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A Century of French Railways: The Value of Remote Sensing and VGI in the Fusion of Historical Data

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Abstract: Providing long-term data about the evolution of railway networks in Europe may help us understand how European Union (EU) member states behave in the long-term, and how they can comply with present EU recommendations. This paper proposes a methodology for collecting data about railway stations, at the maximal extent of the French railway network, a century ago.The expected outcome is a geocoded dataset of French railway stations (*gares*), which: (*a*) links *gares* to each other, (*b*) links *gares* with French *communes*, the basic administrative level for statistical information. Present stations are well documented in public data, but thousands of past stations are sparsely recorded, not geocoded, and often ignored, except in volunteer geographic information (VGI), either collaboratively through Wikipedia or individually. VGI is very valuable in keeping track of that heritage, and remote sensing, including aerial photography is often the last chance to obtain precise locations. The approach is a series of steps: (1) *meta-analysis* of the public datasets, (2) *three-steps fusion*: measure-decision-combination, between public datasets, (3) *computer-assisted geocoding* for '*gares*' where fusion fails, (4) *integration* of additional *gares* gathered from VGI, (5) *automated quality control*, indicating where quality is questionable. These five families of methods, form a comprehensive computer-assisted reconstruction process (CARP), which constitutes the core of this paper. The outcome is a reliable dataset—in geojson format under open license—encompassing (by January 2021) more than 10,700 items linked to about 7500 of the 35,500 communes of France: that is 60% more than recorded before. This work demonstrates: (*a*) it is possible to reconstruct transport data from the past, at a national scale; (*b*) the value of remote sensing and of VGI is considerable in completing public sources from an historical perspective; (*c*) data quality can be monitored all along the process and (*d*) the geocoded outcome is ready for a large variety of further studies with statistical data (demography, density, space coverage, CO_2 simulation, environmental policies, etc.).

Keywords: historical GIS; railway network; meta-analysis; geo-information fusion; information revision; crowdsourcing open data; volunteer geographic information; VGI; Wikipedia geo-information extraction; spatial data quality; data consistency checking

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1. Introduction

Transport infrastructure for people and goods is as old as urban civilizations, e.g., Via Appia, Aemilia, Aurelia, etc. have helped in structuring the European landscape for centuries. From 1920 to 2020, the evolution of road and rail networks is a well known element of their competition [1–3]. Today climate challenges reignite that century-old debate:for instance the European Union (EU) transportation white paper [4] notes that in 2010 rail yielded11 million tons of CO_2, versus road: 191 m tons, but regrets "*… that only limited data are available …*" for measuring the impact of measures by member states. Linking railway data with socio-eco-demographic data in historical geographic information systems (GIS), would contribute to understanding long-term trends. This approach has been developed by Siebert [5], and, in Europe by Gregory et al. [6], and Morillas-Torné [7] with a very similar goal, and uses several European public datasets, which record main rail lines (no secondary rail lines).

This paper describes a method for building a digital representation of all the 'stations' (we use the French term '*gare*') that have existed, between the maximum extent of the French railway network (1920s) and now, a century later. The goal is to deliver a dataset to answer questions such as: *Does a commune possesses a gare*? *How far from the closest gare*? Also, the aim is to give a comparison at different dates. For that we need: (a) to link *gares* to each other along their 'rail line' (we use French term '*ligne*'), (b) to link every *gare* to a 'city or town': we use the French term '*commune*', the smallest French administrative level at which most basic statistical data are collected.

There is no digital dataset providing all French *gares* at the maximum extent of the network, and even their number is unknown. There are two kinds of source: public records (open data from French public institutions: SNCF, Insee, IGN over 2014–2020), and a lot of volunteered geographic information (VGI), either collective through Wikipedia, or individual, providing sparse data about old *gares* (even simple stops) and *lignes*.

Sections 2 and 3 present materials and methods, respectively for public and VGI sources, with the goal to "geocode" all the *gares*, in a reliable, controllable way; as "points-of-interest" multi-source matching is presented in Li et al. [8].

Multi-source datasets are expected to show discrepancies between names (toponym changes), as investigated by Tian-Lan and Longley [9], and locations (existence and geocoding) of each individual *gare*. In order to resolve discrepancies, target constraints are formulated, and a schema is proposed. Each source is scrutinized by a "*meta-analysis*" [10,11], in order to identify what may conflict the constraints. Then public datasets are inputted in a *fusion* process, following Bloch [12], which more precisely is an asymmetric *revision*, as in Benferhat et al. [13], in a background similar to Reichgelt [14].

Issues raised by VGI have been addressed, e.g., by Johnson and Iizuka [15] successfully combining OpenStreetMap features and Landsat image classification; by Younghoon et al. [16] integrating several crowdsourcing sets in a single graph,or possibly developing collaborative platform such as *FeatureHub* [17]; or multiple platforms as in Juhász et al. [18]. The specific goal assigned to VGI in this paper is to gather data for revising some already geocoded *gares* (whose quality is questioned), and mostly for integrating more *gares*, not recorded in public datasets. Chen et al. [19] have developed *CrowdFusion*, a framework aiming at data refinement (a hard non-polynomial task), while Gouvëa et al. [20], and Hastings [21], have focused on toponym conflation and gazetteer-based geo-referencing.

Section 3 describes routines querying Wikipedia for coordinates of *gares*, and mostly to parsing railway-oriented "*Infobox*" [22]. There are some inspiringpapers about how to populatethem [23], or to extract information based on common-sense rules [24]. An *Infobox* is a very valuable means to obtain at once the information about a *ligne*, the other *lignes* it connects with, and the *gares* it encompasses. The parsing of the information that complies with target constraints is one important contribution of the present work, because, beyond French peculiarities, railway semantics is shared by most countries. Next,Section 3 describes several ways in querying various VGI sources, mostly about *gares* on secondary *lignes* (e.g., the popular *rural tramways* in France, between WWI and WWII). The last opportunity to resolve failed geocoding issues, is to exploit remote-sensing images, old aerial photographs, and contemporary or 20th-century maps.

Issues of enacting data quality within a data collection process have been addressed by Vasseur et al. [25], who evaluates the quality in the context of a target use, and [26,27], two reviews about quality control in crowdsourcing, by Daniel et al. and Senaratne et al.

The mix of manual and software steps presented above, combines into what we name the computer-assisted reconstruction procedure (CARP). Finally, the resulting CARP dataset is cleaned up by an assisted data quality control.

2. Materials and Methods. Part 1: Public Data, Revision and Control

2.1. Shaping the Expected Target

2.1.1. Target Goal, Constraints and Initial Schema

The target should allow us to answer questions such as:

- For each of the French *commune*s, how far from its center is the closest *gare*?
- Between closest *gares*of *communes* A and B, what is the closest path (kilometers)?
- Comparing today and a century ago.

For that purpose, we need the minimal information to linking *gares* with *communes*, and to linking *gares* with *lignes*. That minimal information can be aligned with some components of the standards for transportation networks developed by the European infrastructure INSPIRE [28] or the Open geographic consortium OGC [29]. Four classes seem the minimum required: *gare*, *commune*, *ligne*, and a *node* class that allows one *gare* to be attached to several *lignes* (a "*junction*" *gare*).

The UML-class diagram (Figure 1) illustrates the relationships and their cardinalities, between these classes, and some additional constraints.

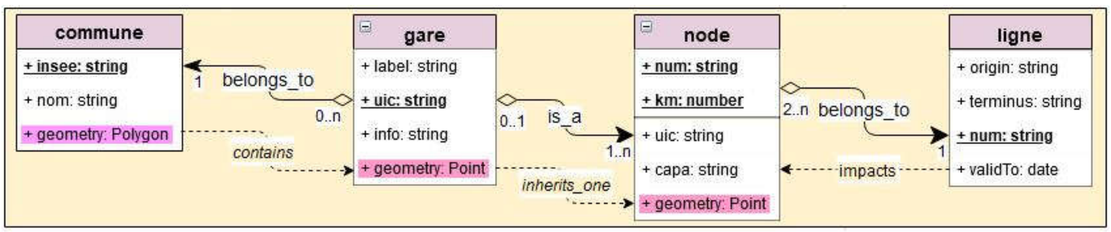


Figure 1. Conceptual target schema for *communes*, *gares*, *lignes* and *nodes*(primary key: bold font).

The "belongs_to" relationships of Figure 1, are very important:

- The *gare–commune* relationship is straightforward, once all *gares* are geocoded;
- The *gare–ligne* relationship is the challenge: how to find old *lignes* and all their *gares*.

Additional spatial constraint (*contains*) controls that a *gare* 'belongs_to' a *commune*, and (*inherits_one*) states that at least one *node* gives its coordinates to the *gare* (what about the other ones, if any? This is anissue studied in the sequel).

Some target concepts matching some INSPIRE ones (Figure 2), e.g.,

- node → *RailwayNode* | | *RailwayStationNode*;
- gare → [*RailwayNode*(West), *RailwayStationNode*, *RailwayNode*(East)];
- `km` (*point kilométrique*) → linear referencing,
- `uic` (Union Internationale des Chemins de fer, the Worldwide Railway Organization (UIC) code) → *RailwayStationCode*, etc.

2.1.2. Target Attributes for Classes *Commune*, *Gare*, *Ligne*

Main attributes (mandatory) are:

- `insee` = [**primary key**] official unique code for a *commune*, (may evolve with time);
- `num` = [**primary key**] official number for a *ligne*, or any given unique code.;
- `uic` = [**primary key**] official *RailwayStationCode*for a *gare*, given by the UIC, the international railway organization, or any given unique code;
- `km` = *linear referencing*, French:"*point kilométrique*", German: "*Streckenkilometer*";
- the couple (`num`, `km`) is [**primary key**] for a *gare* (not two equal `km` for one `num`);
  Geographical attributes (mandatory):
- `point` = geocode of a *node*, and for the associated *gare*;
- `polygon` = contour of a *commune*;
- `geometry` in the sequel, is used to denote either `point`, or `polygon`.

Time attributes (mandatory, only one by now):

- `validTo` = year of end of service of a *ligne* (hence of all its *gares*). A *ligne* can be disused partly (% of full length) at different dates, definitively (French: *déclassement*) or reversibly. Most recent year is used (INSPIRE: *validTo*).

Additional attributes (useful for display purposes, quality control):

- `label` = name given to a *gare* (should be in bijection with `uic`) or a *node*;
- `nom` = toponym for a *commune* (when used for a *gare*, may differ from the `label`);
- `capa` = use status, e.g., 'cargo only', 'border point', etc. used for display purposes.

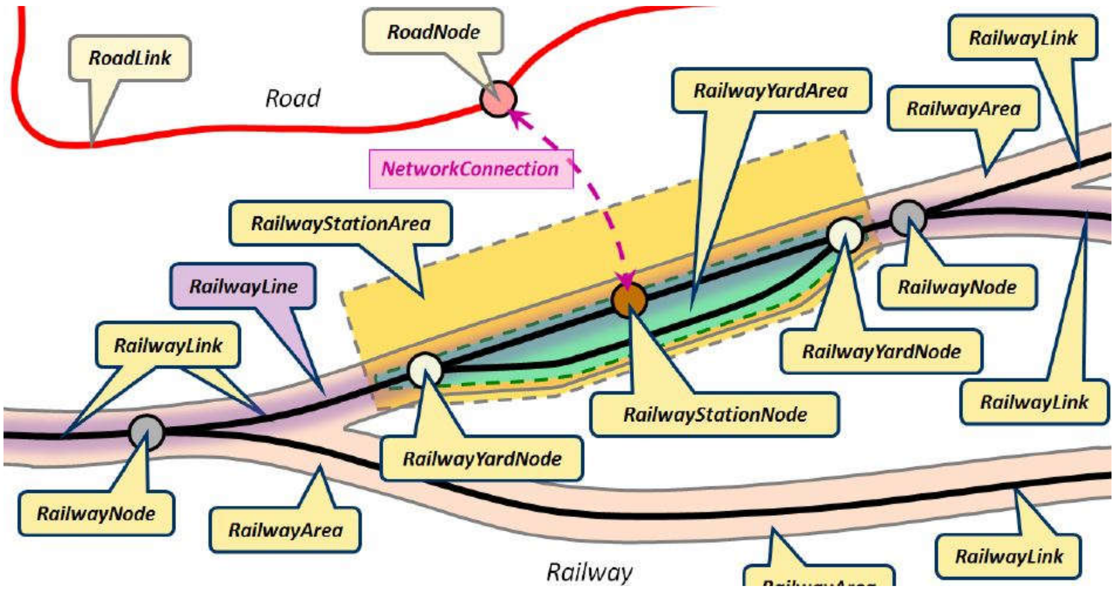


Figure 2. an illustration from the INSPIRE railway network standard (excerpted from [28]).

Summing up the constraints that must be satisfied:

(1). Every *gare* belongs to one existing *ligne*: `num` is mandatory (see Section 3);
(2). A couple (`num`, `km`) must be unique;
(3). A couple (`num`, `label`), must be unique (see Section 2.3.1 and Appendix B);
(4). The subset of all *nodes* of a same *ligne* (= `num`) must be strictly ordered by `km`;
(5). Every *gare* belongs to one *commune*, whose `polygon` contains the *gare*`point`. Sometimes, purposely, a *gare* has been built at the border of two *communes* (only one is recorded);
(6). Every *ligne* has two ends: an `origin` node, and a `terminus` node. One *ligne* either is "*active*", or has a "*validTo*" (alias "*end*") date;
(7). Every *gare* has one or more *node(s)*, but a *node* may have no *gare* (e.g., a *fork*);

Constraints (1–4) are checked a priori (*go*/*no-go*), also a posteriori for quality control.

Constraint (5) can be checked a posteriori, setting, or controlling the `insee` value.

Constraint (6): a failure must trigger a search for additional information (Section 3).

Constraint (7): several *nodes* attached to the same *gare*, may differ in `geometry`, what is a major cause of indecision in the fusion process.

2.1.3. Target Notation and Generic Step-by-Step Approach for Collecting Values

The overall objective is to gather as many *gares* as possible that have ever existed. Therefore, the process starts with an initial dataset, then grow it, in a logical consistent way, by adding complementary or supplementary information from more available data.

To add a *gare*, means to create a *node* and to fill in attribute data step by step (Table 1), starting with the knowledge that a *gare* named `label` belongs to the *ligne* identified by `num`. In general, information about a *ligne* contains a list of the *gares* in between `origin` and `terminus`, which allows to set `km` values in correct order, although approximate in kilometers.

Table 1. Step-by-step generic approach for adding a *gare* into the reconstructed network.

(a).	`LABEL`: the *gare* with that name belongs to the *ligne* identified by `num`, which has at least an `origin`and a `terminus`; If working from a given list of *gares*: to start at origin.
(b).	`KM`: if unknown, can be interpolated between adjacent *gares*, or between `origin`, `terminus`, using the `length` of the *ligne*. The hard assumption is about the strict order of the list;
(c).	`Point[LONGITUDE,LATITUDE]`: coordinates to be obtained by software or visual inspection. The geocoding, and its quality, is extensively addressed in the sequel.
(d).	If working from a list: to iterate with next *gare* in list, until reaching `terminus`.

Attribute `uic`, is either given and the *node* is linked to this *gare*, or derived from (`num`, `km`).

Attribute `insee`, is either given or derived from `geometry` of *gare* and,*commune*.

Attributes `capa`, `info` are merely informative (voidable).

The baseline goal is to build a dataset, compliant with the above target constraints.

Constraints are flexible enough for semi-structured VGI (Section 3), while allowing consistency checking at every stage, for every source, and for the result as well.

