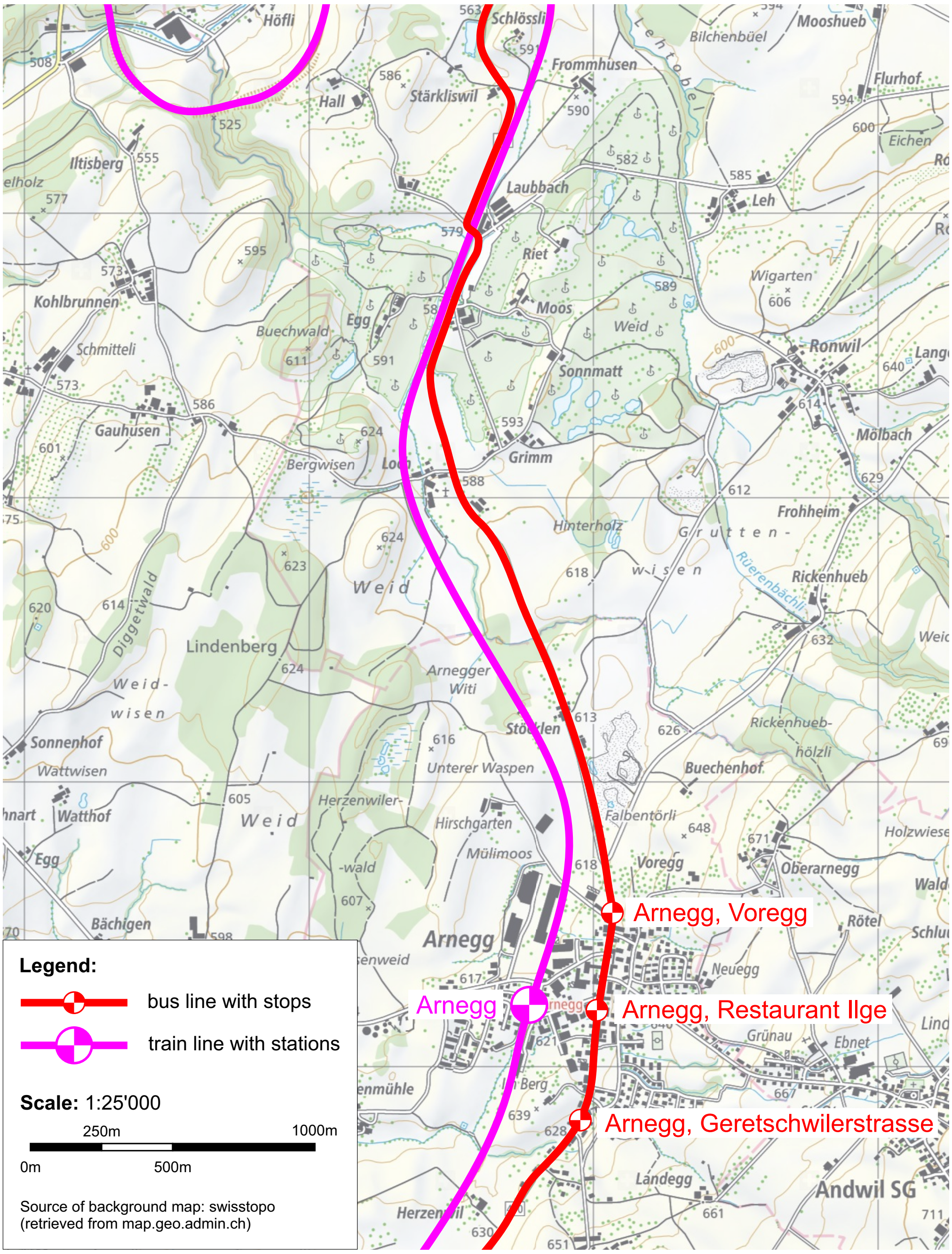


FIGURE 7: Map of corridor Gossau – Sulgen (continued)

4.2 Scenario Definition

FIGURE 7 provides a map of the entire corridor. It shows the current railway line with its stations. The alternative bus services uses the main road on the majority of its route. From Gossau to Arnegg it serves the stops of an bus existing line connecting Gossau to Andwil via Arnegg. **Three train scenarios** with different frequencies, but same schedule (corresponding to the current one in 2019) as of FIGURE 8 are considered:

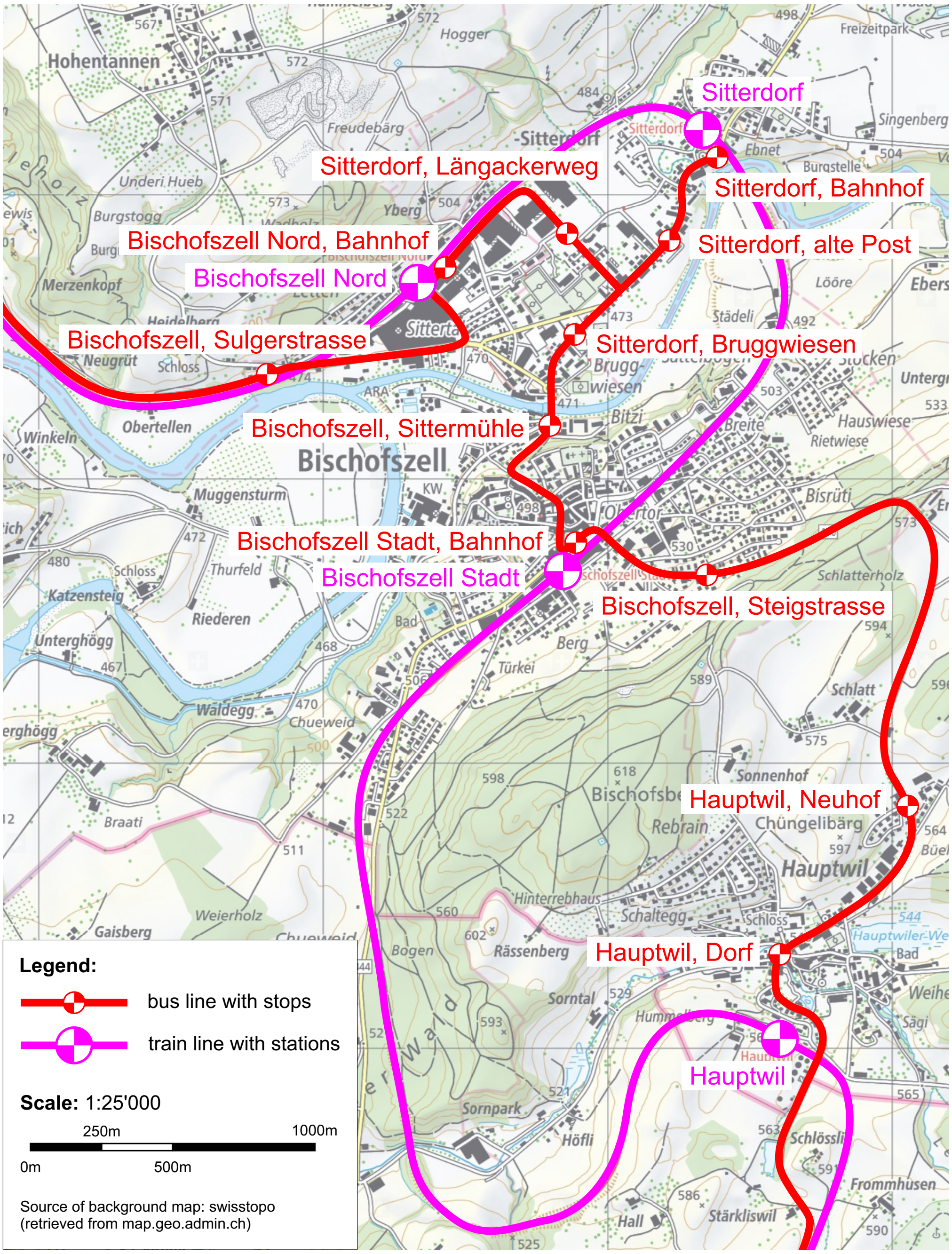


Figure 7: Map of corridor Gossau – Sulgen (continued)

- **F1:** hourly service St. Gallen – Weinfelden with additional courses in peak-hours whenever necessary for capacity reasons (after lengthening of trains),
- **F2:** status quo with 30 min frequency between Weinfelden and Bischofszell and 60 min frequency with additional peak-hours courses between St. Gallen and Bischofszell,
- **F3:** 30 minutes frequency on the entire route.