Connectivity is not explicit in that model, but can be retrieved from the existence of several couples (`num`, `uic`) for a same `uic`, which denotes a "*junction-gare*", or by the explicit identification of a *fork* between 2 *lignes* (see Discussion and Appendix B).

2.2. Public Open Data Sources, and the Information Revision Problem

In a project it is customary to define a baseline, which encompasses: goal, constraints (listed above), resources (listed below), estimated cost (time to target goal).

Baseline resources are versions (2020, 2017, 2014) of a public datasets originating from *SNCF-Réseau* (French national operator) [30], somewhat similar to the target schema.

Baseline cost is the cost per *gare* times the number of expected gares. The cost for one *gare*, depends on the steps outlined in Table 1. The number of expected *gares*, has not been found in the literature: for instance Auphan [31] estimates the maximum length of the network at70,000 km in 1920, but does notmention a number of *gares* or *communes* impacted at that time. An estimation can use length and density of the network, e.g., 24,000 km today, serving 3029 "*gares du réseau français*" [32], gives a *gare* every 7.92 km. That inter-*gare* distance was lower in 1920, with stops in every crossed *commune*: a sampling on already reconstructed data gives about 6 km. Therefore, the number can be up to 12,000 *gares*.

2.2.1. Description of the Available Public and Administrative Sources

The public datasets that provide *gare* and *node* information (no explicit difference), are listed in Table 2, with data schema, version, and availability. The public datasets about *communes* and *lignes*, listed in Table 3, are used for joining information (`insee`, *num*) and for display purposes.

Table 2. Public data sources for stations: '*gare*' or '*node*' features.

Sncf2020: "Réseau ferré de France", last update: 2020, accessed: 8 March 2020
url: `https://ressources.data.sncf.com/explore/dataset/liste-des-gares/`
Schema (geojson) and counts (4148 features, with geometry):
`{code_ligne, libelle, fret, voyageurs, code_uic, pk, departemen, commune} +{geometry}`
Sncf2017, or`SNCF2`: "Réseau ferré de France", last update: 2017
url: (authors copy) not available anymore since end 2019,
Schema (= SNCF2020) and counts (7702 features, only 6812 with geometry):
Sncf2014, or`SNCF1`: "Réseauferré de France", last update: 2014, accessed : 8 March 2020
`https://data.gouv.fr/fr/datasets/gares-ferroviaires-de-tous-types-exploitees-ou-non/`
Schema (CSV) and counts (6442 features, all attributes: 6442):
`[code_ligne, nom, nature, latitude (WGS84), longitude (WGS84)]`

Table 3. Public data sources for cities and towns: '*commune*', and railway lines: '*lignes*'.

Insee-new: `official codes for` *commune* `(+2003–2021 administrative changes)`
`url: https://www.insee.fr/fr/information/2028028`
`CSV, counts (35589 features, 2577 changes in 2018, no geometry)`
Insee-geo: *commune* `contours (curated by G. David)`, accessed: 8 March 2020
`url: https://france-geojson.gregoiredavid.fr/`
`geojson, counts (35798` *communes* `contours with geometry)`
Lignes: "**SNCF** Réseau ferré de France", created: (before 2017), accessed: 8 March 2020
`https://ressources.data.sncf.com/explore/dataset/formes-des-lignes-du-rfn/`
Schema (geojson) and counts (1779 features, with geometry): `{libelle, code_ligne, mnemo}+{geometry}`

2.2.2. Matching Attributes of the Public Sources with Target Attributes

Among the attributes, there are some direct, or some indirect matches:

- `Target.num`: matches `SNCF*|Lignes:code_ligne`, primary key for *lignes*. Mandatory;
- `Target.label`: matches `SNCF1:nom`, and `SNCF2*:libelle`;
- `Target.km`: matches `SNCF2*:pk`. Mandatory. Order must reflect the strict order of the *nodes* on the *ligne*;
- `Target.uic`: matches `SNCF2*:code_uic`. In `SNCF1`, uses `Target.label` instead;
- couples `SNCF1:(code_ligne, nom)` and `SNCF2:(code_ligne, pk)`, are used as primary key for *nodes* what requires to check its uniqueness;
- `Target.capa`: derived from `SNCF:nature`, `SNCF*:fret,voyageurs` or `Lignes:mnemo`, whichever available;
- `Target.geometry`: matches `SNCF1:(latitude,longitude)`, `SNCF2*:geometry:point`,
- `Target.insee`: present in `Insee-geo` or `Insee-new` datasets, is primary key for *communes*, and must be retrieved for a *gare*, by identifying which *commune* verifies `Point_in_Polygon(geometry(`*gare*`),geometry(`*commune*`))`;
- `Target.nom`: matches `SNCF2:commune`, would rather be retrieved via `Target.insee`;

2.3. Meta-Analysis of Public Sources, Building a Similarity Measure, and Corrections

The various ***Sncf*** versions provide scarce metadata [28], only about their lineage:how to check if a dataset complies with the target constraints? the only way is to perform a "*meta-analysis*", a technique using "individual participant data" (IPD-MA), mainly developed in medicine [9,10].

The math behind *meta-analysis* uses variance-covariance matrices. In this application, "individual participants" are *nodes* of *gares*, and data are qualitative: hence, only equality can be checked, leading to *true/false* values. Therefore mathematics boils down to simple counts of items sharing equal attribute values. The *meta-analysis* is applied directly on the individual items of each dataset, and proves useful in the subsequent fusion.

Counting single attribute occurrences performs an*univariate meta-analysis*, counting joint occurrences by a couple of attributes performs a *multivariate meta-analysis*.

This subsection is devoted to detailing what issues are revealed by the *meta-analysis*, helping to design the steps of a fusion approach. For aquick read, skip directly to Section 2.4 to discover the fusion, and return later to understanding the reasons why.

2.3.1. Meta-Analysis of Each Dataset, and Comparison

This is performed by the *metaAnalysis* routine (Appendix A).

- Step 1: *univariate meta-analysis* with `num` and `label` values. Result: each *node* has a `num` and a `label` value, in both **2014** and **2017**, what fulfills the target first requirement. All 6442 nodes have a `geometry` in **2014**, but only 6812 *nodes* have a `geometry` in **2017**.
- Step 2: *multivariate meta-analysis* with `uic, label`, and (`uic-label`) values: **2017**only.

There are 6813 different `label`, but 6817 different (`uic-label`) values, what means that 4 couples (=`label`, ≠`uic`) are denoting a *toponym ambiguity*, e.g.: "Cernay". Ambiguity is inherent to toponymy (in most countries): this is a well known issue [20,21]. Several mismatching examples and an explanation are proposed in Appendix B for what is named the "*toponym-pattern*".

- Step 3: *multivariate meta-analysis* with (`label-num`) and (`uic-num`) couples

In both **2014** and **2017**, 6 *nodes* have equal values (=`label`, =`num`) or (=`uic`, =`num`), meaning data duplication e.g.,"Saintes" (cf. routine `disDuplicate` in Appendix A).

- Step 4: inspect the `geometry` of Step3 couples: if a same `label` or `uic` occurs in several *nodes*, it denotes a *junction-gare* (= `uic`, ≠ `num`). Associated `geometry`are expected to be equal: the computed deviation is broken down into five distance intervals (Table 4).

Table 4. Breakdown of distances between the multiple nodes of gares.

Intervals (nb. Nodes)	[0, 150 m]	[150, 300]	[300, 1 km]	[1 km, 2 km]	[2 km, ∞]
	"Close Enough"			"Rather Far"	
SNCF2014(642 nodes/6442)	550	48	32	6	6
SNCF2017(1360 nodes/7702)	541	184	375	157	103

The choice of the values (150 m, 300 m, 1 km, 2 km) is explained in Section 2.4.

In **2014**, among 642 *nodes*, 93% are "close enough", and 1% "rather far". For instance, above 2 km, the "`Bauvin-Provin`" case, is named a "*fork-pattern*", for the closure of a *ligne* has "moved" the *node* to a remote location at the last *fork* on that *ligne*. An analysis of the "*fork-pattern*" is proposed in Appendix B.

In **2017**, among 1360 *nodes*, 53% are "close enough", but 635 are not (47%). The cause of so many discrepancies is that more "*fork-patterns*" are taken into account in **2017**.

It's impossible to choose the right `geometry` without extra information, moreover, the wrong location is not an error, but a meaningful *node*: the solution is to mark it (Section 2.4).

- Step 5: inspect the cardinal of Step3 couples, for every `num` value: thisgives the number of *nodes* per *ligne* (Table 5).

Table 5. Breakdown of *lignes* according to their number of nodes.

Datasets and Link Attribute	Isolated Gare	2-Gares Ligne	3 to 7-Gares	8 to 15-Gares	16 to 30-Gares	31 to Max Gares	(Total)
`SNCF2017 num`	107	76	245	171	91	44	734
`SNCF2014 num`	94	62	191	130	76	40	593

A *ligne* with one *gare* denotes an "isolated" *gare*, which is a conflicting constraint. Most of these errors correspond to *lignes* now closed to traffic (*fork-pattern* again), which requires extra information, not available at that stage.

2.3.2. Conclusion of the Meta-Analysis

The meta-analysis has been applied to the two main public datasets providing *gare* information: the result is a better understanding of what data must be handled, which helps designing a fusion approach to merging data from **2014** and **2017**. In particular, it helps in understanding that the "*toponymy-patter*" and the "*fork-pattern*" constitute hurdles in the fusion process, and will require additional information from external VGI sources.

The meta-analysis can be used as a quality control tool at any time at any stage of the reconstruction process, and will be used to control the result (Section 4).

Concerning ***Sncf2014*** and ***Sncf2017***, some metadata can be summarized (Table 6).

Table 6. Initial metadata after meta-analysis of the individual datasets.

METADATA***Sncf2014***: { "mime":"csv", "year":"2014", "nbfeatures":6442, "schema#": {"label":6442, "num":6442, "nature":6442, "geometry":6442}, (1) "unos#": {"label":6098, "num":593},"duos#"{"num-label":6436} (2) }
METADATA***Sncf2017***: { "mime":"geojson", "year":"2017", "nbfeatures":7702, "schema#": {"label":7702, "uic":7702, "num":7702, "km":7702, "capa":7702, "geometry":6812}, "unos#": {"label":6813, "uic":6817, "num":734} }

(1) notation `schema#` stands for: count of all occurrences of properties. (2) `unos#` and `duos#`: count of unique value occurrence for some properties or couple of properties.

The outcome of the *meta-analysis* of the initial datasets, is that 890 *nodes* are not geo-coded, and 635 otherhave a poor geometry (Table 4), and would rather be avoided in the fusion process.

2.4. Combining the Available Sources: The Fusion/Revision Problem

Versions ***Sncf2014*** and ***Sncf2014*** probably have a same origin, then evolved separately. ***Sncf2017*** has more attributes, notably the `km`, and `uic`, and a few more geocoded features (6812 versus 6442) although we do notknow which version would provide the best quality.

The expectation is that ***Sncf2014*** and ***Sncf2017***, either confirm each other on some *nodes*, or add up unique *nodes* (Figure 3).

The relational approach, although natural with tabular-like datasets, has been refuted by the *meta- analysis*, which revealed that 1525*nodes* have poor or no geometry, and that `label` is not a reliable attribute.

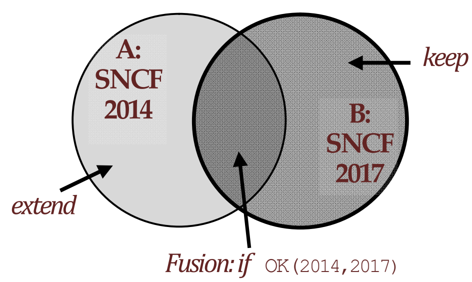


Figure 3. Matching ***Sncf2014*** and ***Sncf2017***.

Let's consider instead the fusion approach, following Bloch [12]:

DEFINITION. *Fusion of information consists of combining information originating from several sources in order to improve decision making.*

More precisely, let usconsider the context of *Revision*, or *reverse-Updating* [13] for we aim at reconstructing the past. Revising ***Sncf2017*** by ***Sncf2014***, means to compute $OK(x, y)$ in order to undertake "pairing" x (*2014*) with a y (*2017*), then merging x attributes with those of y, or "impairing" x, if no y fits, then adding x into ***Sncf2017***, after some conversion. All "impaired" y of ***Sncf2017*** remain unchanged.

Following Bloch, three steps are required: measure, decision, combination.

2.4.1. Knowledge Representation and Measure of Similarity

Consider a declarative approach based on the notion of neighborhood $V(x)$ of a *node* x, and a measure of membership to that neighborhood: $|y \in V(x)|$, degree of similarity of another *node* y to x.

The *meta-analysis* tells us that, once duplicates and ambiguities are solved, a dataset is complying with the target constraints, and has an attribute space into which to define "neighborhoods", and to build a "similarity" measure (Table 7), which is a function $OK: (x, y) \rightarrow [0,1]$, where 0 can be interpreted as *false* and 1 as *true*.

Table 7. The similarity measures membership to V(x). Dissimilarity measures non membership.

$\lvert y \in V(x) \rvert$ = $\lvert$ *similarNumLabel*(x,y)–*normalizedShortDistance*(x,y) $\rvert$	(a)
similarNumLabel(x, y): (`num`(y) = `num`(x)) ∧ (slug(`label`(y)) = slug(`label`(x))) → 1 or 0	(b)

normalizedShortDistance(x, y):
let d = *distanceGreatCircleInMeter*(`geometry`(y), `geometry`(x));
if ($d \le D_1$) → 1; elseif ($D_1 < d \le D_2$) → ($D_2 - d$)/(D_2-D_1); elseif ($d > D_2$) → 0
	(c)

$\lvert y \notin V(x) \rvert$: $\lvert$¬*similarNumLabel*(x,y)–*normalizedGreatDistance*(x,y) $\rvert$	($\bar{a}$)
¬*similarNumLabel*(x, y): (`num`(y) ≠ `num`(x)) ∨ (slug(`label`(y)) ≠ slug(`label`(x))) → 1 or 0	($\bar{b}$)

normalizedGreatDistance(x, y):
let d = *distanceGreatCircleInMeter*(`geometry`(y), `geometry`(x));
if ($D_4 \le d$) → 1; elseif ($D_3 < d \le D_4$) → ($D_4 - d$)/($D_4 - D_3$); elseif ($D_3 > d$) → 0
	($\bar{c}$)

Let usdescribe that similarity/dissimilarity measure components:

(a) and ($\bar{a}$) quantify `num`, `label`, `geometry` for both x and y, into the [0,1] interval;
(b) is qualitative (*true*/*false*: 1/0). Checking equality on slug(`label`) rather than on `label`;
(c) uses threshold values $D_1$and D_2, ($\bar{c}$) uses D_3 and D_4, whichmeans that dissimilarity is not the complement of the similarity measure.

The initial step is to seek, for each ***2017*** *nodey*, the closest ***2014*** *nodex*:

$$distance(x, y) = \min_{z \in B} distance(z, y),$$

to form a pair of "closest *nodes*", using the *GreatCircle* algorithm, whose precision is sufficient in this application, in the range [0, 100 km]. This routine is part of Annex A.

Table 8 gives the distance breakdown for "direct pairs" = pairs of closest nodes with the same label, and "reverse pairs", with the closest **2017** counterpart of each **2014** *node*.

Table 8. Breakdown by distance intervals of (2014, 2017) direct pairs; and (2014, 2017) reverse pairs.

Intervals	**[0, 50 m]**	**[50, 100]**	**[100, 150]**	**[150, 200]**	**[200, 250]**	**[250, 300]**	**[300, 1 km]**	**[1 km, ∞]**
direct positive	4618	1082	375	161	113	72	321	58
reverse positive	4501	1072	348	135	70	48	129	18

The histogram of the distances grouped by 50 m intervals (Figure 4), provides a clue about choosing relevant thresholds:

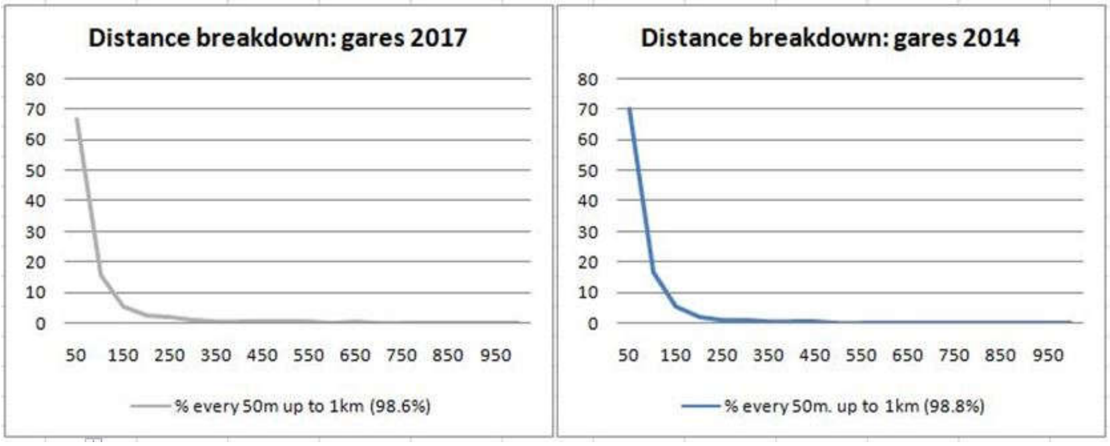


Figure 4. Breakdown by 50m distance intervals: typical shape and best inflection position.

- the number of directpairs (left) decreases rapidly up to 150 m (88%), and slows down after 300 m (93%); and for reversepairs (right): 92% at 150 m, 96% at 300 m;
- both kinds of pair are less than 1.5% after 1 km; and only a few after 2 km.

Therefore the choice for D_1–D_2 is 150–300 m, and 1–2 km or D_3–D_4.

2.4.2. Decision to Include a Node in the Similarity Neighborhood

To include x in class C_i according to the absolute majority (or threshold rule):

$x \in C_i \ if \ |y \in V(x), y \in C_i| > \alpha * |V| \ , with: \alpha \in]0,1[$

α= % means: at least % of the *nodes* of *V(x)* must be in C_i

The inferential aspect of the declarative approach [14] ensures that:

(a) rules are independent of the actual knowledge in the knowledge base;
(b) rules are not restricted to the conceptual schema representation.

The choice to "pair" x and y is made by comparing $|y \in V(x)|$ to some threshold, causing to keep x and y whose distance is α% between D_1 and D_2: x and $y$are "positive" candidates to fusion. The uncertainty is that some of them can be "false positives". Similar *nodes*, whose dist≥ D_4, are tagged "supposed negative" (**SN**).

The choice to "impair" an x, is to consider, using D_3 and D_4, that $x$cannotbe compared to any y, and is candidate to be "integrated" to the final result. However, we may get "false negatives". Dissimilar x whose dist ≤ D_1, are tagged "supposed positive" (**SP**).

About "undecided" (**und**) *nodes*, the choice is between: (1) to reduce the D_2–D_3 gap, even to D_3=D_2, whichreduces the number of **und**, but increases the number of both false negatives and false positives; or (2) to obtain only a few FNs and FPs, and many undecided.

The overall tagging decision is sketched in Figure 5, with different possible tags.

Corresponding results for direct and reverse revision, are provided in Table 9 (a,b), where signs + and ¬ denote respective use of similarity or dissimilarity measure. Undecided cases (**und**) are grey cells. Counts for the direct revision do not include the *nodes* with no `geometry`.

	highly positive	*probably positive*	*undecided*	*probably negative*	*highly negative*
	0 − − − − − − − $D1$	. . . . $D2$		$D3$	$D4$ − − − − − − − − ∞
	↓	↓	↓	↓	↓
Similar.	**AP**	**PP**	**und**	**und**	**SN**
Dissimi.	**SP**	**und**	**und**	**PN**	**AN**

Figure 5. Decision diagram depending on the distance in fusion-candidate pairs of *nodes*. Notations: **AP**:"assumed positive", **PP**:"possible positive", **AN**:"assumed negative", **PN**:"possible negative", **SP**:"supposed positive", **SN**:"supposed negative", **und**:"undecided".

Table 9. (a) From 6979 direct pairs (only those with geometry among 7702). (b) From 6442 reverse pairs (all with geometry).

(**a**)

intervals	**0–D$_1$ = 150 m.**	**D$_1$–D$_2$= 250 m.**	**D$_2$–D$_3$= 1000 m.**	**D$_3$–D$_4$= 2000 m.**	**D$_4$–∞.**
direct +	6070 **AP**: 87.2%	353 **PP**: 5.0%	*total undecided*	←	9 **SN**: 0.1%
direct ¬	59 **SP**: 0.8%	→	450 **und**: 6.4%	18 **PN**: 0.2%	25 **AN**: 0.4%

(**b**)

intervals	**0–D$_1$ = 150 m.**	**D$_1$–D$_2$= 250 m.**	**D$_2$–D$_3$= 1000 m.**	**D$_3$–D$_4$= 2000 m.**	**D$_4$–∞.**
reverse +	5944 **AP**: 91.9%	251 **PP**: 3.9%	*total undecided*	←	4 **SNs**: 0.3%
reverse ¬	46 **SP**: 0.7%	→	163 **und**: 2.5%	4 **PN**: 0.2%	30 **AN**: 0.8%

The role of the `fusionTags` routine (Appendix A), is to set the tag value (**AP**, **AN**, **PP**, **PN**, **SP**, **SN** or **und**), of every *node* and to store it together with the closest counterpart *node* and distance of that pair, resulting in:

2017*-node*: `f + {"tag":tag(f), "dist":dist(f,g'), "closest":link_to-2014(g')}`
2014*-node*: `g + {"tag":tag(g), "dist":dist(g,f'), "closest":link_to-2017(f')}`

`dist(a,b)` measures the distance between *node* from A and its closest B counterpart.

Then a fusion sort is made into three classes, *fusionable*, *integrable* or *undecided*:

- *fusionable*: means that the *node* and its counterpart (`closest` is ok) are supposed to inform the same real *gare* and we can proceed with the fusion of their data;
- *integrable*: means that the *node* has no counterpart (`closest` is irrelevant) and can be kept as is (if in the right set), or adapted for integration (if from the other set).

Using *f* for **2017**and *g* for **2014**, the decision follows the rules:

- direct revision:

$$(tag(f) = \mathbf{AP}) \vee (tag(f) = \mathbf{PP} \wedge dist(f, g') \ \leq D_1) \Rightarrow fusionable(f), quality: ok$$

$$(tag(f) = \mathbf{PP} \wedge (D_1 < dist(f, g') \ \leq D_2)) \Rightarrow fusionable(f), quality: medium$$

$$(tag(f) = \mathbf{AN}) \vee (tag(f) = \mathbf{PN} \wedge dist(f, g') \ \leq D_4) \Rightarrow integrable(f), quality: ok$$

$$(tag(f) = \mathbf{PN} \wedge (D_4 > dist(f, g') \geq D_3)) \Rightarrow integrable(g), quality: medium$$

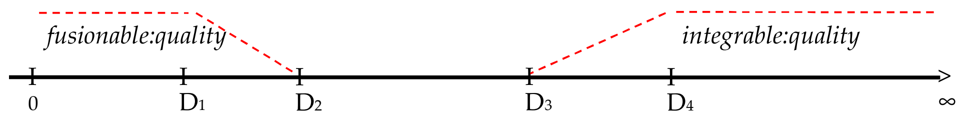
- reverse revision (for integration of "forgotten *nodes*"):

$$(tag(g) = \mathbf{AN}) \vee (tag(g) = \mathbf{PN} \wedge dist(g, f') \ \leq D_4) \Rightarrow integrable(g), quality: ok$$

$$(tag(g) = \mathbf{PN} \wedge (D_4 > dist(g, f') \geq D_3)) \Rightarrow integrable(g), quality: medium$$

Among the tags, only**AP**, **PP**, **AN**, and **PN** are reliable enough to be used in the decision. Indeed, we must question the **SP**-pairs (`dist`< D$_1$, ≠`label`), for most uncertainty is due to the *toponym-pattern* (Appendix B.1). Also we must question **SN**-pairs (`dist`> D$_4$, =`label`): see *fork-pattern* (Appendix B.2).

Theses tags and distances are helpful when confronting extra open data, for instance with a specific lexicon, e.g.: *Insee-new* list of toponym changes, *SNCF* list of *gares* at different dates (see Section 3). Also helpful for further processing is the *quality* of the fusion decision which can be a fuzzy measure between [*D*$_1$, *D*$_2$] or [*D*$_3$, *D*$_4$] respectively:



2.4.3. Fusion Combination, Integration, Revision and Conclusion

The last fusion step is to make a single "fused" *node* from a *node* pair, that is choosing appropriate values for every attribute, e.g., best coordinates?, or to convert into the attribute schema of the other dataset.

The fusion-combination of ***2014*** attributes concerns:

- `nature`: which can be translated into a `capa` value (though losing some specificity).
- `geometry`: the maximal distance being D_2, use ***2017*** coordinates;
- `info`: add approximation info about `geometry` (depending on `dist`).

The integration of ***2017*** *nodes*is straightforward.
The integration of ***2014*** *nodes*is more difficult, concerning:

- `geometry`: straightforward, use ***2014*** coordinates;
- `nature`: translate into a `capa` value (rather easy);
- `km`: seek for the closest 2 *nodes*on the same *ligne*, then interpolate a value;
- `uic`: build a unique code using `num`and `km`;
- `info`: add uncertainty info about `km` and `uic`.

The revised dataset is the new "baseline-resource" for the rest of this work. It complies with target constraints (see metadata: Table 10). Quality information is added whenever an approximation is made.

Table 10. Updated metadata after the revision process (differences with Table 6 are underlined).

METADATA***Sncf2014***: {
 "mime":"csv", "year":"2014", "nbfeatures":6442,
 "sch#": {"label" … :6442, "closest":6442, "fusable":6189, "integrable":33}
 }

METADATA***Sncf2017***: {
 "url":"g2017", "mime":"geojson", "year":"2017", "nbfeatures":7702,
 "sch#": {"label" …:7702, "closest":6984, "fusable":6415, "integrable":41,
 "coordinates":6984}
 }

Overall conclusion before Section 3:

- Software fusion is safe (6415 **AP** + **PP** tags = almost no false positives);
- Software integration is safe (74 **AN** + **PN** tags = almost no false negatives).
- The remaining 250 *nodes*from ***2014*** and 564 from ***2017*** for which the fusion decision is too uncertain, plus 718 with no geometry, from ***2017***are in total 1532.

The important information after the fusion is that:

- 6489 *nodes* have been qualified;
- 1532 *nodes* (`label-num-km`) -i.e.,: about 950 *gares*– can be confronted to VGI and remote sensing imagery for setting a controlled geometry.

3. Materials and Methods Part 2: Voluntary Geographic Information (VGI) Data Integration and Control

So far, the revision process has yield an important and consistent dataset, complying with target constraints (unique code, revised `label`, correct `km`, …), plus some quality information. However, the target horizon, amounts to twice as many*nodes*.

Doubling up the total, starting by investigating the 1532 *nodes*left behind, then discovering thousands more "forgotten" *gares*, and further improving the overall quality are the challenges that we ask the VGI to help us overcome.

This section investigates Wikipedia, focusing on its semantic aspect, which makes profit of the UIC ontology (Section 3.1), then investigates various VGI sources, developing some helpers to integratesparse data from less structured and less semantic web data, and it takes advantage of the aerial pictures archives made publicly available by the French IGN.

3.1. Gathering Information from Wikipedia Railway Specific Pages

There are many pages devoted to railways. Luckily, standardization efforts of the UIC (UIC: Union Internationale des Chemins de fer, the Worldwide Railway Organization, since 1922) propose an international ontology (thousands terms in the UIC railway Dictionary), allowing the design of semantic Wikipedia "templates" for *gares*, *lignes* and *communes*.

3.1.1. Extracting Coordinates from Wikipedia

Let usstart with a simple use: the extraction of the coordinates of a *gare* named `label`.

The Wikipedia API (application program interface) gives access to the coordinates, at the highest level. Querying it with "Gare de `label`", returns the `coordinates` (if any), or "`missing`".

The `wikiCoordinates` routine (Annex) is an asynchronous code that must be used in a "Promise" (technology to awaiting answer, provided by most computing languages).

In case of a "`missing`"result, we can query the API with "`label`" as *commune* toponym, for quite often a *gare* is labeled by its *commune* name. However the *gare* can be somewhat far from the center. For instance, with Martigues (Figure 6), the distance is 5.3 km (great-circle distance). Therefore, coordinates obtained by that means provides only a rough positioning, which may help when using remote-sensing imagery.

Figure 6. The coordinates of a *commune* center and its *gare* (5.31 km apart in that example).

The `wikiCoordinates` routine is used for improving the "revised" dataset, when several location compete for one `label`, for instance, in the case of `Saintes` (Section 2.3), the distance between the duplicates was 348 m, and the answer of `wikiCoordinates` is:

Query`:`"`Gare de Saintes`" → geometry: `[-0.617596,45.748672]`, Quality:"`good`"

That result is removing the uncertainty.

3.1.2. Extracting Semantic Information Using Wikipedia's Infobox

The Wikipedia API-v2 provides much richer information from an "ontology-driven" *Infobox* [22].

An *Infobox* is a panel, usually next to the lead section, which uses a specific ontology:

- *commune:* `{{Infobox Commune de France}}` contains coordinates, `insee` and more (Figure 7);
- *gare:* {{`Infobox Gare` …}}, contains coordinates, `nom` of the including *commune*, all or some of the *`lignes`* that connect to that *gare* (Figure 8).
- *ligne:* `{{Infobox Ligne ferroviaire …}}` see next Section 3.1.3.

```
/* complies with Modèle:Infobox_Commune_de_France */
{"batchcomplete":true,"query":{"pages":[{"pageid":279049,"ns":0,"title":"Ercé","revisions":[{"
slots":{"main":{"contentmodel":"wikitext","contentformat":"text/x-wiki","content": "{{Infobox
Commune de France\n | nom = Ercé\n | ...abridged... \n | région = [[Occitanie]]\n |
département   = [[Ariège]]\n | ...abridged... \n | insee = 09113\n | cp = 09140\n
|...abridged... \n | longitude = 1.29027777778\n | latitude = 42.8502777778\n | alt mini =
574\n | alt maxi = 1903\n | superficie = 40.75\n | population =  ...abridged... }}
```

Figure 7. *Infobox* for a *commune* (`Ercé`). Relevant items underlined (excerpt from screen console).

```
/* complies with Modèle:Infobox_Gare */
{"batchcomplete":true,"query":{"pages":[{"pageid":667531,"ns":0,"title":"Gare de Rennes",
"revisions":[{"slots":{"main":{"contentmodel":"wikitext","contentformat":"text/x-wiki",
"content":"{{Infobox Gare\n| nom = Rennes\n| ...abridged... \n| lignes = [[Ligne de Paris-
Montparnasse à Brest| Paris-Montparnasse à Brest]]<br> [[Ligne de Rennes à Redon|Rennes à
Redon]]<br>[[Ligne de Rennes à Saint-Malo - Saint-Servan| Rennes à Saint-Malo]]<br>[[Ligne de
Châteaubriant à Rennes| Châteaubriant à Rennes]] \n| ...abridged...
```

Figure 8. *Infobox* for a *gare* (`Gare de Rennes`). Relevant items underlined.