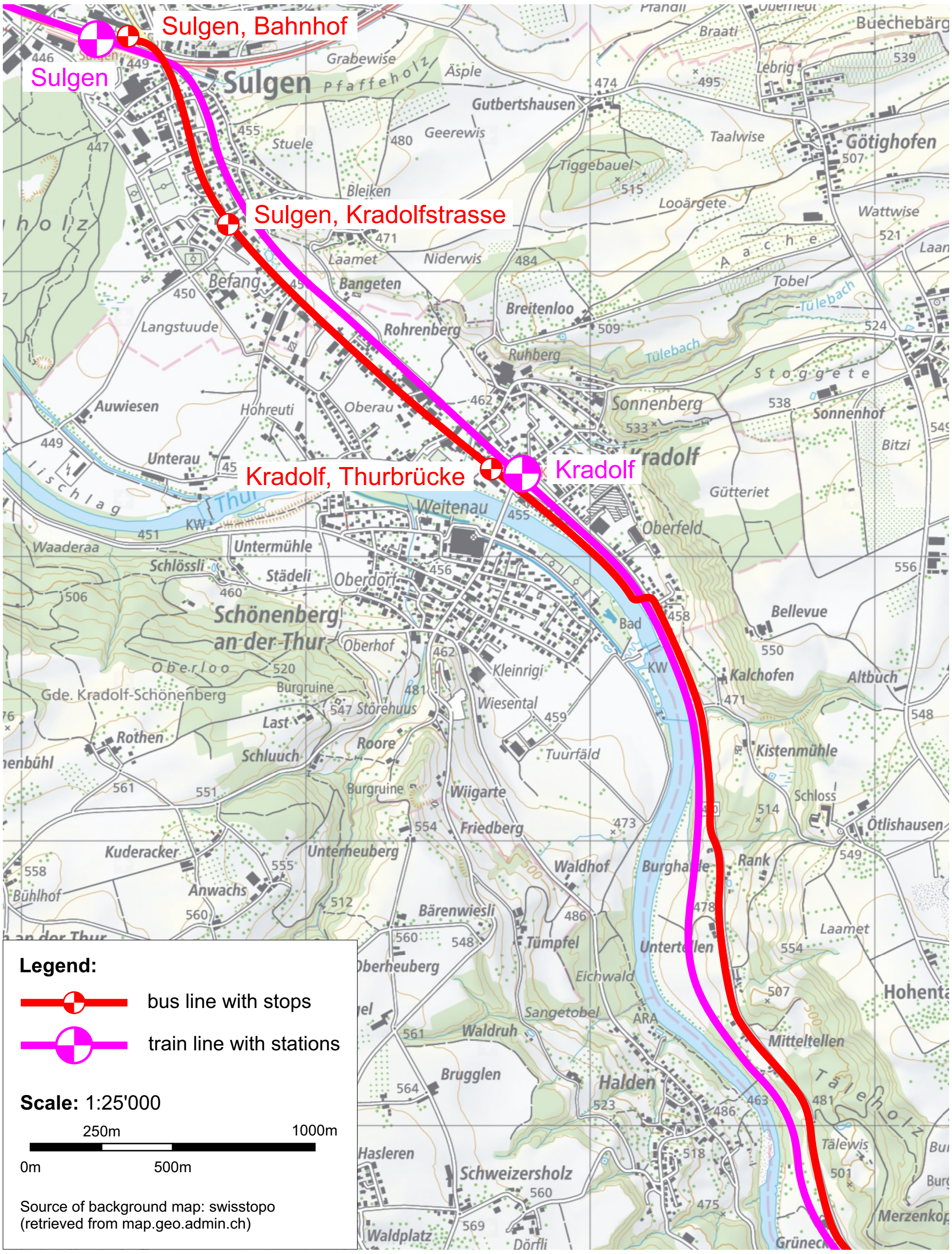


FIGURE 7: Map of corridor Gossau – Sulgen

Two train types with different capacities are considered:

- the longer, three-car version of the GTW with 160 seats, officially referred to as GTW 2/8 (Stadler Rail, 2008),
- the 4-coach Flirt with 200 seats in the same configuration as for the previous case study.