The routine `wikiInfobox` (Appendix A) can parse both types of `Infobox`.

3.1.3. Extracting Data for all the Garesof a Same Ligne: The Routemap Semantics

Given a *ligne* name, e.g., `Ligne_d'Audun-le-Tiche_à_Hussigny-Godbrange`, we can query the Wikipedia API, and get an `{{Infobox Ligne ferroviaire …}}` description.

That *Infobox* (French template) contains simple items, such as length (*longueur*), gauge (*écartement*), the official num (*numéro*), closing date (*fermeture*), …, and a much more complex item: a table whose syntax is intended to display a "*routemap*" (*schéma*) of that *ligne*.

The *routemap* semantics (French sites,) refers to `Modèles/BS` ("BS" stands for *Bahn-Strecke* for the model has been initiated by Germans). English sites refer to the general Route diagram template description [33,34].

A simplified version of a *ligne Infobox*, is in Table 11. The "*schéma*" extracted from this *Infobox*, is presented in a simplified version, in Table 12: it is a `{{BS-table}}`, complying with the `BS` model, which gives the ordered list of *nodes*, along that *ligne*.

Table 11. Simplified version of an example of `Infobox_Ligne_ferroviaire`.

```
{{Infobox Ligne ferroviaire\n| nomligne = d'Audun-le-Tiche à Hussi-
gny-Godbrange\n| mise en service = 1880\n| fermeture = 1966\n| fermeture2 =
1987\n| numéro = 196000\n| longueur = 8.8\n| écartement = normal\n| … … (more
items) …
schéma = \n{{BS-table}}\n …
{{BSnn}} … series of items describing the nodes along that line (see next Table)
… \n{{BS-table-fin}}\n
}}
```

Table 12. Simplified version of the `BS-table` (of the same *ligne*).

`{{BS-table}}`	
`{{BSbis|...|  ... ... |Ligne d'Esch-sur-Alzette à Audun-le-Tiche}}`	
`{{BS3bis|...| ... ... |Frontière entre la France et le Luxembourg}`	border
`{{BS5bis|...| ... ... |Ligne de Fontoy à Audun-le-Tiche}}`	
`{{BS5bis|...| ... ... |(1) Ligne non déclassée, non exploitée}}`	origin
`{{BS5bis|...| 21,144|Audun-le-Tiche |(301 m)}}`	
`{{BS5bis|...| ... ... |Ancienne voie vers Villerupt-Micheville}}`	branch
`{{BSbis|...|  2,4xx|  |Bif vers raccordement d'Audun-le-Tiche|}}`	label
`{{BSbis|...|  4,6xx|Rédange |(340 m)}}`	tunnel
`{{BSbis|...|  5,5xx|  |Tunnel d'Adlergrund|(409m)}}`	km
`{{BSbis|...|  6,6xx|  |Ancienne frontière France - Empire allemand}}`	branch
`{{BS5bis|...| ... ... |Ligne de Longwy à Villerupt-Micheville}}`	terminus
`{{BSbis|...|  8,8xx|Hussigny-Godbrange |(346 m)}}`	
`{{BSbis|..|   ... ... |Ligne de Longwy à Villerupt-Micheville}}`	
`{{BS-table-fin}}`	

The right column indicates which attribute to be parsed (values underlined on left): origin to terminus, *gares* with label, km, also *forks* to other lines, bridges, international border crossings, etc.and most of the expected information, except the geometry.

Wikipedia parses the BS-table to draw a graphic representation of the *ligne* (Figure 9).

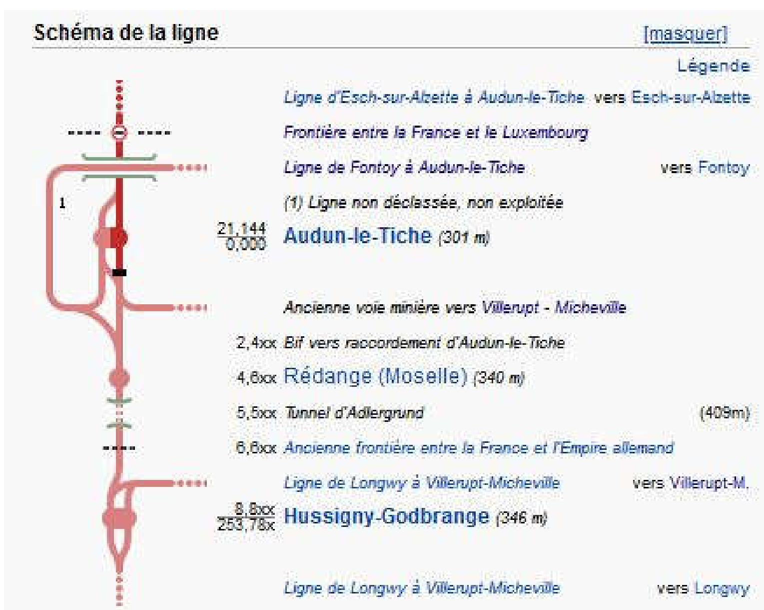


Figure 9. Infobox_Ligne_ferroviaire with `Ligne_d'Audun-le-Tiche_à_Hussigny-Godbrange`.

There are 1000 such Wikipedia pages for French *lignes*, each *ligne* being linked to one or several other *lignes*. Therefore, it is worth developing a specific routine for the parsing of an *Infobox* and its `BS-table`.

However, the hard part is twofold:

- the *Infobox* BS-table complies with Modèles/BS, whose syntax is somewhat tricky, but was parsed successfully in most cases: only a few code failures, hard to overcome, have been met. Figure 10 illustrates a simple case of {{BS-table}}, code and result.
- The other difficulty is to deal with the cascade of asynchronous Internet requests for processing a single line.

```
{{BS-header|Ligne Origine - Endville}}
{{BS-table|affichage=déroulé}}
{{BS3bis||uexKBHFa||0+00|Origine}}
{{BS3bis||uexHST||6+25|Midterm}}
{{BS3bis||uexKBHFe||15+00|Endville|(128m)}}
{{BS-table-fin}}
{{BS-fin}}
```


```
{"label":"Audun-le-Tiche", "num":"196,000", "km":"0+0", "info":"origin
Ligne_d'Audun-le-Tiche_à_Hussigny-Godbrange"}, "geometry":null,
{"label":"Rédange", "num":"196,000", "km":"4+570"},"geometry": null,
{"label":"Hussigny-Godbrange", "num":"196,000", "km":"8+8x", "info":
"terminus"}, "geometry":null,
```

Figure 10. Top: *Infobox* sample code (left) and display (right). Bottom: result of processing the *Infobox* of: 'Ligne_d'Audun-le-Tiche_à_Hussigny-Godbrange' (Figure 10).

Attributes are set from the parsing:

- num is in the *Infobox* main part (*Infobox* attribute numéro = 196,000);
- label, kmare in the BS-table, and km can be interpolated, if absent;
- nom is often given (if differing from label), insee must be determined later;
- geometry is null, but can be seekon 'Gare d'Audun-le-Tiche', 'Gare de Rédange',etc.

Routine `wikiBSTable` (Appendix A) shows how the parsing of one table can trigger a cascade of asynchronous requests: initial fetch, possible second fetch if there is an indirection on the BS-table, then a fetch trying to get the geometry of each individual *gare* found in the BS-table. The full code is much longer, and out of the scope of that paper.

Moreover, when parsing a *ligne*, one or several connected *lignes* can be found, and for every such *ligne*, we can trigger a new request for that new *ligne*, and so on. Piling up these requests should in theory allow us to browse the entire network, but in practice rapidly saturates memory and computing resources, at least on a personal computer.

To develop a full scale "big-data" procedure would improve greatly the time spent linking data, from *lignes* to *gares*, and from *gares* to their geocoded location. Instead, we are querying Wikipedia with only a few (2 to 4) *lignes* requests at a time.

3.2. Gathering Information from VGI Pages

Wikipedia is a great, irreplaceable source of collaborative VGI, covering almost the full range of the *lignes* that have been included in the main French railway network. However, "secondary" *lignes* (*rural lines* and *tramways*), which were never embraced in the nationalization of 1937 into what became the SNCF [27], have not yet been treated so extensively: a dozen or two are fully described (with BS-table). About 100 are qualitatively described in the page of their owning operator, e.g., "Voies_ferrées_des_Landes" lists 12*lignes*, only two having their specific page (w/o BS-table).

However, in France as in most countries, railways arouse vocations for "volunteers", and a lot of French websites (Table 13) are devoted to keep track of past *gares*, *lignes*, viaducts and tunnels. Even the collection of street-signs ("*place de la gare*", "*rue du petit-train*") is valuable: it is the toponymy-memory of the location of a past *gare*.

Table 13. Some websites about railway *lignes* and *gares* in France (short name on the left).

Archef	`http://archeoferroviaire.free.fr` accessed on: 8 March 2021 records hundreds of secondary lines, including industrial, military lines, at a high-resolution
cdfFR	`http://chemindeferenfrance.blogspot.com` accessed on: 8 March 2021 gathers cartographic records about a hundred ancient lines
GeoCF	`http://www.train.eryx.net/hscff/` accessed on: 8 March 2021 records hundreds of secondary lines (in revision)
Ligou	`https://www.lignes-oubliees.com` accessed on: 8 March 2021 “forgotten lines” records 1768 *gares* and 361 *lignes*
RDrail	`http://rd-rail.fr/` by the author of “Les 400 profils des lignes voyageurs du réseau” (2 volumes)
Routes	`https://routes.fandom.com/wiki/Portail:Transport_ferroviaire_français` accessed on: 8 March 2021 several tables about ancient lines, about chronology
RuePT	`https://rue_du_petit_train.pagesperso-orange.fr` accessed on: 8 March 2021 records 6800 street signs mentioning the presence of a former *gare* (useful for disambiguating precise localization)
Traver	`http://chemins.de.traverses.free.fr` accessed on: 8 March 2021 gathers photographs and cartographic records about ancient *lignes*

The variety of information, and unstructured representation, make it difficult to code any generic software. But some routines may help, which are proposed in thissection.

There are two critical steps in the overall process described in Section 2.1.3:

- First step(a): identifying the existence of a *gare* onto a *ligne*;
- Last step(d): obtaining coordinates data.

The generic approach to extracting *gare* information from VGI starts with step(a): fortunately, most mentioned VGI providesome data, loosely structured by *ligne* (be a text or a table), for instance:

`“ligne A to B has such characteristics, and comprises: gare1, gare2 ... ”,`

The challenge is then to code a “parser” that delivers a list of *nodes* such as:

```
{label:"A", num:"AtoBcode", km:"0", info:"origin of A to B, characteristics"}
{label:"gare1_name", num:"AtoBcode", km:"somerank information, or 1"}
{label:"gare2_name", num:"AtoBcode", km:"somerank information, or 2"}
...
{label:"B", num:"AtoBcode", km:"max = length, or max rank", info: "terminus"}
```

Here, follow three cases that are common among several VGI.

3.2.1. HTML-Style Tables

As opposed to a Wikipedia *Infobox*, the HTML <table> tag is not a semantic tag, and it is uneasy to determine its content, unless by direct reading (no simple artificial intelligence (AI) routine at hand, although research is becoming active). For decision making, the most important question is:

is there a relevant key in that table? (e.g., num, insee, label?).

A few cases, from **Routes** or **RDrail**, were processed this way, giving information only about origin-terminus, and some *ligne* characteristics (closing date, gauge, length):

- visual: make a decision about relevance;
- manual: copy and paste the table text into a spreadsheet; convert into CSV format;
- software: fetch CSV file; join objects with routine `mergeLigneInfo` (Appendix A).

3.2.2. Coordinates Lists (Polyline for a *Ligne*) in Google KML or GPX Format

Some contributors have digitalized *lignes* using the *GoogleMyMaps* facility, and sometimes, *gare* are individualized in such kinds of data. The procedure is:

- manual: export the *ligne* data into KML format (from the Google page);
- software: convert into *geojson*, and if the *gare* is individualized: add it directly, or:
- manual: copy and paste the relevant *geojson* of the *ligne*;
- visual: (see Section 3.3) locate each expected *gare* along that *ligne*.

This has been used with source **Traver** and a few *lignes* from **cdfFR** (Table 13).

3.2.3. Simple Lists of *gares* in Plain Text

It is not easy to automate a detection, but the result proves useful in obtaining a list of *gares* along a same *ligne*:

- manual: copy-paste the text into a string constant;
- software: check if that *ligne* is already documented, or add a new *ligne* number num.

The routine stationsAlongLine (Annex) is used in parsing the example of (Figure 11).

```
/* text copied from Archef page: use `backticks` to group multiline text */
const SST = `Ligne :Chantelle - Ebreuil, 23 km
Gares : Chantelle (correspondance pour Saint-Pourçain et Commentry), Ussel-d'Allier, Charroux-d'Allier, Saint-Bonnet-de-Rochefort (correspondance pour Montluçon et Gannat), Vicq, Ebreuil
Ligne ouverte en 1892 fermée en 1939, Société générale des chemins de fer économiques (CFE)`;
```

```
/* intermediate object, result of parsing */
{"origin":"Chantelle", "terminus":"Ebreuil", "length":23, "lifetime": [1892, 1939], "operator": "Société générale des chemins de fer économiques", "acronym":"CFE", "stations": [
{"label":"Chantelle", "junction":true}, {"label":"Ussel-d'Allier"}, {"label":"Charroux-d'Allier"}, {"label":"Saint-Bonnet-de-Rochefort", "junction":true}, {"label":"Vicq"},
{"label":"Ebreuil"}] }
```

```
{"label":"Chantelle", "num":"CFE1", "km":"0", "info":"origin Ligne Chantelle - Ebreuil"},
{"label":"Ussel-d'Allier", "num":"CFE1 ", "km":"5"},
{"label":"Charroux-d'Allier", "num":"CFE1", "km":"9"},
{"label":"Saint-Bonnet-de-Rochefort","num":"CFE1","km":"14","info":"junction"},
{"label":"Vicq", "num":"CFE1", "km":"18"},
{"label":"Ebreuil", "num":"CFE1", "km":"23", "info":"terminus"},
```

Figure 11. Example of semi-structured input text with list of *gares* (**top**); result of the parsing (**middle**); and resulting *geojson* list of *nodes* (**bottom**).

Parsing the text extracted from one page of **`Archef`** provides an ordered list of *gares*, from `origin` to `terminus`, a length, creates the *ligne*num, and two dates for its lifetime.

3.3. Remote-Sensing Information for the Assisted Visual Geocoding of Gares

If the direct geocoding of a *gare* (`wikiCoordinates`) has failed, the last opportunity is to visually inspect maps or aerial pictures to locate that *gare*, in a way similar to [35] with land-cover.

For geocoding a *gare*, there is a two-step procedure:

- *(1) software*: use a geocoder API (e.g., Google), querying coordinates for: French word "gare" + `label`. For instance, with *Cardet* (*Gard*), we can try a few query variants (Table 14). It is impossible to know which query will give the best answer (distance data have been added in Table 14, only after visual inspection);

Table 14. Example of geocoding queries for `gare_de_Cardet` (*département*: *Gard*).

Query	[lat,lon]	dist
… true coordinates (see: Figure 14 and Section 3.3.3) =	[44.023710, 4.088814]	0
`[lat,lon] = geocode("gare, Cardet, France")`	[44.026042, 4.081059]	672 m
`[lat,lon] = geocode("rue de la gare, Cardet, France")`	[44.010420, 4.084597]	1515 m
`[lat,lon] = geocode("chemin de la gare, Cardet, France")`	[44.019122, 4.086764]	536 m

- *(2) manual/visual*: use any approximation, or skip first step, and input the toponym into an online map facility providing, preferably ancient, maps and aerial photos.