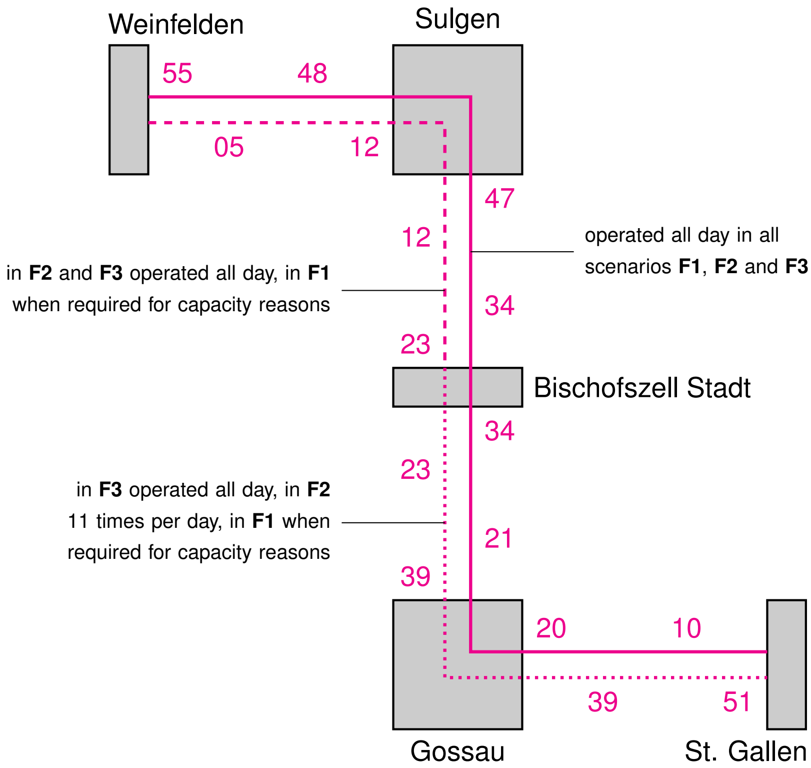


FIGURE 8: Train schedule St. Gallen – Weinfelden

On the **bus side, only one scenario with minimal frequency of 30 min** is considered. Passenger demand is such that one hourly course would only suffice in the very early morning or late evening. The corresponding cost difference would be too small to justify full analysis. Instead, two bus capacities as a consequence of different levels-of-service LOS are considered:

- an **articulated bus with 50 seats** (standard LOS),
- the same bus type while accepting a few standing passengers during peak hours from 06:00 to 09:00 and 16:00 to 19:00, thus increasing capacity to **60 passengers** (adjusted LOS).

The schedule of the alternative bus service is shown in FIGURE 9 (next page). The bus service is only running between Gossau and Sulgen where it connects to S-Bahn lines S1 and S10 to St. Gallen and Weinfelden respectively. Their departure and arrival times in Gossau and Sulgen correspond to the current schedule. The travel time of the S1 between Gossau and St. Gallen has been extended by 2 minutes in order to serve all stops currently served by the S5. Transfer times in Gossau and Sulgen are all around 8 minutes. These are not very attractive, but they are inevitable consequences of the schedules of the S1 and S10 on the one hand and the bus travel time of 41 min between both stations on the other hand. A shift of the schedule of either

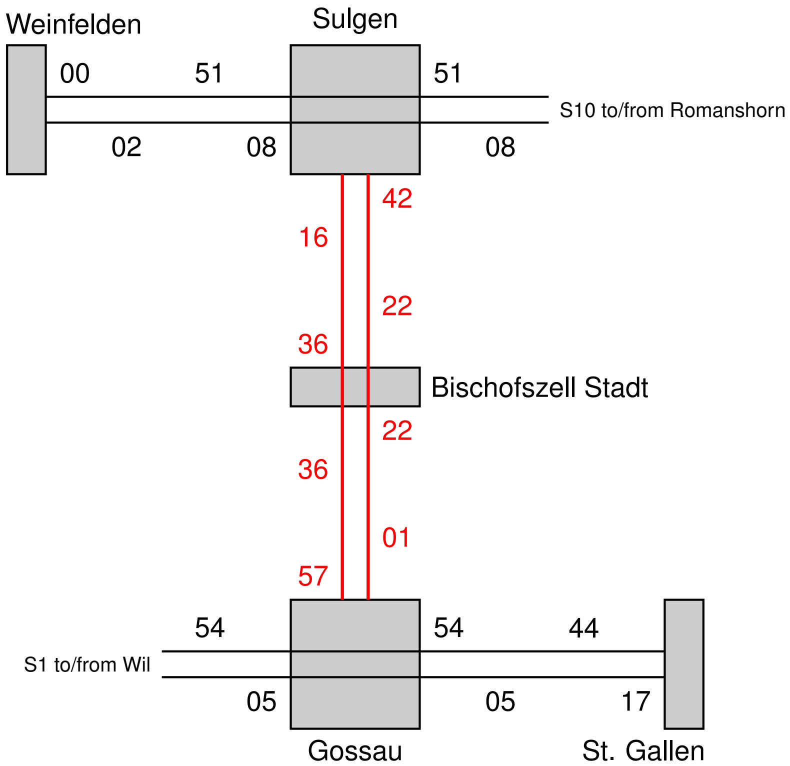


Figure 9: Bus schedule St. Gallen – Weinfelden

S-Bahn line is not possible. The slot of the S1 is dictated by the dense traffic of IC, IR and freight trains between St. Gallen and Wil (and onwards to Winterthur and Zurich). The S10 is bound by connections in both Weinfelden (IC/IR services to/from Zurich) and Romanshorn (RE to/from St. Gallen). In return, the proposed schedule allows very efficient rotations of the bus with turnaround times of only 4 minutes at both ends. The cost of possibly needed extra capacity on either the S1 or the S10 is not further considered in the case study.

4.3 Comparison of Operating and Total Costs (Levels 1 & 2)

Operating and total costs at levels 1 and 2 respectively (as of Figure 1) have been calculated for all of the previously explained train and bus scenarios, both in conventional operation as well as automated / autonomous operation. Computation of train costs at level 2 is more complex than for the previous case study. Besides the section Gossau – Sulgen exclusively used by the S5 service, [4] the latter also includes infrastructure shared with other users (IC, IR, other S-Bahn lines and freight traffic). Attributing the entire annual infrastructure maintenance cost of these

[4] For the sake of simplification, freight trains to/from Bischofszell Nord (via Sulgen) serving the local industry are neglected.

sections to the S5 service does not catch reality. Hence, costs at level 2 have to be understood as follows regarding infrastructure:

- the section Gossau – Sulgen exclusively used by the S5 is included at level 2 according to Figures 2(b) (conventional) and 3(b) (automated),
- the sections St. Gallen – Gossau and Weinfelden – Sulgen shared with other users are accounted for at level 1 as of Figures 2(b) and 3(b).

Infrastructure maintenance cost is again a function of the chosen frequency (F1, F2 or F3) and vehicle type due to the variable component depending on the number of seat-km. The number or length of the relevant infrastructure items has been retrieved from Schweers + Wall (2004) and aerial imagery by Bundesamt für Landestopographie (swisstopo) (2018). Table 8 on the following two pages draws the comparison of train and bus costs at both levels 1 and 2. The following findings are worth noting:

- The cost difference between train and bus grows at the expense of the train when increasing the minimal frequency *ceteris paribus*. The difference between frequencies F1 and F2 is much larger than the one between F2 and F3 (valid for both levels of comparison as well as both conventional and automated / autonomous operation).
- The overall picture is not reversed by automation of either mode. When the automated train is competing against the conventional bus, the scenario with maximum temporal bundling (frequency F1) allows the former to reach a black zero versus the latter. In all other scenarios, the bus is more cost-efficient.
- The cost difference between the two types of train vehicles is very small. In conventional operation there is a slight advantage for the smaller one, while in the automated case there is a small advantage for the larger one. This may seem counter-intuitive but is explained by the vehicle fixed cost which rises with automation. The smaller the individual vehicle, the more of them are needed and thus the greater the effect of this extra cost.
- The acceptance of a lower LOS of the bus service during peak-hours has a significant effect on the overall costs. However, savings related to this measure are reduced with automation. The cost of additional vehicles during peak-hours is much lower if no driver is needed.
- Cost savings thanks to railway automation are the highest for frequency F3, while they are the lowest for F1. This is expectable, as higher frequency also means more productive hours on which money can be saved.

Table 8: St. Gallen – Weinfelden: Cost comparison at levels 1 & 2

Train			Bus		Operating costs at level 1 [CHF/a]			Total costs at level 2 [CHF/a]		
	Frequency	Vehicle		LOS	Train	Bus	Δ *	Train	Bus	Δ *
Conventional	F1 (60 min)	GTW 2/8	Conventional	standard	10'467'000	9'093'000	-1'374'000	11'177'000	9'141'000	-2'036'000
	F1 (60 min)	Flirt		standard	10'483'000	9'093'000	-1'390'000	11'165'000	9'141'000	-2'024'000
	F2 (hybrid)	GTW 2/8		standard	15'550'000	9'093'000	-6'457'000	15'790'000	9'141'000	-6'649'000
	F2 (hybrid)	Flirt		standard	15'594'000	9'093'000	-6'501'000	15'784'000	9'141'000	-6'643'000
	F3 (30 min)	GTW 2/8		standard	17'282'000	9'093'000	-8'189'000	17'348'000	9'141'000	-8'207'000
	F3 (30 min)	Flirt		standard	17'471'000	9'093'000	-8'378'000	17'469'000	9'141'000	-8'328'000
	F1 (60 min)	GTW 2/8		adjusted	10'467'000	8'171'000	-2'296'000	11'177'000	8'220'000	-2'957'000
	F1 (60 min)	Flirt		adjusted	10'483'000	8'171'000	-2'312'000	11'165'000	8'220'000	-2'945'000
	F2 (hybrid)	GTW 2/8		adjusted	15'550'000	8'171'000	-7'379'000	15'790'000	8'220'000	-7'570'000
	F2 (hybrid)	Flirt		adjusted	15'594'000	8'171'000	-7'423'000	15'784'000	8'220'000	-7'564'000
	F3 (30 min)	GTW 2/8		adjusted	17'282'000	8'171'000	-9'111'000	17'348'000	8'220'000	-9'128'000
	F3 (30 min)	Flirt		adjusted	17'471'000	8'171'000	-9'300'000	17'469'000	8'220'000	-9'249'000
Conventional	F1 (60 min)	GTW 2/8	Autonomous	standard	10'467'000	6'761'000	-3'706'000	11'177'000	6'814'000	-4'363'000
	F1 (60 min)	Flirt		standard	10'483'000	6'761'000	-3'722'000	11'165'000	6'814'000	-4'351'000
	F2 (hybrid)	GTW 2/8		standard	15'550'000	6'761'000	-8'789'000	15'790'000	6'814'000	-8'976'000
	F2 (hybrid)	Flirt		standard	15'594'000	6'761'000	-8'833'000	15'784'000	6'814'000	-8'970'000
	F3 (30 min)	GTW 2/8		standard	17'282'000	6'761'000	-10'521'000	17'348'000	6'814'000	-10'534'000
	F3 (30 min)	Flirt		standard	17'471'000	6'761'000	-10'710'000	17'469'000	6'814'000	-10'655'000
	F1 (60 min)	GTW 2/8		adjusted	10'467'000	6'004'000	-4'463'000	11'177'000	6'057'000	-5'120'000
	F1 (60 min)	Flirt		adjusted	10'483'000	6'004'000	-4'479'000	11'165'000	6'057'000	-5'108'000
	F2 (hybrid)	GTW 2/8		adjusted	15'550'000	6'004'000	-9'546'000	15'790'000	6'057'000	-9'733'000
	F2 (hybrid)	Flirt		adjusted	15'594'000	6'004'000	-9'590'000	15'784'000	6'057'000	-9'727'000
	F3 (30 min)	GTW 2/8		adjusted	17'282'000	6'004'000	-11'278'000	17'348'000	6'057'000	-11'291'000
	F3 (30 min)	Flirt		adjusted	17'471'000	6'004'000	-11'467'000	17'469'000	6'057'000	-11'412'000