In France, the best data source for historic (mid-20th century) aerial images and maps, is IGN, the French national geographic organization, which provides the website: `https://remonterletemps.ign.fr`, giving access to:

Today (2016–2018):	Aerial image (≈1 m resolution),	Vector cartography (≈1/10,000)
Past (1947–1960):	Aerial image (≈10 m resolution),	Digitized map (≈1/25,000)

Figure 12 illustrates this website with toponym '`Chantelle`' (cf. Section 3.2.3), at zoom = 16, and two sources (1954-aerial and 1952-map): the *gare* is visible (big arrow) and the *fork* between lines (yellow arrow), about 200m SW of the *gare* (scale at bottom-left corner).

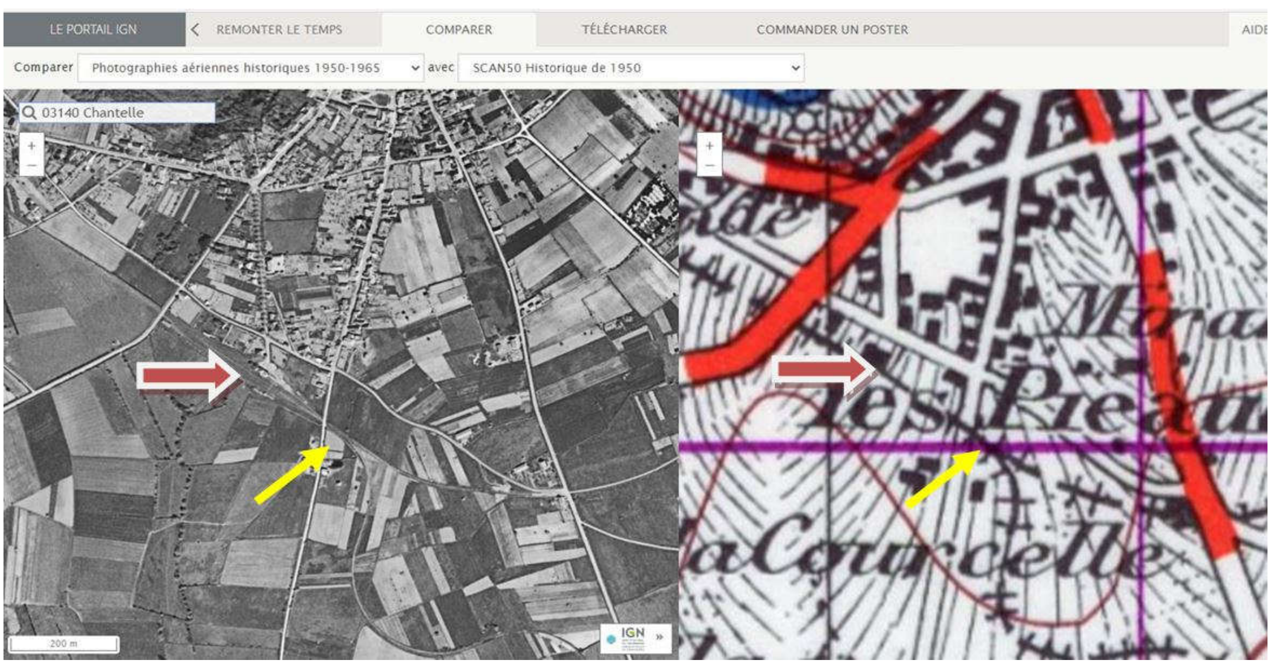


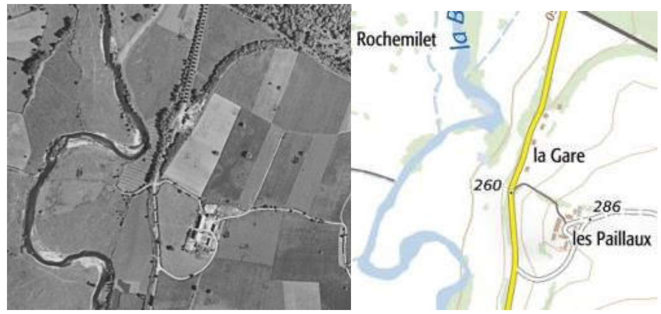
Figure 12. Website 'RemonterLeTemps': geocoding *Chantelle (Allier)* at roughly 1/20,000, using a 1954 aerial image, and the scanned map (1952). The double arrow shows the *gare*, the smaller arrow points to a junction of two *lignes* (the line to *Ebreuil* makes a bend to the south).

3.3.1. Dual Use of the Website RemonterLeTemps, (a) Direct Geocoding of Toponyms

Routine `checkToponymAt` (Appendix A) encodes the identifier URI pointing to the relevant *remonterLeTemps* data for a given `nom`, what we did above with *Chantelle* (Figure 12).

The next step to detecting a *gare*, is visual: quite often rather easy, sometimes more difficult (cf. examples in Figure 13a–c). A *gare* is always at the junction of several linear elements (rail + road), easier to detect when finding the appropriate zoom level.

(**a**) *Jaligny-sur-Besbre (Allier):* a small road is visible, but where is the *gare*? The toponym "*la Gare*" is still present on the recent IGN map: (toponymy memory!), … now we can "see" the ancient railway bending NE (line of trees).



(**b**) *Cardet (Gard):* the railway line is clearly visible (E-W), also two roads converging towards village center, crossing the railway in two places. Where is the *gare*? intersection with the biggest road (east?), or closer to the center (west?). The answer is given later in the text.

(**c**) *Le Cateau-Cambrésis (Nord):* railway very clearly visible, half-circling the city. But where is the stop "Le Cateau-Halte"? Comparing 'km' with previous and next stops, by rough interpolation, the stop should be at the bridge, near "*Faubourg de Landrecies*" in the middle, different from another *gare*, just South of the picture, where two lines meet.

Figure 13. Some examples where visual geocoding is not obvious.

Therefore, the different steps of the procedure can be summarized as:

- software: generate URI using routine `checkToponymAt`;
- visual: start with an intermediate zoom (e.g., z=16) and focus on the section where the line is expected to reach the *commune* (e.g., SW corner);
- visual: inspect map-aerial photo combinations, focus on road-rail intersections;
- manual: input back coordinates into `geometry` of the *gare*.

Adding more automation is beyond the scope of this study. The care brought to this task, must insure a high quality, for it will be very difficult to detect errors later.

3.3.2. Dual Use of the Website RemonterLeTemps: (b) Visual Reverse-Geocoding

To show where a `geometry` points to in aerial or map representation at a given date:

- software: generate URI using routine `checkGeocodeAt` (Annex), cross-check with a *geocoder*, to get *commune* name;
- visual: start with a high zoom (e.g., 19), and inspect map-aerial photo combinations, zoom-out to get neighbor toponyms (railway terminology may appear);
- manual: confirm, or infirm, the quality of the information for that *node*.

3.3.3. Hints for Alternatives

Cartography is notan exact science, even at "*the scale of a mile to the mile!*" (*Lewis Carroll*), different maps may choose to display different toponyms. Sometimes *Bingmaps* or *Googlemaps* may help to solve an indecision, sometimes the "*carte IGN*", what is the case for the *Cardet* indecision (from Figure 13b): the *gare* is at the East intersection, "*Chemin de la Gare*" (Figure 14, right), not at the West intersection, although closer to the center of the village.

The problem is to find the right zoom level, which displays the street name.

Figure 14. Using alternative maps to resolve indecision: there is a "*Chemin de la Gare*" indication.

Note: to the same query: "*Chemin de la Gare, Cardet*", the *Google* geocoder answers a location 563 m (more South), versus 50 m with the *IGN* geocoder. In that particular case, we have the visual result exactly at the crossing with the road.

4. Results: The Overall Procedure, the Reconstructed Network, and Its Quality Control

There are four main results out of this study:

1. the dataset "***CARP***" of French *gares*, over the 1920–2020 time span;
2. the developed routines combined in a computer-assisted reconstruction procedure;
3. quality controls increase confidence, or point out odd/missing data, to be fixed later.

4.1. The Reconstruted Network (CARP)

The Computer-Assisted Reconstruction Procedure –***CARP***- data result from the fusion (Section 4.2.1) and from the VGI integration (Section 4.2.2). So far, as of January 2021:the CARP dataset contains about 10,900 *nodes*, accounting for about 9100 different *gares* (about 100 in neighbor countries), 450 fork *nodes*, and 68 border-crossing *nodes*.

Displaying the CARP Dataset

Figure 15 illustrates a part of the ***CARP*** on the *Region-Bretagne*, active *gares* only are on Figure 16, and disused *gares* on Figure 17. All data are plotted on top of a classical tiled OpenStreetMap, and green *lignes* are from the ***LignesSNCF*** dataset.

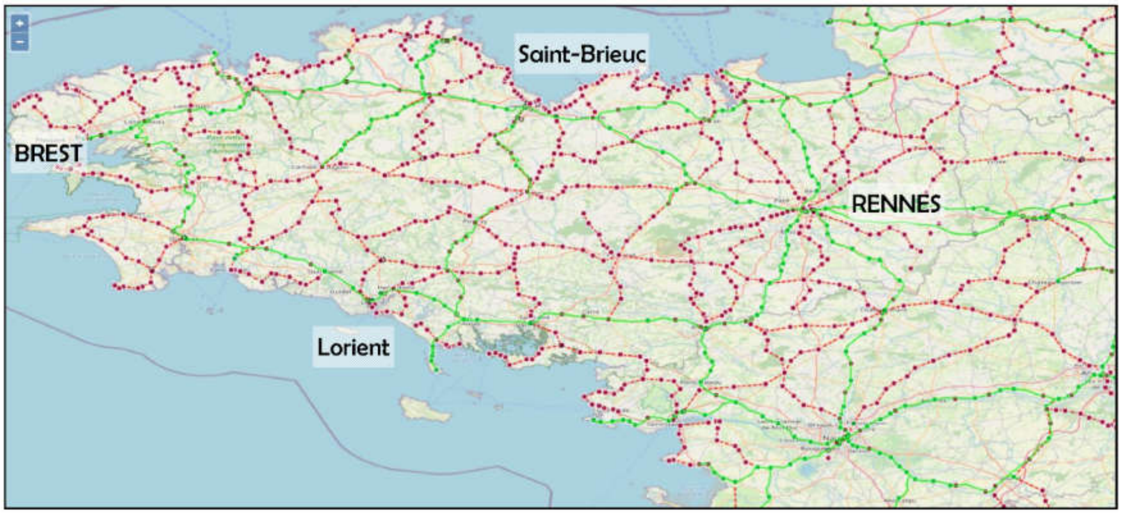


Figure 15. "*Bretagne*" region full set of *gares*, on top of OpenStreetMap: green dots are 2020 active *gares* on green 2018-active *lignes*; red dots are 'past' *gares* (mostly on rural tramways).

All *gares* are sorted by *ligne*, and by `km` increasing order: it allows a simple routine to convert these sequences into a line-string, plotted as dotted red lines that approximate the disused *lignes*: no extra information is added.

The Region Bretagne has been thoroughly processed: the CARP data represent almost 100% of what has ever existed. Region Provence is almost complete as well.

The CARP dataset is deposited, under open license, on the `data.gouv.fr` website. The format is *geojson*. Periodic revisions will bring additional data until full completion.

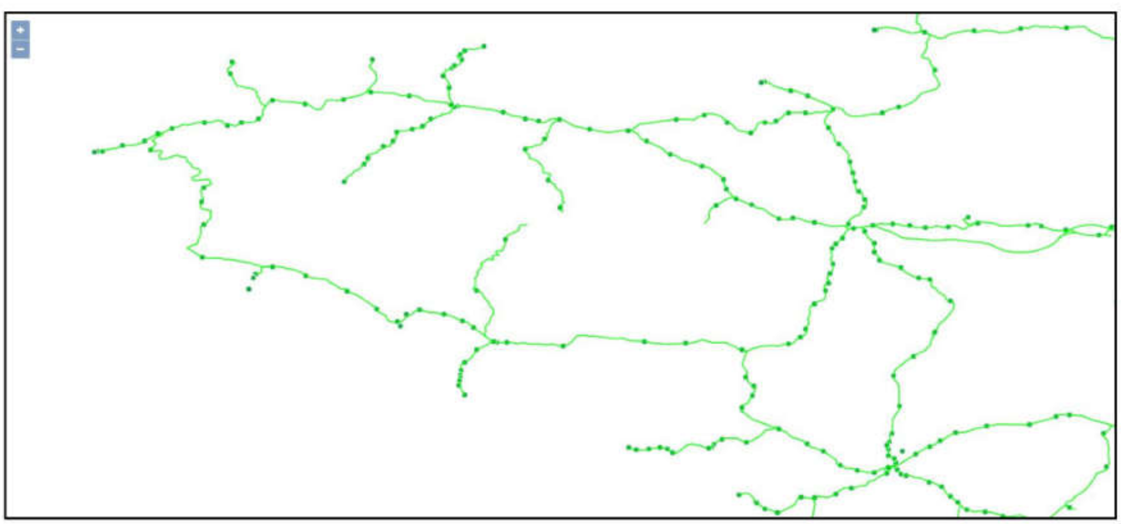


Figure 16. "*Bretagne*": active *gares* (small green dots, 2018) on top of active *lignes*.

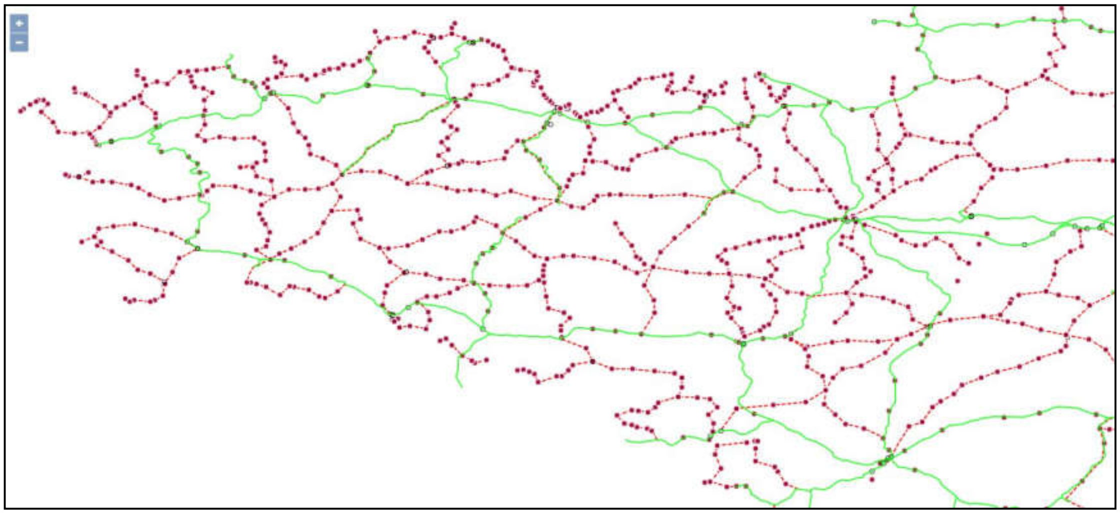


Figure 17. "*Bretagne*": disused or past *gares*, and *lignes*. Small black circles = *forks*.

The *meta-analysis* appliedto ***CARP***, has helped in understanding more discrepancies (systematic bias rather than arbitrary errors):

1. `label` disparity due to change between dates: the *toponym-pattern* (Appendix B.1);
2. `geometry` deviation, due to network evolution and "*fork-pattern*" (Appendix B.2).

The CARP tries to restore the evolution of the data as best as possible, and to bring additional corrections wherever identified.

4.2. The Computer-Assisted Reconstruction Procedure for Past Railway Stations

4.2.1. The Generic Procedure for Reconstruction from Public Datasets: CARP-Main

Procedures described in Sections 2 and 3 result in that CARP, summarized in the next two paragraphs:

- Meta-analysis (Figure 18): production of metadata, counting missing attributes, checking constraints (e.g., uniqueness), correction of ambiguities and duplicates, possibly completing some `geometry`, per-*node* addition of quality information;
- Three-steps fusion: similarity–measure, fusion–decision, attribute–combination (Figure 19), whichyields the revised dataset (=6489 *nodes*), plus dataset of remaining *undecidednodes*, i.e.,: no `geometry` (718), or too uncertain (250 in `2014`, 564 in `2017`);
- Quest for `geometry` of undecided *nodes* (Figure 20), using Wikipedia or any direct geocoder, to get *gare* coordinates: it helped to integrate about 400 additional *nodes*;
- Visual inspection of Remote Sensing / old maps, for final improvements: it gave about 600 additional *nodes* originally in public datasets but without `geometry` (Figure 21).

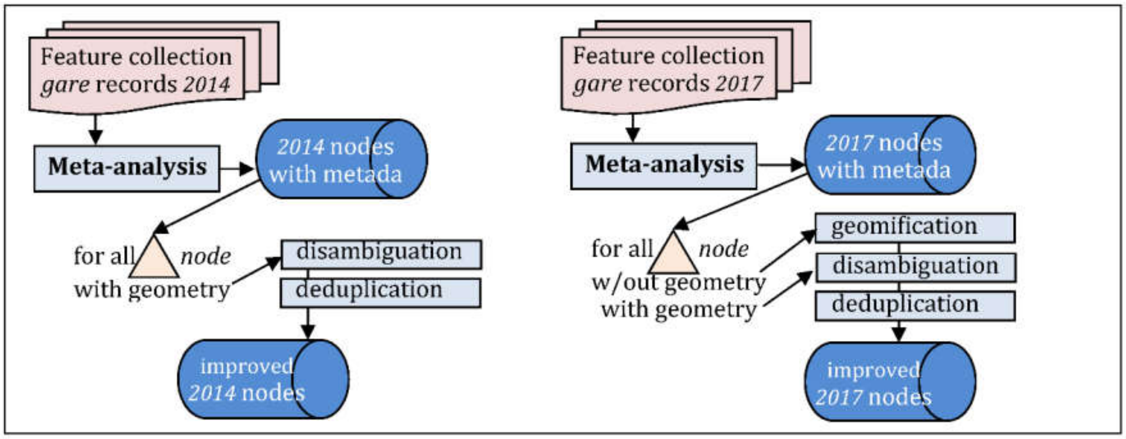


Figure 18. The meta-analysis: metadata and improved datasets.

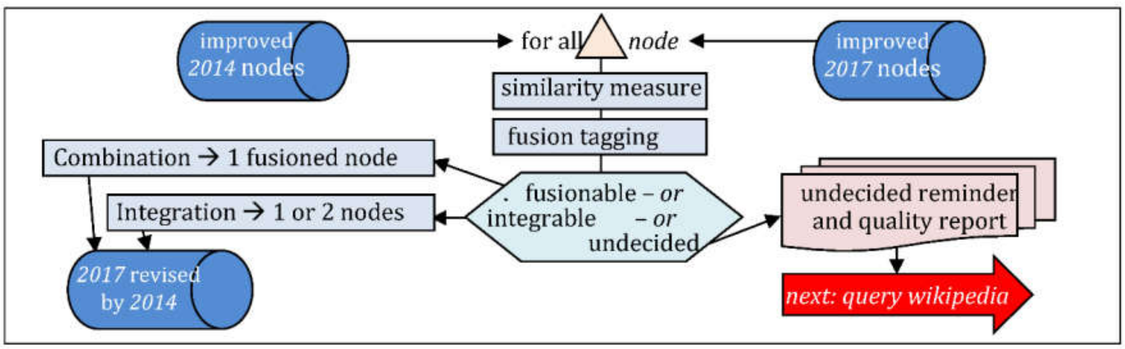


Figure 19. The full revision procedure: 3-steps fusion, integration and reminder.

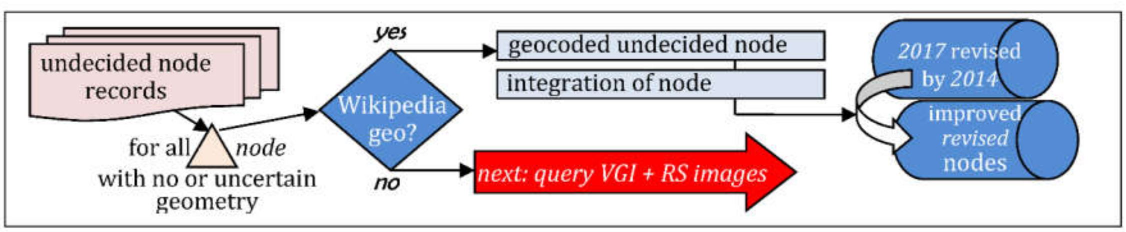


Figure 20. The improved revision procedure: Wikipedia querying, integration and reminder.

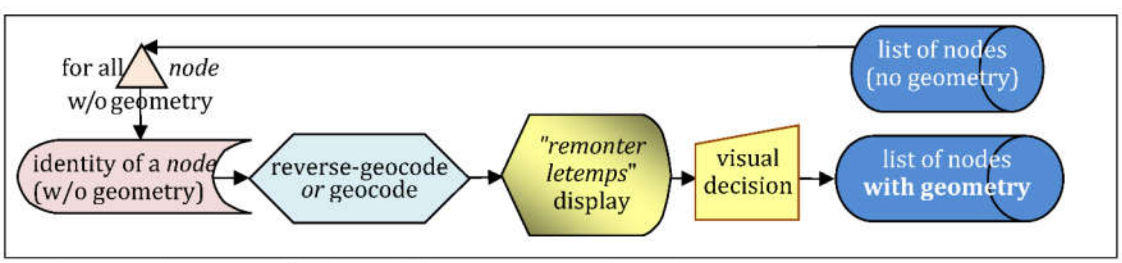


Figure 21. The assisted computer-assisted reconstruction procedure (CARP) visual decision to geo-coding nodes.

Only the last step (Figure 21) is "manual/visual", although assisted by some direct or reverse geocoding, depending on what is available first (toponym, or closest geometry).

The dataset built at this step is named "CARP-main".

4.2.2. Addition of New Lignesand Gares, from VGI

A *gare* exists only if a *ligne* exists to which that *gare* belongs. Most of the 'secondary' *lignes* are not recorded in public datasets, and have no official `num` code. VGI has recorded many of them. Depending on what can be found, various routines may apply.

Figures 22 and 23 sketch the three steps of a possible full software chain:

(a) from a *ligne*: list of *nodes* (routines executed on the server):
`f[i] = {"label":"l", "num":"n", "km":"k", "info":"…"}, "geometry":null;`

(b) for each *node*: ask a geocoder, as in Figure 20, or visual inspection as in Figure 21:
`f[i].geometry = {"type":"Point", "coordinates":[lon,lat]};`

(c) for each *node* with `geometry` (Figure 23), check `nom` and `insee`, check `km` strict order, check `label` uniqueness in CARP dataset, check `geometry` deviation if a gare of the same `label` exists already. Report control result in `info`:

```
{f[i].nom, f[i].insee} = getCommuneFromPoint(f[i].geometry?.coordinates);
f[i].info += " (commune_ok | commune_inconsistent) (km_checked) …";
```

The dataset built at this step is named "CARP-VGI".

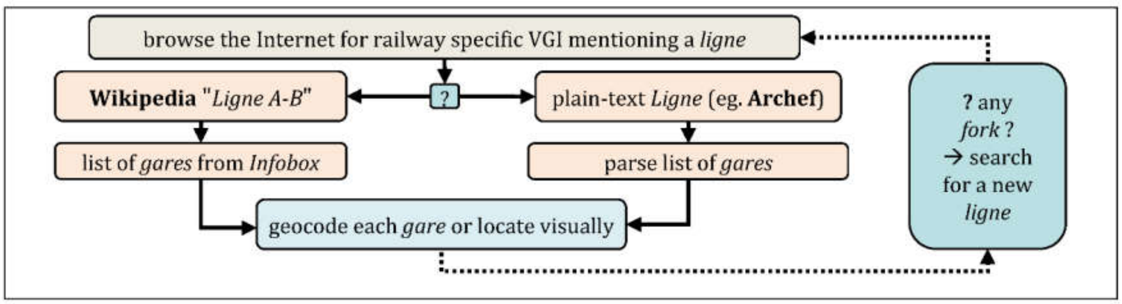


Figure 22. the semi-automated CARP-VGI for integrating a new *ligne* in the network.

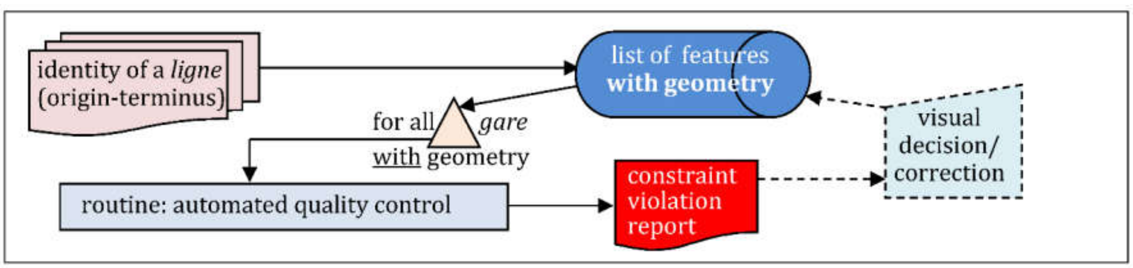


Figure 23. The CARP posterior quality control.

4.3. Posterior Quality Control, Revealing Additional Errors

4.3.1. Enacting Quality through Constraint Checking

The automated constraint checking is performed a posteriori, checking:

1. a *gare* has a `label`, a `num`, and a `km`, identifying it and the *ligne* to which it belongs;
2. all *gares* sharing the same `num`, have their `km` in strict increasing order, from the *gare* tagged `origin` to the *gare* tagged `terminus`, what means at least two *gares* per *ligne*;
3. a *gare* with an `insee`*commune* code, has its `geometry-point` inside the `geometry-polygon` of that *commune*; every *gare* located in France can receive an `insee`*commune* code;
4. a *gare*`label` is consistent with its *commune*`nom` and `insee`. Quite often a `label` is the name of an existing *commune* (sometimes 2 *communes* names).

Rules 1–4were implemented, It helped to reporting a few dozen inconsistencies, e.g.: about 60 ambiguities, and a dozen duplicates were identified and corrected. Only a few having required a manual correction, and only one was interpreted as an arbitrary error identified so far. Some cases revealed a '*fork-pattern*' again, such as this example:

`{"label":"Lézan", "nom":"Lézan", …"coordinates":[4.11488, 44.04241]},`

Checking coordinates, rule 4 answers: `nom` = *Vézénobres*, about 7 km East of *Lézan*. The Wikipedia `Infobox:schéma` (Figure 24) indicates the *fork* just before the viaduct.

Figure 24. Quality control after automated identification of a geographic inconsistency (*rule* 4).

Result: *fork-pattern* again, discovered by the final computer-assisted quality control.

4.3.2. A Posteriori Control of the Reconstructed Network

Meta-analysis of the CARP dataset is compared (Tables 15 and 16) with previous data.

Table 15. Comparing breakdown of *junction-gares*, by distances between their nodes.

Intervals (nb.Nodes)	[0, 150 m]	%	[150, 300]	[300, 1 km]	[1 km, 2 km]	[2 km, ∞]
2014(642 nodes/6442)	550	*85.7*	48	32	6	6
2017(1360 nodes/7702)	541	*40.0*	184	375	157	103
CARP(2116 nodes/10747)	1418	*67.0*	184	344	115	55

Table 16. Comparing breakdowns of nodes according to their count per ligne.

Datasets	Isolated Gare	%	2-Gares Ligne	3 to 7-Gares	8 to Max-	(Total)
2014 num	94	*15.8*	62	191	130	593
2017 num	107	*14.6*	76	245	171	734
CARP num	50	*5.2*	163	259	486	958

The result for ***CARP*** is everywhere better than ***Sncf2017***, and in particular the *lignes* are much better represented with ***CARP***.

5. Discussion

This paper has focused on designing a computer-assisted reconstruction procedure with the goal to gather as many *gares* as possible from any kind of available source of information. Several software solutions were considered and then abandoned forrequiring too much development (concurrent cascading queries), or for having too little expected benefit (deep machine-learning *gare* detection, based on already learned *gare* locations).

Because the spectrum is rather large, we need some guidelines to assess the overall method from an organizational point of view (Section 5.1). Then, to open some perspectives in possible applications, one example is given in Section 5.2, and in European cooperation, because it was the initial motivation of starting this work: to understand how a century of French transportation policies has led to shrinkage of the national coverage so much, what shifts cargo transportation to roads, and what scientific arguments to reverse that policy trends are important. This can be grounded on historical analysis, in comparison with other European countries that have, or have not, followed the same trend in rail transportation policies (the author's feeling is that important differences can be revealed).

5.1. Theoretical Issues in Building a Comprehensive Dataset from Internet Sources

The problem of building a dataset from the vast amount of information available on the Internet has been theorized, noticeably in the medical sector, for instance by Sreenivasaiah et al. [36], which lists four categories of a total 11 issues for integrating information. This present work is confronted with at these categories.

5.1.1. Data Representation and Standards; Interoperability; Data Visualization; Issues in the Development of Tools

These four issues are very critical in geographic information in general, because geography by itself is a reservoir of very strong constraints, which must be consistent with all other constraints: e.g., linear referencing, digraph connectivity,etc.whichhas been studied extensively for decades, leading to the definition of standards by INSPIRE or OGC [28,29], or implementations as in OSM [37]. The *CARP* dataset compliance with such standards should be more extensively checked, whichwould help interoperability [38], in particular if considering other European past railway datasets. For instance, *Linear referencing* (km attribute), and *Network interconnections* (≠gares-same node "tolerance"), are explicit terms of INSPIRE Transport Networks. Moreover, adding time constraints, as happens with a historical railway network, should also be treated more carefully: so far, only an "`end`" (*validTo*) date is provided, when a *gare* is no longer active. We indirectly use the standardization efforts of the UIC (Section 2.4): today railway ontology in Wikipedia benefits from it for keepinghomogeneity in representation, visualization and associated tools (e.g.,`Infobox/BS-tables`). However, toponymy is much less standardized: changes in names and boundaries of administrative objects is accelerating in France, without real retrospective help for data reconstruction (e.g., simple list of *communes* merging, see Section 2.3). Overall, interoperability should be improved with a better compliance with INSPIRE, especially if a European collaboration is foresighted.

Data visualization: has been limited to the use of geojson, which can be displayed on line, by many websites, and which is easily read as an open source. Examples are displayed with *OpenLayers*, on top of OpenStreetMap tiles.

Issues in the development of tools: the code is in JavaScript, well suited to direct interaction with the web, with web-workers (what allows some parallelism if the computer supports this), but the maximum number of actually possible Internet requests is rapidly reached on a personal computer. Any perspective of development would imply working on a stronger architecture more adapted to Big Data. We have not yet started research in that direction although this is a bottleneck issue.