* Δ = bus cost – train cost; color legend: positive / green = train more cost-efficient, negative / red = bus more cost-efficient.

Conclusion **When considering the monetary costs at either level 1 or 2, the train is generally less cost-efficient than the bus.** Only in one specific case – automated train with maximum temporal bundling (F1) against conventional bus – rail manages to break-even. The

Table 8: St. Gallen – Weinfelden: Cost comparison at levels 1 & 2

Train			**Bus**		**Operating costs at level 1** [CHF/a]			**Total costs at level 2** [CHF/a]		
	Frequency	Vehicle		LOS	Train	Bus	Δ *	Train	Bus	Δ *
Automated	F1 (60 min)	GTW 2/8	Conventional	standard	8'937'000	9'093'000	156'000	9'898'000	9'141'000	-757'000
	F1 (60 min)	Flirt		standard	8'932'000	9'093'000	161'000	9'864'000	9'141'000	-723'000
	F2 (hybrid)	GTW 2/8		standard	12'683'000	9'093'000	-3'590'000	13'175'000	9'141'000	-4'034'000
	F2 (hybrid)	Flirt		standard	12'584'000	9'093'000	-3'491'000	13'025'000	9'141'000	-3'884'000
	F3 (30 min)	GTW 2/8		standard	14'011'000	9'093'000	-4'918'000	14'329'000	9'141'000	-5'188'000
	F3 (30 min)	Flirt		standard	14'057'000	9'093'000	-4'964'000	14'306'000	9'141'000	-5'165'000
	F1 (60 min)	GTW 2/8		adjusted	8'937'000	8'171'000	-766'000	9'898'000	8'220'000	-1'678'000
	F1 (60 min)	Flirt		adjusted	8'932'000	8'171'000	-761'000	9'864'000	8'220'000	-1'644'000
	F2 (hybrid)	GTW 2/8		adjusted	12'683'000	8'171'000	-4'512'000	13'175'000	8'220'000	-4'955'000
	F2 (hybrid)	Flirt		adjusted	12'584'000	8'171'000	-4'413'000	13'025'000	8'220'000	-4'805'000
	F3 (30 min)	GTW 2/8		adjusted	14'011'000	8'171'000	-5'840'000	14'329'000	8'220'000	-6'109'000
	F3 (30 min)	Flirt		adjusted	14'057'000	8'171'000	-5'886'000	14'306'000	8'220'000	-6'086'000
Automated	F1 (60 min)	GTW 2/8	Autonomous	standard	8'937'000	6'761'000	-2'176'000	9'898'000	6'814'000	-3'084'000
	F1 (60 min)	Flirt		standard	8'932'000	6'761'000	-2'171'000	9'864'000	6'814'000	-3'050'000
	F2 (hybrid)	GTW 2/8		standard	12'683'000	6'761'000	-5'922'000	13'175'000	6'814'000	-6'361'000
	F2 (hybrid)	Flirt		standard	12'584'000	6'761'000	-5'823'000	13'025'000	6'814'000	-6'211'000
	F3 (30 min)	GTW 2/8		standard	14'011'000	6'761'000	-7'250'000	14'329'000	6'814'000	-7'515'000
	F3 (30 min)	Flirt		standard	14'057'000	6'761'000	-7'296'000	14'306'000	6'814'000	-7'492'000
	F1 (60 min)	GTW 2/8		adjusted	8'937'000	6'004'000	-2'933'000	9'898'000	6'057'000	-3'841'000
	F1 (60 min)	Flirt		adjusted	8'932'000	6'004'000	-2'928'000	9'864'000	6'057'000	-3'807'000
	F2 (hybrid)	GTW 2/8		adjusted	12'683'000	6'004'000	-6'679'000	13'175'000	6'057'000	-7'118'000
	F2 (hybrid)	Flirt		adjusted	12'584'000	6'004'000	-6'580'000	13'025'000	6'057'000	-6'968'000
	F3 (30 min)	GTW 2/8		adjusted	14'011'000	6'004'000	-8'007'000	14'329'000	6'057'000	-8'272'000
	F3 (30 min)	Flirt		adjusted	14'057'000	6'004'000	-8'053'000	14'306'000	6'057'000	-8'249'000