5.1.2. Data Quantity; Computation Intensivity

These two issues are met all along this work: we are working with about 1000 *lignes* 10,000 *gare*s, 35,000 *communes* and a gare-commune join requires 350 M possibly complex tests. For instance, when seeking for `insee` codes of the *gares*, the process (`point-in-polygon`) should, and can, be parallelized for 90% of data, because most *gares* of a same *ligne* are in the same area (5 or 6 large parts of France), excepting a few very long *lignes* (e.g.,`Paris-Nice`). The technology of web-workers has been used successfully on a personal computer with 4 processors. In the Wikipedia realm, it is rather easy to obtain *gares* from a *ligne*, then posting asynchronous queries about coordinates of these *gares*, which is computationally difficult beyond a dozen concurrent *gares*: see above comment about better Big Data access (Section 5.1.1). In the crowd of VGI, where the most sophisticated structure isoften a list of names, the rule is to work "*schemaless*", as proposed in [39], possibly after a text analysis looking for words *ligne* and *gare* (in French, or other language of course), and a "text pattern" identifying a list, then deriving for instance a *ligne–gare* relationship. Important work is yet to be done in the future, in particular if aiming at handling more European countries.

5.1.3. Data Quality; Version Control

Undoubtedly big issues. Data quality issues are addressed in almost every stage of this work, for different quality components:

- Attribute accuracy: `label` (cf. both toponym-pattern and fork-pattern);
- Logical consistency e.g., `label`, `uic` and (`num`, `km`) consistency (cf. ambiguities, duplicates);
- Completeness: e.g., creating missing `km` by interpolation;
- Positional accuracy: cf. fork pattern, computer-assisted visual geocoding;
- Time period and contemporaneousness: e.g., comparing `capa`/*gare* with `mnemo` and `validTo`/*ligne*.

Most standard quality metadata components are concerned and have been used, and a posteriori quality control is largely automated by the systematic constraint checking.

Version control should be better taken into account, in order to track:

- the evolution of the CARP dataset: a Git-type solution would improve it;
- the lineage of data used in setting attribute values. Some retrospective information could be retrieved, partially, for that lineage mixes software and non-reproducible manual steps.

5.1.4. Data Availability; Data Access; Security

These issues are not really addressed in this work. We are considering sources only from public datasets (excepting an author copy of a dataset that is no longer on-line), or Internet accessible open data, and the outcome is archived on a public portal. Together with version control, these aspects should be given more attention.

5.2. A Dataset for Further Social Sciences Studies

The ***CARP*** resulting dataset is open, accessible on a public website, and is intended as a tool, for geographers and transportation specialists to further investigate how long-term trends form and evolve. The present version (Jan.2021) is about 80% complete (?), but compared to the previous public datasets, already shows an increase in all total counts:

nodes: +56%, *lignes* (≠`num`): +30%, *communes* (≠`insee`): +39%.

One typical question used as an example of the opportunity to reconstruct this past network, was: *Does a commune possess a gare? Today? A century ago?* The ***CARP*** dataset can list, and count the number of such *gares* (Table 17).

Table 17. Communes reached by at least one *gare* according to public data versions and CARP.

Sncf2014 (origin 2014)	5266	14.7%	% of the 35,798 communes (updated year-2019)
Sncf2017 (origin 2014)	5279	14.7%	
Sncf2020 (update 2020)	3112	8.7%	
CARP (as of Jan.2021)	7341	20.5%	

To date, 20% of *communes*, have been checked as having been connected to the railway network, at least by a simple stop for some time between 1920 and now. This is already significant material for demographic, socio-economicand even electoral studies. Almost 4000 additional *nodes* have been geocoded and quality checked.

Also in ***CARP***: every national border crossing with neighbor countries (68 such places), showing how European rail liaisons, from or to France have evolved since WWII (Figure 25).

In particular, surprisingly, some French *gares* are still in operation only because they are served by foreign trains from Luxembourg (`Audun-le-Tiche, Volmerange`), or Germany (*SaarBahn* to `Sarreguemines`) or Switzerland (*Line* 10 of the *Basel tramway*).

This ***CARP*** dataset, can also confirm broadly to some local patterns mentioned in the literature [2–3,29,40], for instance the *lignes* that have been closed just before WWII in Region *Bretagne*, or in the late 1990s.

These observations are intended to be studied further in collaboration with transport geographers, including those at a European level. Already cited papers [2,7] demonstrate that there is an interest in developing such research in Europe.

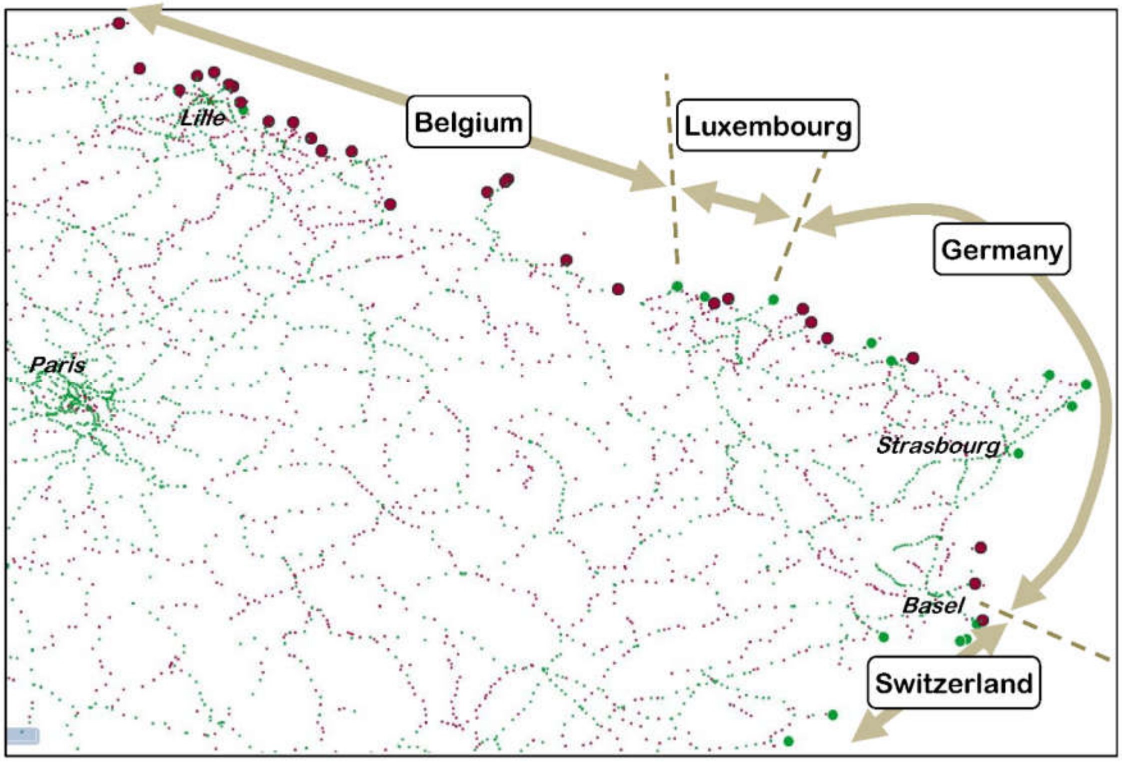


Figure 25. Display of rail border crossings (bigger dots) North-East of France. Color indicate which *border points* are presently open (green).

5.3. Similar Past Railway Network Reconstruction for European Countries

Though the present work has been specifically developed, for France, several aspects demonstrate that similar work can be undertakenin other countries.

For instance, a Wikipedia entry for a same *ligne* or *gare*, may exist in many languages, because the different *Infobox*-templates, share a common semantics for a *ligne* (e.g., `num`, `gauge`…) translated in *spoorlijn*, or a *gare* (e.g., `label`, ...) translated in *station*. Example: (all accessed 8 March 2021)

```
https://nl.wikipedia.org/wiki/Spoorlijn_Audun-le-Tiche_-_Hussigny-Godbrange
https://fr.wikipedia.org/wiki/Ligne_d'Audun-le-Tiche_à_Hussigny-Godbrange
and
https://nl.wikipedia.org/wiki/Station_Audun-le-Tiche
https://fr.wikipedia.org/wiki/Gare_d'Audun-le-Tiche
```

Presentation may differ (Figure 26), but the underlying semantics is quite the same, what would make translatable most of the procedures presented in this paper.

In Belgium, some *lignes*, near the border with France, have been processed directly with `wikiInfoBox`., e.g., `https://fr.wikipedia.org/wiki/Ligne_73_(Infrabel)`.

In Germany *routemap* tables are used instead, instead of BS-tables, e.g.: `https://de.wikipedia.org/wiki/Stuttgart_Hauptbahnhof`, uses `Infobox_Bahnhof` a similar template, whose `Strecken` entry (= list of *lignes*), has a different syntax.

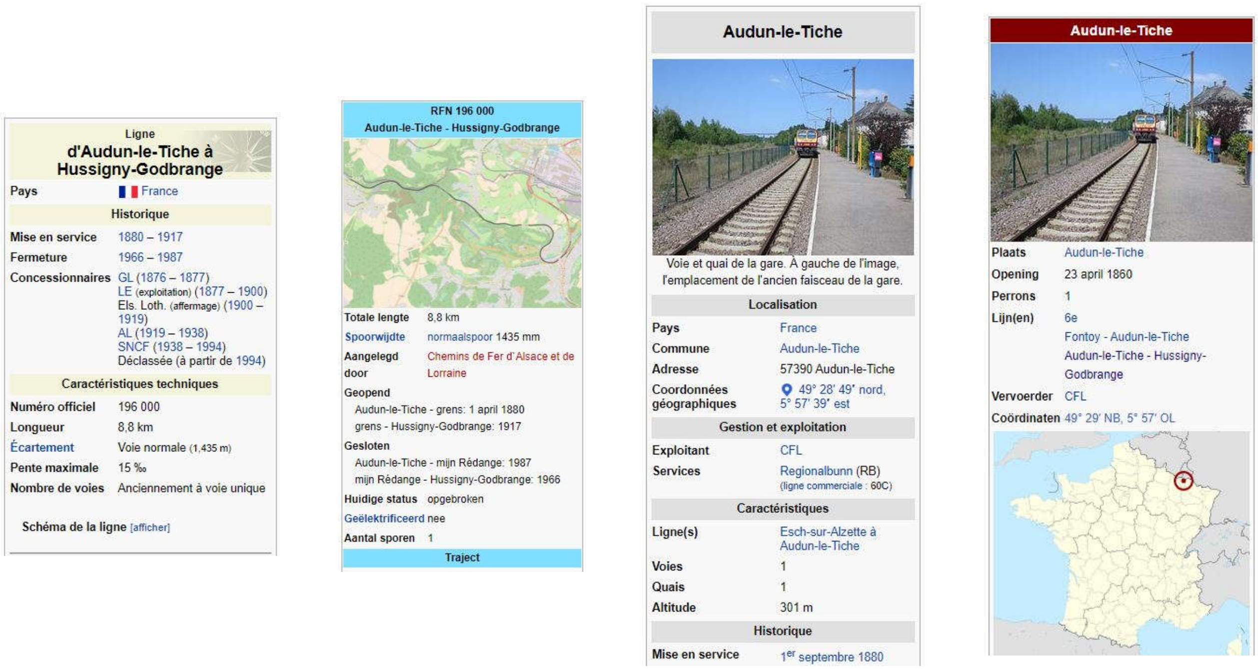


Figure 26. Internationalization of the Wikipedia-*Infoboxes* for *lignes* (left), and *gares* (right).

Other templates have been developed for most European countries, also Russia, China, … (total 22 different), whichmeans that analogs to the wikiInfobox routine (Section 3.1.2), tailored for the French template, can be developed, at the cost of some adaptations.

5.4. Conclusions

Making observations about the long evolution of the network is important, in particular for environmental policies.

The deviation between the EU White Paper objectives [4], and decisions made by member states cannot be understood without understanding in turn the combination of multiple factors, by multiple actors, over several decades. In France, rail carried 9.9% of inland freight transport in 2018, versus 18.7% for average EU [41], while the EU report observes that road freight is about 100 times more polluting than rail, and that between 2008–2013 road freight increased from 70% to 72%, which was opposite to the goal of shifting 30% freight from road to rail/maritime by 2030.

An EU recent update [42] states: "National projections compiled by the European Economic Area (EEA) suggest that transport emissions in 2030 will remain above 1990 levels, even with measures currently planned in Member States. Further action is needed particularly in road transport, the highest contributor to transport emissions, as well as aviation and shipping …", whichwe can read as: rail is the only transportation mode able to significantly decrease CO_2 and greenhouse gas (GHG) emissions.

The first sentence of the EU report's executive summary states: " The fact that only limited data are available and that the impacts of most of the initiatives cannot yet be observed do not allow the proper assessment of the effectiveness of the measures adopted so far and their contribution to reaching the goals ". Therefore, better long-term data could help the EU to better measure the adoption of its recommendations by the member states, and better understand what hurdles exist on the route.

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Appendix A. Code Description for Routines Mentioned in the Text

Routines A1–A7 are components of the meta-analysis and fusion, both methods applied to the public datasets. and meta-analysis applied to the CARP result.

Routines A8–A15 are components of methods for gathering data from VGI, and assisting location geocoding from remote-sensing visual inspection.

Table A1. The `metaAnalysis` routine (pseudo JavaScript).

```
const metaAnalysis = (ff) => {
    /* maps nodes by same value of
       single attribute: (f.properties[key] = v)
       or couples of attributes: [k1,k2] with (v,w) */
};
metaAnalysis(gares); // analyzes quality based on keys and values
```

Table A2. The `disDuplicate` routine.

```
const disDuplicate /* marks "duplicate"= to be removed / to be kept */
gares.map(f =>disDuplicate(f))
```

Table A3. The `slugify` routine.

```
const slugify = (lib) => { /* light version, more rules may apply */
    const dia = "éèêàâ...", nodia = "eeeaa..."; /* diachritics */
    lib.replace("St-","Saint-"); /* also:"Ste-","Sainte-" */
    lib = lib.toLowerCase(lib);
    dia.split().forEach((x,i) =>lib.replace(x,nodia[i]) /* removes */
    return lib;}
const similName = (fp, gp) => slugify(fp.label) == slugify(gp.label);
```

Table A4. The specific `disAmbiguous` routine.

```
const disAmbiguous /* adds the correct department, marks "disambig" */
gares.map(f =>disAmbiguous(f));
```

Table A5. The `geom_ify` routine.

```
const sameuic = (uicf) => /* lists nodes whose uic = uicf, with geometry */
const bestgeo /* choose best geometry among list, or null */
const geom_ify /* if(bestgeo(list)) return (f.geometry = geo) or void */
gares.filter(hasGeometry).map(f =>geom_ify(f, sameuic(f.properties.uic));
```

Table A6. The `checkIsolated` routine.

```
const uniques = (ff) => /* array of nodes whose num is unique */
const checkIsolated  = (f,ff) => {
    const garesOnNum = (ff,num) =>ff.filter(f =>f.properties.num == num);
    const is_closest = (f,g,cum) => /* returns g, or cum, if closest to f */
    const getClosest /* extracts: is_closest(f,g,cum) for each node */
    f.properties.unic = getClosest(f, garesOnNum(ff, num));
    return f;}
uniques(ff).map(f =>checkIsolated (f,ff));
```