* Δ = bus cost – train cost; color legend: positive / green = train more cost-efficient, negative / red = bus more cost-efficient.

overall cost advantage of the bus is partially due to the fact that the train cost covers the through-service between St. Gallen and Weinfelden, while the bus cost only refers to the section Gossau – Sulgen. In order to obtain a comprehensive picture, we thus need to include the cost of the additional transfer (comparison level 3), which is being addressed in the following section.

The sensitivity analysis further down in this section will analyze how a direct bus service from St. Gallen to Weinfelden performs.

4.4 Benefit Criteria

4.4.1 Travel times

Schedules of all train and bus scenarios are given in Figures 8 and 9. The train has a trip time of 45 min from St. Gallen to Weinfelden. The bus takes 41 min from Gossau to Sulgen.

4.4.2 Access & Egress distances

Table 9 provides the access and egress distances weighted by the actual number of habitants and jobs with their actual location of residence or workplace. Depending on the town, distances to the nearest bus stop are 5 % to 50 % shorter than distances to the nearest railway station. Reductions are the most significant for Hauptwil and Sitterdorf. In the former, the railway station is located at the southern end of the town. The residential areas on the opposite hill are not well connected (see map on page 22). In Sitterdorf, the railway station is centrally located. Access and egress distances of the bus are smaller nevertheless, as the irrigation of the town by bus stops is finer. At the other end of the spectrum, access and egress distances in Kradolf are barely reduced. Due to presence of only one bridge over the river Thur (see map on page 23), there is exactly one meaningful location for a public transport stop/station, used by both the railway and the bus.

4.4.3 Transfers

The through-traveling passengers in Gossau and Sulgen have to transfer. Their share has been assumed to be 80 % of the load of the immediately contiguous section.

4.4.4 Summary

Table 10 provides a summary of the above benefit criteria, including their monetarization. WTP-values as of Table 1 are used. Access distances are converted to times by using a walking speed of 6 km/h. The values in the bottom part of Table 10 are again generalized cost components, thus the lower the value the better the service for passengers. As for the previous case study, the longer access distances of the train are overcompensated by far by its shorter travel times.

TABLE 9: St. Gallen – Weinfelden: Access and Egress distances

	# inhab.	**# jobs**	**Distance to railway [m]**			**Distance to bus [m]**		
			inhab.	jobs	average	inhab.	jobs	average
Arnegg	1’645	570	601	469	567	426	380	414
Hauptwil	1’129	344	778	790	781	398	296	374
Bischofszell Stadt	5’440	3’117	656	524	608	511	433	483
Sitterdorf	830	278	475	609	509	276	227	264
Bischofzell Nord	5’440	3’117	656	524	608	511	433	483
Kradolf	2’744	860	566	614	577	538	581	548

TABLE 10: St. Gallen – Weinfelden: Summary of monetarized benefit criteria

		WTP-value		**Train**	**Bus**
TIME	**travel**	15.92 CHF/h	[pax-min/d]	107’312	178’677
	stay	15.92 CHF/h	[pax-min/d]	11’780	60’525
	access	26.63 CHF/h	[pax-min/d]	32’318	23’516
Transfer		2.70 CHF	[pax/d]	—	7’645
TIME	**travel**		[CHF/a]	10’393’000	17’304’000
	stay		[CHF/a]	1’141’000	5’812’000
	access		[CHF/a]	5’236’000	3’810’000
Transfer			[CHF/a]	—	7’534’000
TOTAL			**[CHF/a]**	**16’769’000**	**34’509’000**

NOTE: Travel times refer to the section Gossau – Sulgen only. The continuation to St. Gallen and Weinfelden is not included, as it is identical for both modes.

Furthermore, the transfers in Gossau and Sulgen significantly contributes to the total generalized costs of the bus service. The difference of total monetarized benefit criteria between train and bus service is much larger than for the previous case study. It is also significantly higher than the cost differences at level 2 given in TABLE 8. These are a consequence of the much higher patronage than in the corridor Schwanden – Linthal. Monetarized benefit criteria linearly grow with rising demand.

4.5 Comparison of Generalized Costs (Level 3)

TABLE 11 (next page) contains the comparison of generalized costs at level 3. The overall picture is fundamentally reversed compared levels 1 and 2 where the bus was always by far (except in one specific scenario) the more cost-efficient option. The contribution of the benefit criteria is

Table 11: St. Gallen – Weinfelden: Generalized cost difference at level 3, all cost values in [CHF/a], positive = in favor of train, negative = in favor of bus

Bus operation	Train Frequency	Train Vehicle	Bus LOS	Train operation: Conventional	Train operation: Automated
Conventional	F1 (60 min)	GTW 2/8	standard	15'704'000	16'983'000
Conventional	F1 (60 min)	Flirt	standard	15'716'000	17'017'000
Conventional	F2 (hybrid)	GTW 2/8	standard	11'091'000	13'706'000
Conventional	F2 (hybrid)	Flirt	standard	11'097'000	13'856'000
Conventional	F3 (30 min)	GTW 2/8	standard	9'533'000	12'552'000
Conventional	F3 (30 min)	Flirt	standard	9'412'000	12'575'000
Conventional	F1 (60 min)	GTW 2/8	adjusted	14'783'000	16'062'000
Conventional	F1 (60 min)	Flirt	adjusted	14'795'000	16'096'000
Conventional	F2 (hybrid)	GTW 2/8	adjusted	10'170'000	12'785'000
Conventional	F2 (hybrid)	Flirt	adjusted	10'176'000	12'935'000
Conventional	F3 (30 min)	GTW 2/8	adjusted	8'612'000	11'631'000
Conventional	F3 (30 min)	Flirt	adjusted	8'491'000	11'654'000
Autonomous	F1 (60 min)	GTW 2/8	standard	13'377'000	14'656'000
Autonomous	F1 (60 min)	Flirt	standard	13'389'000	14'690'000
Autonomous	F2 (hybrid)	GTW 2/8	standard	8'764'000	11'379'000
Autonomous	F2 (hybrid)	Flirt	standard	8'770'000	11'529'000
Autonomous	F3 (30 min)	GTW 2/8	standard	7'206'000	10'225'000
Autonomous	F3 (30 min)	Flirt	standard	7'085'000	10'248'000
Autonomous	F1 (60 min)	GTW 2/8	adjusted	12'620'000	13'899'000
Autonomous	F1 (60 min)	Flirt	adjusted	12'632'000	13'933'000
Autonomous	F2 (hybrid)	GTW 2/8	adjusted	8'007'000	10'622'000
Autonomous	F2 (hybrid)	Flirt	adjusted	8'013'000	10'772'000
Autonomous	F3 (30 min)	GTW 2/8	adjusted	6'449'000	9'468'000
Autonomous	F3 (30 min)	Flirt	adjusted	6'328'000	9'491'000

Data source: cost differences at level 2: Table 8; monetarized benefit criteria: Table 10.

so significant that the train is in all cases by far the superior option. Travel times and transfers are the two key non-monetary aspects which lead to this result. Generally speaking, these are potential comparative advantages of the train which keep their importance with automation of either or both modes. Differences between the two train vehicles or between the two bus LOS do not change compared to level 2. Neither of them enters into the calculation of the monetarized benefit criteria. The previous statements in these regards apply identically to level 3.

4.6 Conclusion

For the corridor St. Gallen – Weinfelden the main findings are:

- At **comparison levels 1 and 2, the bus is** in all examined scenarios (except one) **the most cost-efficient option**. Automation of either mode does not reverse this ranking. However, it has a notable effect on the cost difference between both modes. Automation helps saving costs for both modes.
- The **absolute amount of the cost saving achievable through automation strongly depends on the specific scenario parameters**, first and foremost frequency and LOS. In some scenarios, the bus saves more through automation (e.g. train at frequency F1), while in others the train saves more (e.g. at frequency F3).
- When comparing the **generalized costs at level 3, the situation looks completely different.** The train is by far the superior mode. The higher patronage than in the previous case study leads to much higher monetarized benefit criteria, which again play in favor of the train. Shorter travel times and the absence of transfers are key comparative advantages. The slightly longer access and egress times are outweighed by far by the two aforementioned strengths.

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