Table A7. The `fusionTags` routine.

```
const closestNode /* gets: closest node to f (f,old,new) */
const breaks = [ D1,  D2,  D3,  D4, Infinity]; /* thresholds */
const pos = ["AP","PP","und","und","SN"], neg = ["SP","und","und","PN","AN"];
const dd = /* geographic "greatCircle distance" in meters */
const tt = /* starts with "und", then update tag[i] depending on:
            similar label and rank in breaks[i-1] */
const fusionTags /* returns {fuse: tt; dist: dd; closest: closestNode } */
const garesA = fetch("A_dataset"), garesB = fetch("B_dataset");
garesB.filter(hasGeometry).map(f =>fusionTags (f,closestNode(f,garesA)));
```

Table.A8. Routine `prefixWithGare` for preparing Wikipedia API to get "article" coordinates.

```
/* Wikipedia English sites postfix any toponym N →N_railway_station,
   French sites have a variety, e.g.: Gare_de_Martigues, Gare_d'Audun,
   Gare_des_Aubrais, Gare_du_Havre ... */
const prefix = [Gare_de_, Gare_d', Gare_des_, Gare_du_];
const prefixWithGare = N => prefix[correctIndexOf(N)] + articleRemoved(N);
```

Table A9. Routine `wikiCoordinates`: get geometry of "topon" from Wikipedia.

```
const Q1 ="…/api.php?action=query&prop=coordinates&format=json&titles=";
const ccOf /* get coordinates */
const ggOf = (cc,k) => cc? ({"coordinates": cc, "quality":k}): null;
const P1 = fetch(encodeURI(Q1 + prefixWithGare(topon))
    .then(a =>a.json()).then(b => !b.contains("missing")?
        ggOf(ccOf(b.query.pages),"ok"):
        fetch(encodeURI(Q1 + topon))  // no prefix
            .then(a =>a.json().then(b =>ggOf(ccOf(b.query.pages),"approx"));
/* then use that promise P1 in combination with other promises */
```

Table A10. Routine `wikiInfobox`: parsing a simple Wikipedia Infobox (no tables) for "topon".

```
const Q2 = Q1.replace("prop=coordinates",
    "prop=revisions&rvslots=*&rvprop=content&formatversion=2");
const boxOf = json =>json.query.pages[0]?.revisions[0]?.slots?.main?.content;
const addItem /* seek for item in boxOf */
const parseBox = (box, list) => box &&list&&list.length> 0 &&
    list.reduce((acc,x) =>addItem(acc,x,box), {}) || ({"missing":true});
const P2 = fetch(encodeURI(Q2 + topon)).then(a =>a.json)
    .then (b => parseBox(boxOf(b), ["latitude", "longitude", "insee", "lignes"
/* and as many as available */ ]);
```

Table A11. Routine `mergeLigneInfo`: get additional info (e.g., dates) from VGI.

```
const A = "URI_of_LignesSNCF", B = "URI_of_CSV_file";
function CSV2Json(txt) /* returns JSON from CSV [{num, enddate},..] */
function mergeLigneInfo(a, b){
    const match = (s,r) => r.enddate? (s.enddate= r.enddate&& s): s;
    return a.map(s => match(s, b.find(r =>r.num === s.num)[0]))
}
const P3 = Promise.all([fetch(A).then(a=>a.json()),
                        fetch(B).then(a=>a.text()).then(CSV2Json)])
        .then(([a,b])=> mergeLigneInfo(a,b))
```

Table A12. Routine `stationsAlongLine`: from VGI list of gares to list of geojson nodes.

```
const SST = `semi_structured_text`, Q2 = "cf A.10", num = "unique_number";
function prefixLigne (A,B) { /* returns "Ligne_de_A_à_B" …*/ }
function SSTtoJSON /* returns {origin, terminus, length, gares} from SST */
function stationsAlongLine (json, num) {
    const km = /* interpolates km according to length and rank */
    const info = /* sets: "origin" or "terminus" or ... */
    const properties = {"label":json.gares[i], num, km, info};
    return json.gares.map((s,i,t) => ({properties, "geometry":null});
}
const json = SSTtoJSON(SST);
/* check if line exists, apply wikiBSTable, or stationsAlongLine */
fetch(Q2 + prefixLigne(json.origin, json.terminus))).then(a =>a.json())
.then(b => wikiBSTable(boxOf(b)), /* resolve with Routine */
      b =>stationsAlongLine (json, num)); /* process the reject */
```

Table A13. Direct geo-location of an expected gare around a given commune toponym.

```
/* GEO-LOCATION: open a window with RLT around toponym location - if found */
const RLT = "https://remonterletemps.ign.fr/comparer/basic?mode=doubleMap" +
"&layer1=ORTHOIMAGERY.ORTHOPHOTOS.1950-1965" +
"&layer2=GEOGRAPHICALGRIDSYSTEMS.MAPS.SCAN-EXPRESS.STANDARD";
/* then locate visualy */
```

Table A14. Reverse geo-location from a given (lon-lat) couple of coordinates.

```
/* REVERSE GEO-LOCATION: open window at mkURI(lon,lat) */
const RLT = "as above";
const nom = reverseGeocode(lon,lat);  // fromany online geocoder (or via API)
const mkURI = (x,y) => RLT + "&x="+x +"&y="+y +"&z=20";
/* then locate visualy */
```

Table A15. Routine `wikiBSTable`: from Wikipedia list of gares to list of geojson features.

```
/* const Q2, constboxOf(json) from A.10 */
function prefixLigne (A,B) /* returns "Ligne_de_A_à_B" or "Ligne_d'A …*/
function parseBStable(box){
/* get relevant items using parseBox(box, itemlist) */
const share = parseBox(box, ["num", …, "schema", "schema2"]);
if(share.missing) return null; // page doesn'texist
if(share.schema) return processBStable(share.schema);
if(share.schema2) /* thereis an indirection to another page */
returnfetch(schema2).then(a =>a.json()).then(processBStable); //recursion!
}
constlineName = prefixWithLigne("Audun-le-Tiche", "Hussigny-Godbrange");
const P3 = fetch(encodeURI(Q2 + lineName)).then(a =>a.json())
    .then(b =>parseBStable(boxOf(b)),
          b =>reject (b, "some comment"));
```

Appendix B. The Toponym-Pattern, the Fork-Pattern, and Graph Representation Issues

Two recording patterns, not documented in the public datasets, were causing headaches until it has been possible to analyze them, and to name them, respectively the *toponym-pattern* and the *fork-pattern*.

Appendix B.1. Revealing "Toponym-Patterns" from Suspect Fusion Examples

There are multiple causes of toponymy ambiguities. With French toponyms, here are some usual ones:

- accents: e.g., `Benauge` is sometimes recorded with an accent `Bénauge`;
- abbreviations: e.g., `St-Paul` instead of `Saint-Paul`;
- non-standard way of associating two `names`, e.g., the *gare* "`Ermont - Eaubonne`" is between two *communes* in `Val d'Oise`, sometimes written `Ermont-Eaubonne` (hyphen w/o space);
- non-uniqueness of a *commune* name: e.g., `Cernay` exists in five French *départements*. To distinguish them, add a department name: `Cernay (Haut-Rhin)`;
- *commune* merging (2500+ merges in 2015–2019, versus 50 splits) in France, implies using a lexicon (Insee-geo) for converting to today's nom and insee values;
- also: `Paris-Nord` can be `Paris Gare du Nord` and many similar cases of a *base-name* plus a *specifier* (no rule applies).

The accents, extra spaces, and "*St.e*" versus "*Saint.e*", and space around hyphen, can be handled using what is named a "*slug*" version of the toponym. Also, a specific lexicon (*department* names) can be used to "specify" a toponym in order to removing ambiguity (the case of `Cernay`, `La Joux`, etc.). These two techniques are mixed into `slugify` and `disAmbiguous` routines (Annex.A) useful when confronting *gares* and *communes* datasets.

However, the negation *slug(a)≠slug(b)*does notprove that related *gares* are really different. More complex string distances (*Hamming* or *Levenshtein*), did not prove satisfactory on the remaining ambiguities, which are too scarce, to deserve specific software development.

Besides the cases of `Cernay/Cernay (Haut-Rhin)` and other `department-specified` toponyms, let us recall some other examples of suspected false negatives (**SP**) in TableA16.

Table A16. Cases for false negatives out of the (2014, 2017) direct pairs (top); and lists (bottom).

Cause	Label2017	Dist(m)	Label2014
SP: label ≠ and dist ≤2 m.	`Ambérieu-en-Bugey`	0	`Ambérieu`
	`Arras`	0	`Achicourt`
	`Paris-Nord-Surface`	0	`Paris-Nord-Souterraine`
	`Bainville-sur-Madon`	0	`Bainville`
	`Paris-Austerlitz`	1	`Paris-Austerlitz (Banlieue)`

Question is: *Why different names at a same place*?

Some pairs: `Ambérieu-en-Bugey/Ambérieu`, `Bainville-sur-Madon/ Bainville`, `Crécy-en-Brie-La Chapelle/Crécy-La Chapelle`, `Vernon (Eure)/Vernon-Giverny`,… have a "base" name with or without a "*specifier*". The difference is explained by a change in the name, as it occurs from time to time. The pair should be "*fusionable*".

Other pairs: `Blanzy/Blanzy-Canal`, `Châteaulin/Châteaulin-Ville`, `Huningue/Huningue (IE)`, `Paris-Nord-Surface/ Paris-Nord-Souterraine`, `Argenteuil-Triage/Le Val-d'Argenteuil`, `St-Césaire/St-Césaire (MIN)`… have a precise "*typespecifier*": a French word (`Ville`, `Canal`, `Banlieue`, `Surface` …), or an acronym (`IE`, `MIN`, `TT`, `TER`, `TGV` …), pointing the specific function of a nearby but different *gare* (e.g., cargo-only. vs. voyager, or tram-train. vs. conventional train). Then, both *nodes* of the pair should be kept as "*integrable*".

We have now an identified list: accents, Saint.e abbreviations, spaced-hyphens, three kinds of basename - specifier association (department, new name, gare-type), which may explain toponym changes. We name that recording pattern the*toponym-pattern*.

To distinguish cases and resolve pairs either "*fusionable*" or "*integrable*" is difficult.The solution is to undertake manual editing, or to keep both *nodes* as if really different.

Appendix B.2. Revealing "Fork-Patterns" from Suspect Fusion Examples

Let us name *fork-pattern*, the recording pattern consisting in attributing the `label` of some *gare*, to the last (active) *node* located where the *ligne* forks towards that *gare*. This is the case with the INSPIRE illustration in Figure 2: a *RailwayNode* just before a *RailwayStationNode*.

The case `Bauvin-Provin` is also a *fork-pattern*: a former, partly dismantled *ligne*, going to that *gare*, ends then (at recording date) at a *forknode*, therefore this is the last fork before `Bauvin-Provin` (see Figure A1). The case of `Saintes`, mentioned with the duplicates, is also a *fork-pattern*.

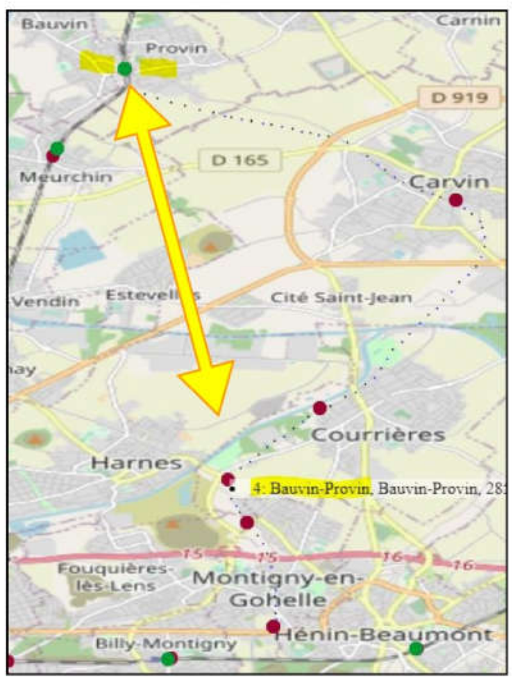

Figure A1. The Bauvin–Provin "fork-pattern".

The *gare* location is on top of the image, between toponyms Bauvin and Provin, the same label in a pop-up print, near the Harnes toponym is explained by the history of the *ligne* (small blue dots passing through Harnes, Courrières and Carvin).

That *lignen*°285,000 (*ligned'Hénin-Beaumont à Bauvin-Provin*) has been closed by segments between 1960 and 1970, and the geometry of the terminus has been attributed twice: (1) the original terminus Bauvin–Provin, was at km = 233.0, (2) then the segment end was near the Harnes*gare*, at km = 222.39, but with the Bauvin–Provin label, although 11.6 km further.

Let's use some examples in Table A17, of the suspected false positives (**SN**) that were mentioned in Section 2.4.2.

Table A17. Cases for false negatives out of the (2014, 2017) direct pairs (top); and lists (bottom).

Cause	Label	Dist (m)
SN: label = & dist > 2.2 km	Reims	2273
	Champdôtre-Pont	2299
	Sillé-le-Guillaume	2342
	Argentan	2355
	Toucy-Ville	3446
	Épinal	3644
	Fougères	4964

Question is: *Why the same gare names so far away*?

In the example of Reims, there are 4 *nodes*, two being very close (Reims on picture Table A16), one for the North *ligne*, and the farthest *fork* (N-E) being 2.273 km away.

In the example of Fougères (Figure A3, next section), two locations are 4.964 km apart: one is the now a closed *gare*, the other is the last *fork* of the former *ligne*, still located on an active *ligne*.

All cases in the list (Table A17) result from the *fork-pattern*. It was right to tag them "suspected negatives", and to not fusion them with their respective *gares*.

Appendix B.3. The Target Schema and the Graph Representation of the Network

The case with the initial UML-class diagram is that it is does nottake into account correctly the difference between a *gare-node*, and *a non-gare-node*, such as a *fork*. This is not an issue, for instance when confronting *gares* and *communes*, which requires a simple "point_in_polygon" algorithm. But a simple example (Figure A2) illustrates the problem: one *gare* (yellow double circle) is at the junction of two *lignes* coming from two simple *gares* (yellow simple circle), and a *fork* (white circle) gives the exact location of where the two *lignes* meet (Figure A2-case a).

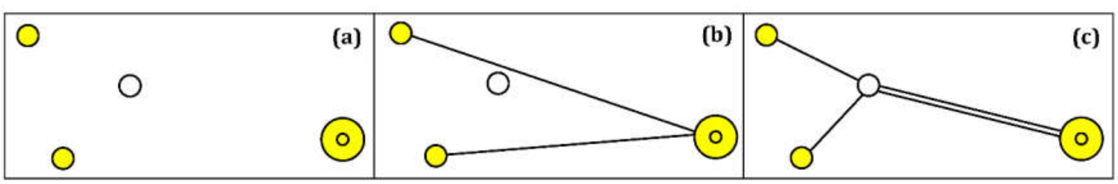

Figure A2. Mixing [*simple*]*gare*-node, [*junction*]*gare*-node and *fork*-node: (**a**) no link, (**b**) links ignoring the *forks*, (**c**) links preserving *forks*.

Case (b): the fork is ignored and a simple "digraph" representation will work correctly with algorithms: *shortest-path* (well known algorithm also named after Dijkstra), or *path-contraction*, an algorithm to build the *minor graph* of the original graph, which ignores intermediate [*simple*] *gares* and *nodes* (not terminus, not junction).

Case (c) is more complex: it preserves the information of the fork, whichleads to a better visual result. With an historical viewpoint, archiving more geographical information about the past network is much better.

The *fork-pattern* example of Fougères (Figure A3), involves four *lignes* (N, S-E, S-W, N-W). In the original data, the fork North was the last node in the list, hence plotted as the terminus: this is solution (b), illustrated on the left. Solution (c) is on right.

Figure A3. Example of the *gare* of *Fougères* before and after addition of the *fork* on ligne North-West.

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